# *Strategic Research and Innovation Agenda 2024*

ELECTRONIC
COMPONENTS AND SYSTEMS

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## ELECTRONIC COMPONENTS AND SYSTEMS

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Smart Systems Integration

Inside
Industry Association

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# INTRODUCTION AND OVERVIEW

# 0. Introduction and Overview

## 0.1 Goals and purposes of ECS-SRIA 2024

This is the seventh edition of the ECS Strategic Research and Innovation Agenda (ECS-SRIA), jointly developed by the experts of the ECS community, coordinated by the three industry associations: AENEAS, Inside Industry Association (formerly ARTEMIS-IA) and EPOSS. This revision was conducted with the goal to reflect the most recent technological and strategic trends of our industry, and provide support for the European Chips Act, which came into effect in September 2023. In particular, it further builds on the 2023 SRIA amendment, which established links between the SRIA research focus areas and the Design Platform and Pilot Lines which will be implemented as part of the Chips Act. It addresses the irruption and disruption of AI tools in the practices of the ECS community, and the digital society at large. While already present in earlier edition, quantum technologies are getting additional attention in this new edition. This edition also develops a tighter integration with the research topics identified by the report "RISC-V and Open Source Hardware", included as an annex, with a number of chapters referring to it. One initial key area in which RISC-V is expected to be a strategic asset is in the domain of automotive, where the European ambition is to define and develop the requirements and the elements for building a European Automotive RISC-V Reference platform. In a later stage RISC-V can be applied to multiple other application domains, as documented in a Position Paper of the European Working Group on this topic.

On top of these general trends, individual chapters also reflected the latest evolutions: **Chapter 1.1**, Process Technology, Equipment, Materials & Manufacturing, introduced quantum sensing technologies and its advantages vs. conventional sensors, and included some quantum computing technologies in its long-term timeline. Updates in **Chapter 1.2**, Components, Modules & Systems Integration, cover several topics, including lidar, radar and vision integration as well as photonics integration. **Chapter 1.3**, Embedded Software and Beyond) introduced discussions on safe and secure programming, as well as the support of Artificial Intelligence and Machine Learning in the software development cycle. It also includes a new major challenge on hardware virtualization for efficient software engineering. The main updates in **Chapter 1.4**, System of Systems, pertain to evolvability and controllability of system of systems, as well as illustration of the impact of AI and machine learning, and the challenge of inclusion of legacy systems in system of systems. Regarding Cross Sectional chapters, in **Chapter 2.1**, Edge Computing & Embedded AI, updates mainly focused on AI accelerators: state of the art, sustainability of edge AI, requirements for execution of generative AI at the edge. **Chapter 2.2**, Connectivity, included an in-depth presentation of the main frequency bands being considered for 6G, and discussed the synergies with the Design Platform and the Pilot Lines which will be implemented as part of the Chips Act. **Chapter 2.3**, Architecture and Design: Methods and Tools, stressed the topics of virtual verification and validation and of validation of AI-based systems, and in particular strengthened the research topics in Electronic Design Automation. It also identified links between its research focus areas and the Design Platform. In **Chapter 2.4**, Quality, Reliability, Safety and Cybersecurity, Major Challenges 4 (Ensuring safety and resilience) and 5 (Human systems integration) have been extensively rewritten. Regarding the Application chapters, in **Chapter 3.1**, Mobility, requirements for system-on-chip, linked to the design platform, have been added, the software-defined vehicle chapter was reworked, and green deal requirements for existing mobility fleets were introduced. **Chapter 3.2**, Energy, covers the challenges to cope with the Green Deal targets for the transition to a net zero emission society, was assessed and is unchanged. **Chapter 3.3**, Digital Industry, is unchanged in its structure and focuses on European manufacturing expected technological evolutions toward sustainability, resilience and sovereignty, while European picture facts and trends have been updated, together with links with main European initiatives. Challenges for **Chapter 3.4**, Health and Wellbeing, remain the same, while the text insists on the necessary reconfiguration of the healthcare ecosystem in Europe. The update of **Chapter 3.5**, Agrifood and Natural Resources, focuses on agriculture decarbonisation. **Chapter 3.6**, Digital Society, has been updated to incorporate the advent of AI in general and ChatGPT in particular. Finally, in **Chapter 4**, Long term vision, one subsection has been added on Machine Learning and Artificial Intelligence, as well as one on Quantum Computing.

**Why this ECS-SRIA?**

This document describes the Major Challenges, and the necessary R&D&I efforts to tackle them, in micro- and nanoelectronics for smart systems integration, all the way up to embedded and cyber-physical systems, and System of Systems. This SRIA is intended to be funding-programme-agnostic, and can be used as a basis for the various cooperative programmes across Europe.

However, the scope of our work, and of this document, is firmly within the ECS domain. For details on developments in the specific application areas further up the value chain, please consult the SRIAs of other associations or public/private partnerships (PPPs) addressing those specific areas.

The range of this ECS-SRIA is very wide, going from transistors within silicon chips acting as individual electrical switches for integration in smart systems up to global System of Systems performing complex cognitive tasks and interacting with numerous humans and machines over a wide geographical spread. A very simplified view of this ECS technology "stack" is illustrated in **Figure 0.1** with an example.

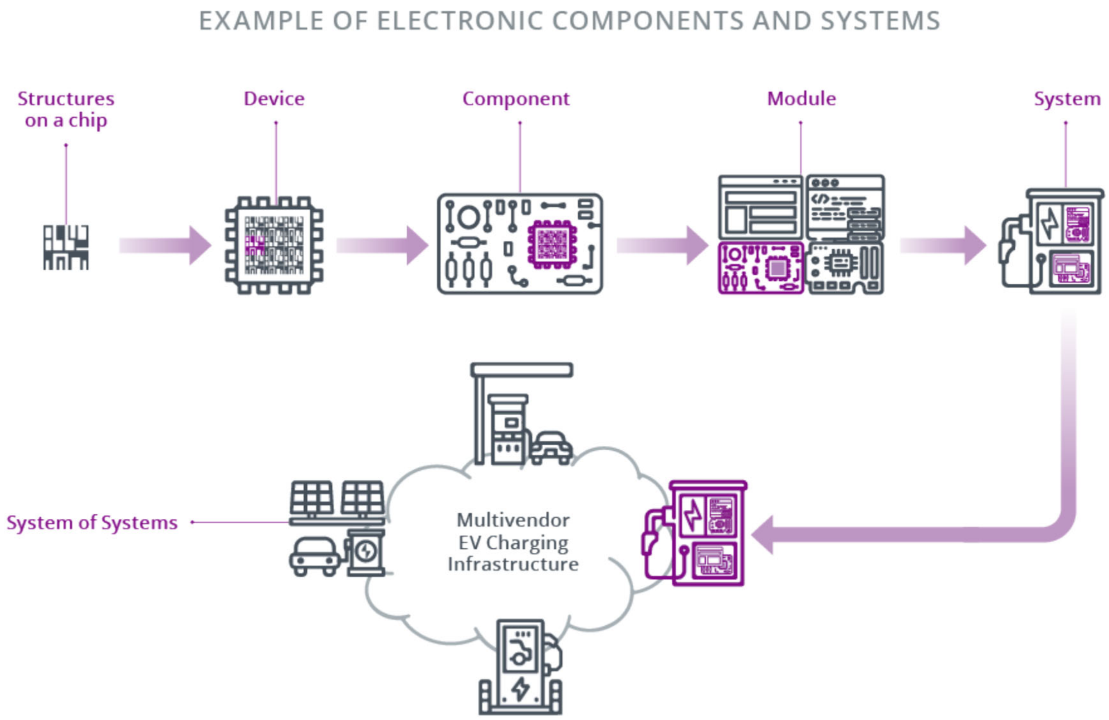


*Figure 0.1 - Different integration levels illustrated by the example of an EV charging infrastructure*[1] *(Source: Eurotech)*

Designing such artefacts requires an interdisciplinary hierarchical approach, whereby various ECS specialists are working at different abstraction levels. As a result, the same term can have different meanings for specialists of different ECS domains: for instance, a “system” designed and implemented within a given development process may be integrated as a “component” into a higher-level “system” within another development step of the engineering process. Nevertheless, to avoid confusion, since 2021 the ECS-SRIA includes a glossary, where many of the key terms are defined, to avoid inconsistency across the various chapters. It was also felt that developing a common language was important in building a strong and integrated ECS community. In addition, some of the bricks of the ECS technology “stack” are further detailed below.

- Device: in the context of the ECS-SRIA, and if it is not further qualified, a device will be defined as a “packaged chip”, whether it is a packaged integrated circuit (e.g. system on a chip, memory, processor, or microcontroller) or a micro-electromechanical system (MEMS)/micro-opto-electro-mechanical system (MOEMS). A device performs a general electrical, electronic or electrical/electronic/physical transduction role.
- Component: a combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case. A component is not self-contained in all its functions, as it requires the close support of other components for operation (e.g. in data processing, power handling, and embedded software).
- Module: a combination of correctly integrated components in which their assembly embodies a specific functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and software, making it interchangeable between systems, and allowing a higher abstraction level in systems design.
- System: for the purpose of this SRIA, a system is a set of electronic-based constituents (subsystems, modules and components, realised in hardware, software, or both) that are integrated in a way that allows the system to perform a desired (set of) function(s). Due to ECS typically being constructed hierarchically, a “module” (e.g. camera or other sensor) being part of the electronic “system” in an autonomous car might itself be referred to as a “system” when being designed (e.g. while integrating lower-level components together to achieve the “camera” function).
- System of Systems (SoS): a collection of independent and distributed embedded and cyber-physical systems dynamically composed to generate a new and more complex system, provided with new functionalities and driven by new goals not present in the constituent embedded and cyber-physical systems individually. The difference between a “system” (comprising subsystems, modules and components) and a “System of Systems” (also comprising subsystems) is that the subsystems of a system are chosen and integrated during design-time (i.e. completely under the control of the engineers), while in a System of Systems the constituent (sub)systems are physically independent and dynamically form a System of Systems at run-time.

**The structure**

The first part of the ECS-SRIA is composed of four chapters focused on the **Foundational Technology Layers** and their technical challenges along the technology stack, from materials and process technology to components, modules and their integration into electronic systems, embedded software developments and software technologies, to full systems and Systems of Systems. These foundational layers are characterised by hierarchical dependencies due to the inherent nature of ECS and the way they compose and integrate in complex structures. Advances in all **Foundational Technology Layers** will be essential to creating new electronic chips, components, modules, systems, and systems of systems along the value chain: these are the fundamental elements required to build the digitalisation solutions of the future.

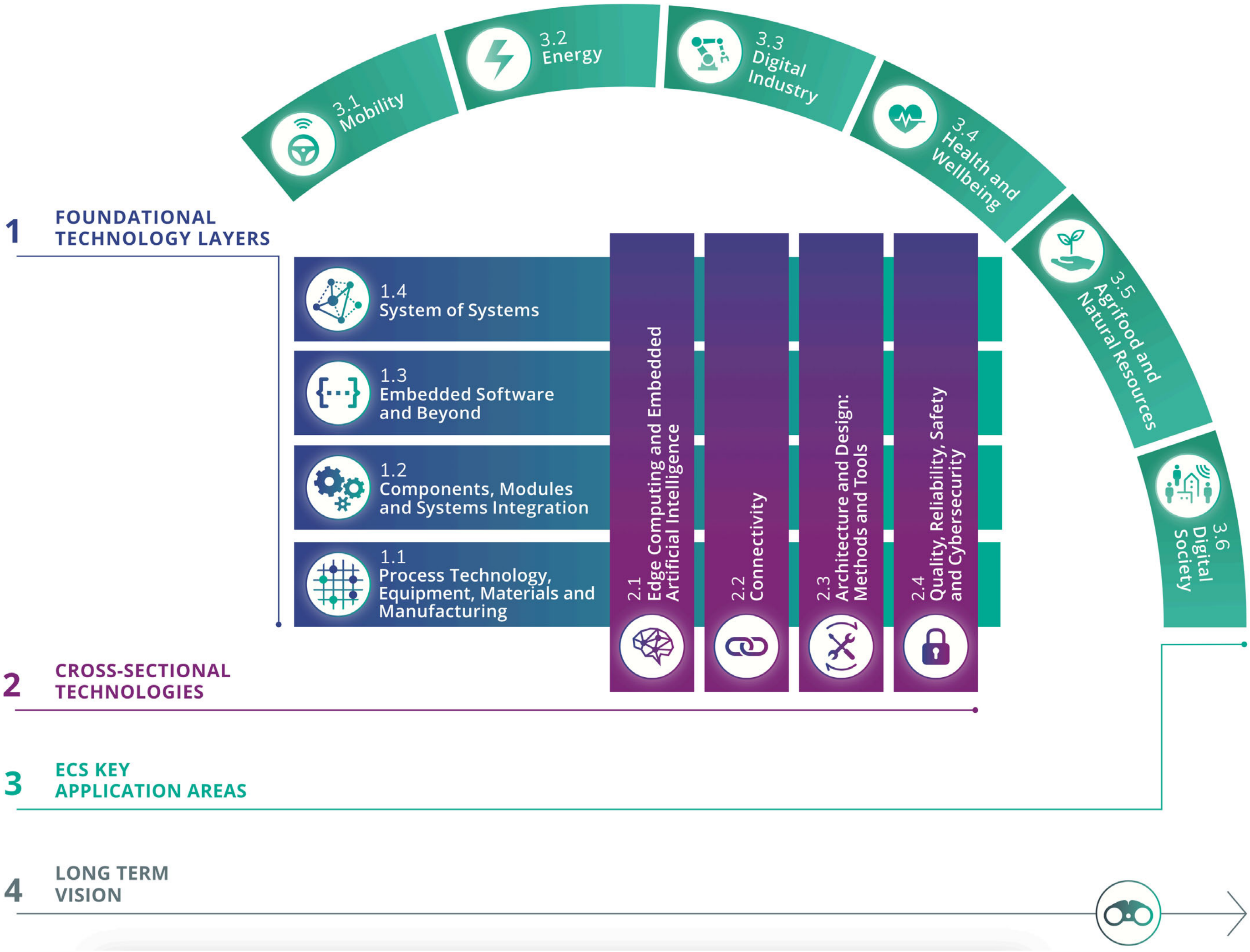


*Figure 0.2 - The structure of the ECS-SRIA*

The foundational layers represent a very fertile ground where new interdisciplinary technologies, products and solutions can grow. They are then complemented in the second part of the ECS-SRIA by four **Cross-Sectional Technology** chapters that focus on transversal areas of scientific research and engineering, where innovative results emerge from the joint contribution of the foundational layers to those specific areas. **Edge Computing and Embedded Artificial Intelligence**, or **Connectivity** (e.g. 5G to 6G) will require new integrated circuits to develop innovative electronic components that can be used to develop smarter and more connected components, modules and entire systems, running smart software that will offer new functionalities and capabilities. That will allow these systems to interact, cooperate and merge in larger systems of systems. Similarly, **Architectures and Design: Methods and Tools** have to be further developed to provide support to each of the foundational layers, covering all domains along the technology stack, across the entire lifecycle of technologies and products. The same applies to **Quality, Reliability, Safety and Cybersecurity** concepts that can only be addressed successfully if they are encompassing the whole ECS process flow along the entire value chain.

The innovation generated by these cross-sectional technologies will be applied across foundational layer stacks and amplify the effect of innovation in all key ECS application domains. Of course, there is some overlap among the eight technology chapters since they are closely linked, but as they examine the individual challenges from different perspectives, this overlap is extremely constructive and generates valuable synergies.

In the third part of the ECS-SRIA, six **Application c**hapters describe the challenges arising from specific ECS application domains that are key for Europe and identify the R&D&I efforts required by these application domains as regards ECS.

Finally, the **Long-Term Vision** chapter illustrates our vision of the ECS beyond the time horizon covered by the other chapters. It seeks to identify the research subjects that must be addressed at low TRL levels as foundation and preparation for the crucial developments in European industry over the next decade.

Based on the trends and plans described in the preceding chapters, the long-term industrial requirements are also examined to help research programmes understand which hardware, software and system solutions should be produced most effectively for the continuous improvement of European digital technology.

## 0.2 How to read it

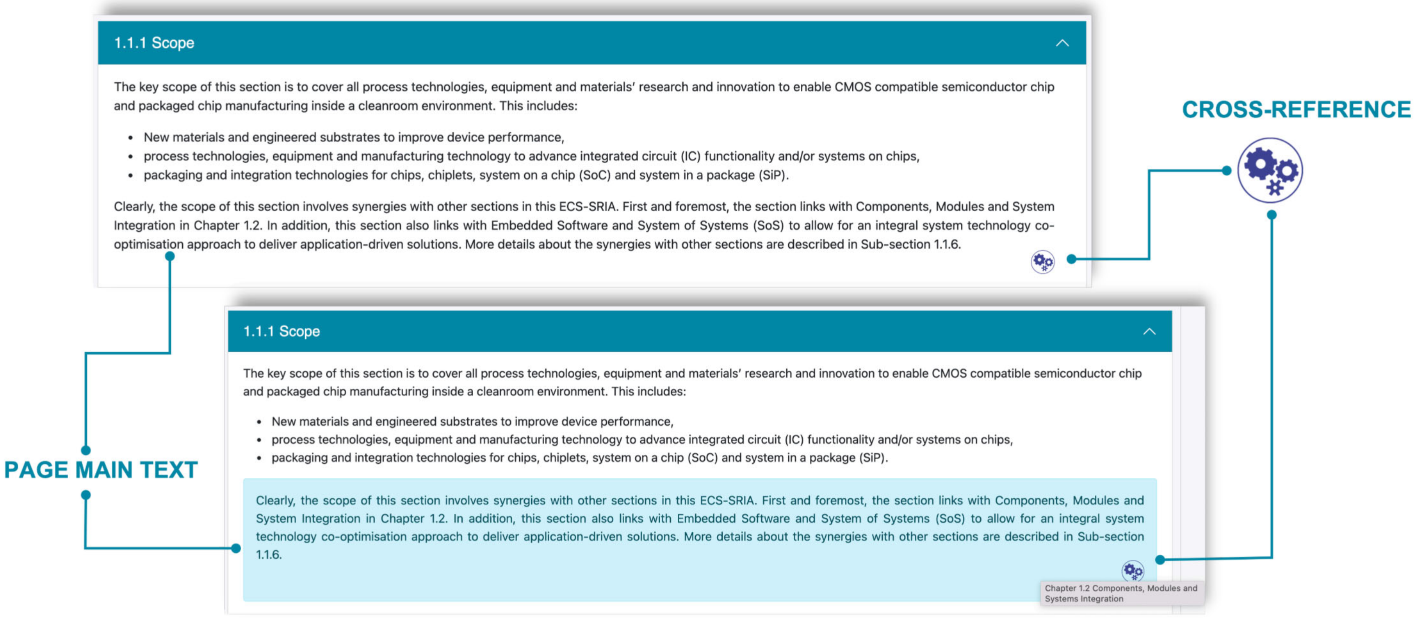
As mentioned, the ECS covered by this document is very wide-ranging, and involves many technical disciplines in materials, processes, hardware and software. This means not many will understand all the technical details presented in the ECS-SRIA, and most readers will only want to read those chapters that cover the disciplines of their interest.

The structure of all the **Foundational Technology** and **Cross-Sectional** chapters is identical. This forms the basis for the authors to explore each application area from a different perspective, with the intention here being that the application demands are the main focus, not the technical challenges.

A **Glossary** describing the terms used in the document, as well as a List of **Acronyms** used in the document, can be found in the **Appendix**. The Analytical Index available in the previous releases of the ECS-SRIA has been substituted by an advanced Search functionality. At the end, the reader can also find a **List of Contributors** who collectively wrote this ECS-SRIA.

Finally, to highlight the synergies/links between the chapters and provide hints to the reader, cross-references have been introduced alongside the text.

Cross-references consist of the chapter icon and appear alongside the text. When hovered on, they indicate the relevant chapter number and the topic or concept described in the text is also highlighted. When clicked on, they will navigate you to the referenced chapter.



1.1.1 Scope

The key scope of this section is to cover all process technologies, equipment and materials' research and innovation to enable CMOS compatible semiconductor chip and packaged chip manufacturing inside a cleanroom environment. This includes:

- New materials and engineered substrates to improve device performance,
- process technologies, equipment and manufacturing technology to advance integrated circuit (IC) functionality and/or systems on chips,
- packaging and integration technologies for chips, chiplets, system on a chip (SoC) and system in a package (SiP).

Clearly, the scope of this section involves synergies with other sections in this ECS-SRIA. First and foremost, the section links with Components, Modules and System Integration in Chapter 1.2. In addition, this section also links with Embedded Software and System of Systems (SoS) to allow for an integral system technology co-optimisation approach to deliver application-driven solutions. More details about the synergies with other sections are described in Sub-section 1.1.6.

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*Figure 0.3 - Cross-references*

**References** within a text are indicated by small numerical markers embedded in the content, e.g. [0]. Upon clicking one of these markers, readers are instantly directed to the corresponding entry within the References section. This feature allows readers to seamlessly access the sources from which the information has been derived.

Furthermore, by clicking on the same footnote number located in the **References** section, readers can effortlessly return to the exact point within the main text where the reference was initially cited. This interactive function not only enhances the reader's comprehension but also streamlines the process of verifying and exploring the sources behind the presented information.

## 0.3 Highlights and common challenges for the next few years

In this ECS-SRIA, the Major Challenges identified by the different chapter teams were analysed and merged into four Main Common Objectives for the ECS community. In addition, three common Roadmaps covering the short term (up to 2028), medium term (from 2029 to 2033) and the long term (2034 and beyond) provide the key milestones derived by the chapter teams.

**Main Common Objectives**

For each technology and application domain, the ECS-SRIA identifies specific challenges, with a focus on the most critical aspects to be tackled from the perspective of innovation. The analysis of each challenge illustrates the state of the art of the associated technology and/or application domains, describes the vision of the ECS community for the future, identifies potential outcomes, and defines research and engineering activities on the key focus areas that are fundamental to successfully address the challenge.

Across this document, 68 different Major Challenges are identified that have emerged from the analysis of the foundational technologies, the cross-sectional technologies and the key application areas. The Major Challenges are frequently interdependent – they influence each other, become increasingly demanding, and have an impact on many areas, including technology innovation, industrial competitiveness, security, safety, business and environmental sustainability, society, etc. From this perspective, the Major Challenges represent key factors for the achievement of the four Main Common Objectives, which are aligned with the European Commission's strategic priorities (see table in Appendix).

**Main Common Objective 1: boost industrial competitiveness through interdisciplinary technology innovations**

Electronic components and systems, by their inherent nature, are the result of interdisciplinary research and engineering. These require competencies in diverse technology domains, including process technology, equipment, materials and manufacturing, electronics, and telecommunications, as well as cross-sectional technologies such as edge computing, artificial intelligence, high-speed connectivity, and cybersecurity. One major strategic trend is the evolution to the use of Open-Source Hardware and Software, whereas RISC-V based architecture solutions will become an asset of a competitive nature for the European industry.

ECS technologies are turning each digital component and equipment into an intelligent cyber-physical system, thereby driving new market demand. Embedded platforms for automotive (electric mobility, autonomous driving, etc.), industrial (Industry 4.0, IoT for agriculture, etc.), medical (medtech for connected patients, etc.), and energy (new energy-aware ECS and more flexible energy management, etc.) will rely extensively and increasingly on ECS technologies.

These trends compel ECS research to be interdisciplinary to benefit from the multiple available sources of innovation, as well as to be research-intensive and market-oriented. This will ensure forthcoming ECS innovations will be of strategic value for Europe and boost its industrial competitiveness in all its value chains, and help building the strong industrial base essential for European strategic autonomy.

With the Chips Act, the KDT JU transits to the Chips JU, with a mandate extended to capacity building activities and related research and innovation activities of four operational objectives of the Chips for Europe Initiative, as set out in the Chips Act article 4:

1. building up advanced design capacities for integrated semiconductor technologies;
2. enhancing existing and developing new advanced pilot lines across the Union to enable development and deployment of cutting-edge semiconductor technologies and next-generation semiconductor technologies;
3. building advanced technology and engineering capacities for accelerating the innovative development of cutting-edge quantum chips and associated semiconductor technologies;
4. establishing a network of competence centres across the Union by enhancing existing or creating new facilities.

These objectives translate in particular into the following additional activities for the JU:

- The development of new capabilities to design, prototype and test innovative chips through pilot lines on semiconductor technologies, with the close collaboration of European RTOs and industrial vertical sectors.
- The establishment of competence centres, which will address the lack of skills that is affecting the European labour market, trying to provide training support for future professionals in the whole ECS domain, consolidating and strengthening the rich knowledge base required by interdisciplinarity.
- The setting up of a new Virtual Design Platform and specific funding instruments which will provide support to the rich, diverse and multidisciplinary ecosystem of European SMEs and start-ups, facilitating investments in research, development, and production and simplifying the process of bringing innovation from "the lab to the fab".

This SRIA is the reference document for all research and innovation activities of both the former (under KDT) and these new Chips JU activities. This extension reflects the intrinsic interdisciplinarity of the SRIA and further strengthens it from different perspectives.

All the new initiatives introduced by the Chips Act have been conceived to boost European competitivity in the ECS market and ECS-based application domains, guiding investments and resources towards strategic areas of semiconductor technology that are most critical for the European industry's competitiveness. This SRIA contributes to the identification of these critical areas and of the associated challenges that will characterise their development in the next ten years. The role of the SRIA is fundamental to identify the key starting points for R&D&I and to setup multi-annual synergies with the pilot lines that will focus on more mature prototyping. The SRIA will also potentially provide the elements for the "first-of-a-kind facilities" envisioned by Pillar 2: the synergies between these three steps represent the key strategy to increase European capacity building, to boost competitiveness, and to anticipate, prevent and effectively manage future crises.

**Main Common Objective 2: ensure EU digital autonomy through secure, safe and reliable ECS supporting key European application domains**

A strong, competitive and sovereign ECS industrial and technological base will help Europe to:

- Fulfil its own digital technology needs in a way that reflects its interests and values.
- Improve the resilience of its critical infrastructure and ICT systems.
- Develop its ability to shape international rules, norms and standards.

European strategic autonomy will rely on a trustworthy and virtuous cycle by supporting the development of innovative ECS technologies focused on security, safety, reliability, dependability and privacy.

These innovative technologies will simplify the implementation of the European Strategy for Data[3], [4], and ensure security, privacy-by-design and strategic autonomy all along the industrial and digital value chains. Such technological innovation will also enable the design and development of secure, safe, reliable, dependable, privacy-compliant electronic components and systems, as well as generate new requirements that will drive the development of new technologies, restarting the cycle.

Threats to Europe's strategic autonomy are to be found in the microelectronics value chain, and downstream in the component user segments of the electronics industry. In this context, the Major Challenges identified by the ECS-SRIA will help develop innovations in secure, safe and reliable ECS technologies for creating EU-based/ made solutions in the key European applications domains of:

- Aerospace, defence, security.
- Automotive, transportation.
- Machinery, robotics, electrical equipment, energy.
- Communications, computing.
- Healthcare and well-being, etc.

European technology-based, secure, safe and reliable ECS, combined with European AI solutions, are critical to securing global leadership and strategic autonomy in key areas such as ICT and to ensure compatibility with EU values.

The Chips Act aims at consolidating and strengthening European strategic autonomy, extending and boosting the KDT with a new specific focus on the upstream of the ECS value chain. Reducing the dependency on non-European suppliers and avoiding future shortages represent the main steps towards strategic autonomy: reaching the independence on non-European suppliers for critical ECS is crucial for ensuring that European industries and key application domains have a stable supply of semiconductors, even during future global disruptions or geopolitical tensions. Technological leadership and strategic autonomy are the primary ingredients required to:

- Control ECS manufacturing to produce solutions designed to meet stringent security requirements; an essential aspect for maintaining secure digital infrastructures and key applications (e.g. automotive, defence, energy, etc.).
- Ensure resilient supply of semiconductors produced in Europe to support the resilience of critical infrastructure, including energy, transportation, and healthcare systems, which rely on advanced chips.
- Achieve a greater control over the technology infrastructure that underpins the European digital economy, ensuring that critical data and systems remain under European jurisdiction.
- Enhance Europe's economic competitiveness, leading to the creation of high-tech jobs, stimulating innovation, fostering economic growth, and making Europe less dependent on external economic forces.

**Main Common Objective 3: establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal**

European strategic autonomy will also require the sustainability and resilience of the entire ECS value chain since the development of innovative technologies focused on sustainability and the Green Deal will support ambitions to achieve a green, resilient and competitive Europe.

Moreover, the serious effects of climate change that we are experiencing daily and the current geo-political situation, which highlights our dependency on non-European fossil energy providers, further reinforce the need for Europe to accelerate its transition to climate neutrality by 2050.

This challenge must be perceived as an opportunity to create a new environment for boosting innovative aspects of technology and business models through achieving the following:

- Relying extensively on ECS-based technologies and digitalisation as key factors for lowering our global energy footprint at all levels of the economy, and by placing sustainability at the heart of combined digital and green transitions.

- Positioning the European players in hardware as front-runners in sustainability to secure a wider market so they can become world leaders. This will need European companies to consider the circular economy, new market positioning (by turning small market shares into specialisation areas), the environmental impact of global manufacturing, etc.

- Establishing this carbon-neutrality challenge, based on a close link between the digital and green transitions at the core of future funded collaborative research and innovation in ECS. This will help ensure a positive impact for each stage of the value chain, and to achieve carbon neutrality right down to the final application/digital service.

This new context is required to fight and reduce the effects of climate change.

Pillar 1 of the Chips Act will contribute to the development of new materials, new manufacturing processes, advanced devices and a higher level of integration, which impact significantly on the power consumption of ECS, on the sustainability of their design and manufacturing, and on ECS-based applications, contributing the objectives of the Green Deal. Sustainability and green are considered as a transversal objective addressed by all the technology and application domains covered by this SRIA, which has already identified the challenges that must be tackled by the new technologies that will be developed within Pillar 1 in the next years (e.g. FDSOI, heterogeneous integration, new design methods and tools, etc.). But the benefits of the Chips Act will extend beyond the pure technological aspects:

- Promoting the principles of a **circular economy** in semiconductor manufacturing can be a significant step. This might involve designing chips for longevity, enabling easier recycling, and minimizing electronic waste.
- Encouraging the use of sustainable materials in chip production can reduce the **environmental impact**. This could involve sourcing low-impact materials, using recyclable substrates, and adopting eco-friendly packaging. This extends also to promoting **environmentally friendly manufacturing** practices, which can reduce the environmental footprint of chip production (e.g. renewable energy sources, reduction of water and resource use, etc.), reduction of $CO_2$ and other greenhouse gas emissions, better recycling and more responsible disposal practices for electronic components and waste.
- The **strategic autonomy** introduced by the Chips Act contributes to **economic sustainability and security**, through a reduced dependency on non-European suppliers, an increased production capacity, more competitive manufacturing processes and products, a resilient supply chain, circular economy promotion, etc.
- A sustainable semiconductor industry is also vital for supporting the sustainability goals of the **application domains** based on ECS, such as those related to renewable energy, electric vehicles, digital industry and sustainable agriculture.

**Main Common Objective 4: unleash the full potential of intelligent and autonomous ECS-based systems for the European digital era**

ECS must have intelligence and autonomy capabilities to control their complexity more efficiently and more cost-effectively. This will help provide novel advanced functionalities and services, limit human presence to only where it is strictly required, improve the efficiency of vertical applications, etc. Intelligence and autonomy are also required for the role of ECS in the application domains, representing an important factor for the sustainability and resilience of the value chains: an ECS-based system that provides intelligent energy management, relying on technologies such as AI, represents a key building block – for example, for smart home and energy applications. Moreover, it also improves the resilience required to ensure optimal energy consumption in critical conditions and contributes to the sustainability of the value chain associated with vertical applications, since it reduces operational costs, environmental impact, improves the quality of service (QoS), return on investment (ROI), etc., thereby strengthening the global competitiveness of European companies and helping to achieve the objectives of the EU's Green Deal.

The Chips Act will allocate significant resources for R&D&I, supporting the development of cutting-edge semiconductor technology that will be crucial to unleash the power of AI: for example, higher levels of integration will contribute to the diffusion of AI, specifically on the edge where the right ratio between dimensions, energy consumption, computing power and cost makes the difference. With an innovative and strong semiconductor industry Europe could improve its competitiveness in the global AI landscape, and this could contribute attracting AI talent, companies, and research initiative in Europe. The Chips Act resources will also be crucial to consolidate the European future position in the AI market and contribute to the supply chain resilience, supported by a robust semiconductor industry in AI hardware. The new resources will boost the R&D&I activities described in Chapter 2.1 of this SRIA, potentially accelerating the related timeline, and ensuring a solid support for all the vertical domains covered by the Application chapters.

**Ensure engineering support across the entire lifecycle of complex ECS-based systems**

Modern ECS-based systems are complex, and they cannot be properly elaborated and used without the appropriate engineering support across the entire lifecycle, from requirements analysis to design, development, deployment/commissioning, operation/management, remote-maintenance repair and overhaul, retirement/recycling and evolution.

Engineering support represents a key factor for achieving the four Main Objectives as it:

- Impacts industrial competitiveness by simplifying life cycle management, and improves the quality of the engineering process, making it more cost-effective and agile.
- Simplifies and improves the development of trustworthy ECS technologies, products and applications.
- Supports sustainability and resilience that reduce lifecycle management costs, as well as ensuring the automation and continuity of operations.
- Is fundamental to unleashing the full potential of intelligent and autonomous ECS, which requires completely new approaches to engineering, design and development methodologies, as well as toolchains and tools.
- Improves professional training and education by strengthening and developing new and specific skills.

ECS engineering plays a key role in Pillar 1 of the Chips Act, which includes specific instruments to support the engineering process, specifically in the critical area of new chips design, to increase design activities and create a strong design ecosystem in Europe. A Virtual Design Platform (VDP), providing design tools, an IP library for various technologies, and PDKs to access the fabs, will be established to simplify and accelerate the process of going "from the lab to the fab", and make that process more accessible for EU companies, start-ups and SMEs, especially fabless. Specific Design Enablement Teams (DET) will support this process providing targeted assistance on designing chips and more complex systems, with the presence of experts in the design flow, foundries, and pilot lines, from virtual prototyping via tape-out and engineering samples to high volume production. To this regard, Competence Centres will be established to address the skills challenges that Europe is experiencing and provide education and professional training solutions for the next generation of chip designers: DET and a Competence Centre will provide advice, training, and skills-building solutions, supported by the industry-grade training framework offered by the Virtual Design Platform. Chapter 2.3 and other chapters address many of the R&D&I challenges that the VDP and Competence Centres will have to face in the next decade.

**Artificial intelligence topics in the ECS-SRIA**

While not a totally new topic (it is used for example in several embedded system for vision, enabling autonomous vehicles), Artificial Intelligence really came to the forefront for the public at large in 2023, with tools such as Chat-GPT (released for public use only on November 30th, 2022) and other generative AI (Dall-E, Stable Diffusion) that grabbed the headlines in mainstream media. The ECS Research and Innovation roadmap interacts with the development of AI tools and algorithms in two symmetrical ways: ECS are an enabler for new AI developments, and AI can in turn be a significant enabler for new ECS advances. Those two aspects are extensively discussed in this current edition of the SRIA.

- ECS as enabler of AI: Chapters 1.1 and 2.1, as well as the Long Term Vision Chapter, stress the importance of moving the processing of AI algorithms locally on a hardware device (in deep-edge devices, edge devices or on-premises computing resource depending on the application) close to where the data is generated (e.g. by a sensor), a trend known as "embedded AI" or "edge AI". Benefits include reducing the energy consumption of the data infrastructure by transmitting only relevant data or pre-treated information, improving data protection, increasing security and resilience due to a reduced reliance on telecommunication links, reducing latency, and decreasing memory footprint. Many of the focus research areas identified in Major Challenge 1 (Advanced computing, memory and in-memory computing concepts) of Chapter 1.1 support this move towards AI at the edge. More generally, energy consumption of AI solutions is a significant issue due to the expected widespread increase of their usage, and new concepts and architectures (bio-inspired and other ones) must be explored to respond to it. Likewise, the four Major Challenges (increasing energy efficiency, managing system complexity, increasing device lifespan and ensuring European sustainability in AI) identified by Chapter 2.1 all cover research topics which will enable the development of a strong European embedded AI ecosystem.

- AI as enabler of ECS: this aspect is discussed in Chapter 2.3, where several examples of AI use are listed to tackle Major Challenge 3 (managing complexity), such as AI-based methods for the architecture exploration and optimisation, to achieve a global optimum, AI-based guidance in the V&V process, and automatic generation of test cases with AI support. Moreover, in its entirely new section devoted to Machine Learning and Artificial Intelligence, the Long Term Vision Chapter states that AI/ML methods are increasingly adopted in design space exploration at several stages of circuit design, as well as in design testing and verification. The potential of these AI-based methods is not limited to circuit design and extend to large scale ECS products encompassing HW and SW, as well as multi-physical, distributed systems. They are also expected to provide guidance to engineers in multi-risk (safety, security, privacy, and other trustworthiness risks) optimisation problems. Gathering / generating the appropriate data to train the models is identified as one of the most difficult issues to be addressed.

A third aspect is that AI adds complexity to the systems it empowers. This in turn raises additional issues at the design phase, as addressed by Chapter 2.3. There, Major Challenge 1 (Extending development processes and frameworks to handle connected, intelligent, autonomous, evolvable systems) and Major Challenge 2 (Managing new functionality in safe, secure and trustworthy systems) stress the need to develop new design and verification and validation methods for AI-based ECS, including ECS evolving during lifetime.

Finally, a purely technical approach to develop trustworthy and explainable AI, or having AI in the loop with verification of its results might not be enough to address the growing public concerns about the potential dangers of AI (pushing many governments across the world to sign the Bletchley Declaration on AI safety). In the years to come, cooperation between multidisciplinary partners with backgrounds in AI, ECS and social sciences, as well as access to "foundation models" by European academia and industry will be required to achieve and ensure the acceptance of efficient and responsible AI-based ECS, reflecting European values.

## 0.4 The ECS global timeline for Europe

The ECS-SRIA 2024 lists a number of milestones to be reached in the short term (2024–2028), medium term (2029–2033) and long term (2034 and beyond) via collaborative research projects across Europe, reflecting the ambition of the ECS industry towards the achievement of the four Main Objectives identified above.

The following figures summarise the most salient milestones to be reached in the various domains covered by the ECS-SRIA over the three time periods:

- **Short term (2024–2028)**
  The industry has a precise idea of what will be achieved during this short-term timeframe.

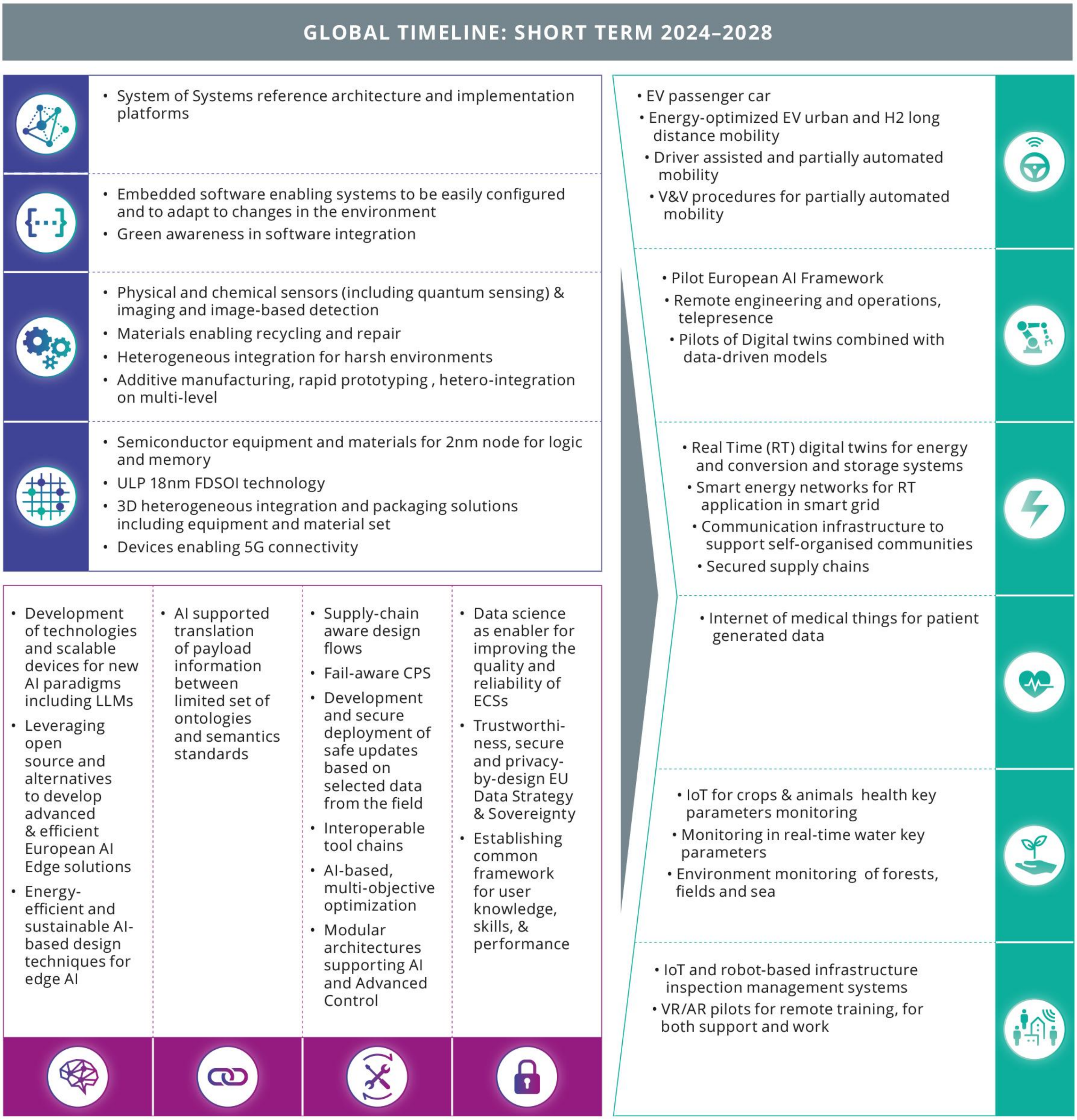
- **Medium term (2029–2033)**
  There is still reasonably good knowledge of what can possibly be achieved.

- **Long term (2034 and beyond)**
  Expected achievements are more of a prospective nature.

Including a milestone in each of these time periods means that the described features are expected to be available at TRL levels 8–9 (prototype or early commercialisation) within that timeframe. For example, the **Components, Modules and Systems Integration** Chapter expects that, within the next five years (short term). The materials that enable recycling and repair will be available. These materials will allow for the deployment of the monitoring of forests, fields and oceans, as envisioned by the **Agrifood and Natural Resources** Chapter over the same time horizon. In parallel, this monitoring will gain in efficiency due to the development of advanced AI edge solutions leveraging open source or alternative strategies, as forecast by the Chapter on **Edge Computing and Embedded Artificial Intelligence**.

**The above example also clearly shows that progresses in the various domains covered by the ECS-SRIA are deeply interconnected. Innovation in one area is building upon, or being driven by, innovation in other areas.** Similar examples could, of course, be developed for the other time horizons, as represented in the Figure 0.4, Figure 0.5, Figure 0.6.

More detailed diagrams, including additional milestones, are presented in the individual chapters.



## GLOBAL TIMELINE: SHORT TERM 2024–2028

- System of Systems reference architecture and implementation platforms

- Embedded software enabling systems to be easily configured and to adapt to changes in the environment
- Green awareness in software integration

- Physical and chemical sensors (including quantum sensing) & imaging and image-based detection
- Materials enabling recycling and repair
- Heterogeneous integration for harsh environments
- Additive manufacturing, rapid prototyping , hetero-integration on multi-level

- Semiconductor equipment and materials for 2nm node for logic and memory
- ULP 18nm FDSOI technology
- 3D heterogeneous integration and packaging solutions including equipment and material set
- Devices enabling 5G connectivity

- Development of technologies and scalable devices for new AI paradigms including LLMs
- Leveraging open source and alternatives to develop advanced & efficient European AI Edge solutions
- Energy-efficient and sustainable AI-based design techniques for edge AI

- AI supported translation of payload information between limited set of ontologies and semantics standards

- Supply-chain aware design flows
- Fail-aware CPS
- Development and secure deployment of safe updates based on selected data from the field
- Interoperable tool chains
- AI-based, multi-objective optimization
- Modular architectures supporting AI and Advanced Control

- Data science as enabler for improving the quality and reliability of ECSs
- Trustworthiness, secure and privacy-by-design EU Data Strategy & Sovereignty
- Establishing common framework for user knowledge, skills, & performance

- EV passenger car
- Energy-optimized EV urban and H2 long distance mobility
- Driver assisted and partially automated mobility
- V&V procedures for partially automated mobility

- Pilot European AI Framework
- Remote engineering and operations, telepresence
- Pilots of Digital twins combined with data-driven models

- Real Time (RT) digital twins for energy and conversion and storage systems
- Smart energy networks for RT application in smart grid
- Communication infrastructure to support self-organised communities
- Secured supply chains

- Internet of medical things for patient generated data

- IoT for crops & animals health key parameters monitoring
- Monitoring in real-time water key parameters
- Environment monitoring of forests, fields and sea

- IoT and robot-based infrastructure inspection management systems
- VR/AR pilots for remote training, for both support and work

*Figure 0.4 - Global Timeline: Short term 2024–2028*

## GLOBAL TIMELINE: MEDIUM TERM 2029–2033

- Evolvable, predictable and controllable composition of functional and extra-functional properties of System of Systems.

- Programming models and virtualization for hardware across computing continuum
- Interface management to prepare for system of systems integration
- Embedded software enabling systems to dynamically (re)-configure after updates or changes in the environment
- Maturity model for robustness of embedded software

- Energy management towards low/zero power
- Integrated systems with heterogeneous integration of different active (e.g. SI, III-V) and passive components on wafer, chiplet and chip levels
- Organic, compostable and biodegradable materials

- In-memory computing
- PCRAM
- 6G connectivity RF & photonics devices
- Smart GaN power devices
- Equipment and materials for sub-2nm node nanowire, nanosheet-based logic and memory

- Holistic development environment and semi-automatic HW/SW codesign exploration flow and tools
- Decentralised, hybrid architectures and federated learning for high performance selected applications
- End-to-end AI-based embedded multimodality systems trustability by design

- Interoperability: General translation of payload information enabling application information usage

- Continuous development processes incl. automated data-flow, based on Digital Twins and KI-based data analysis
- Data-collection at run-time in fail-operational CPS
- Online V&V, safe and secure deployment, supported by modular and evolvable/extendable reference architectures and platforms

- Certification strategy under uncertain & dynamically changing environment
- New self-learning methods to ensure safe operations of complex systems
- SW & HW reliability metrics
- Digital twin as enabler to monitor ECS
- ensuring personal data against cyber-attacks in the data-driven economy

- Automated mobility in specific areas
- Validation procedure for automated vehicles
- Fuel cell passenger car and light weight mobility
- Energy-optimised rural mobility systems

- Pilot of advanced human-machine joint intelligence
- Deeper integration of service-provider to end-user industrial processes

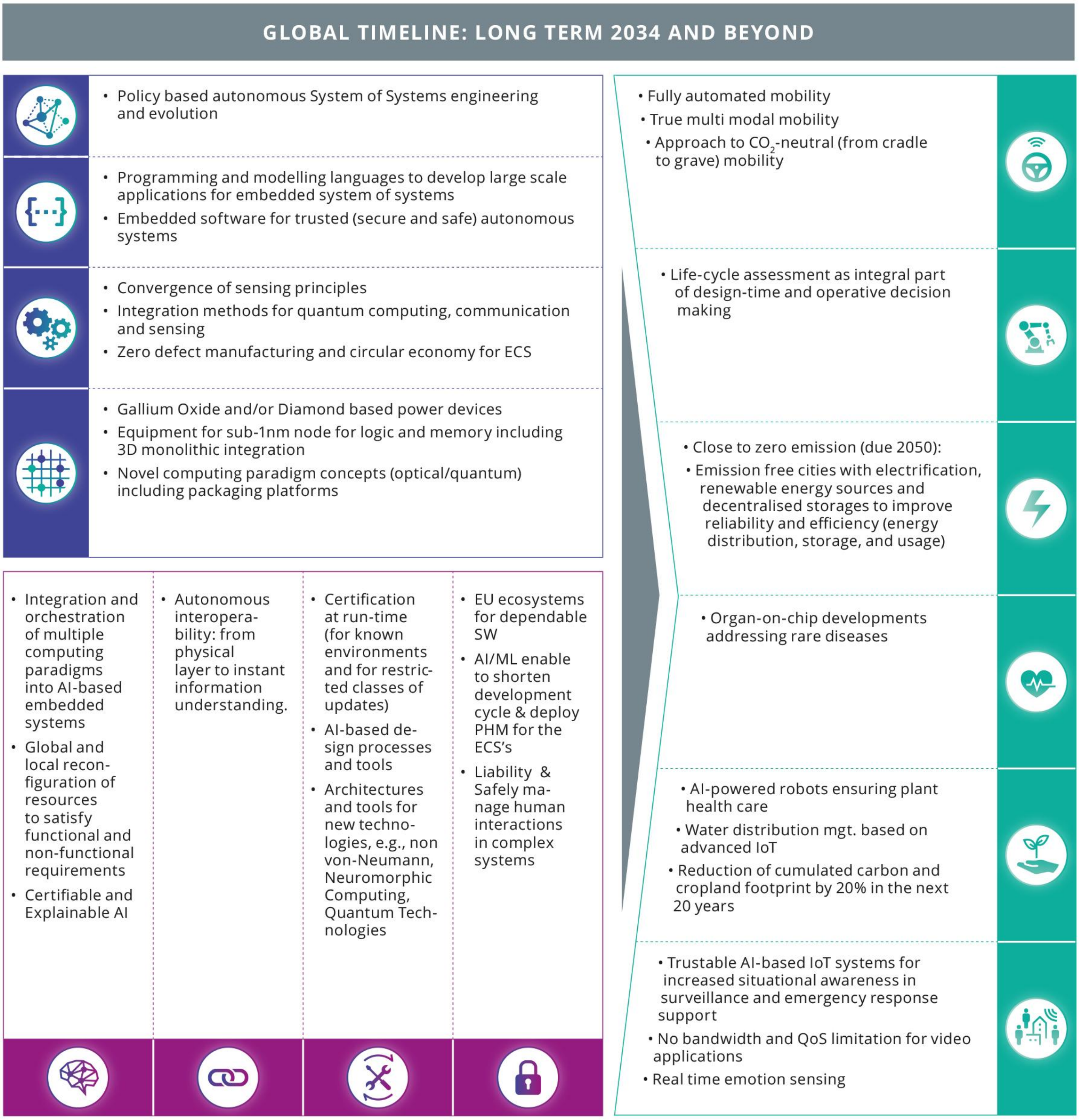
- Further energy efficiency, security and reliability improvements
- Storage devices providing flexibility, stability and reliability in the grids
- Local DC-coupling of various technologies for fast charging at home

- Next generation (patch-like) drug delivery systems part of the Internet of Medical Things
- Precision diagnosis to prevent hospital readmission

- Food Traceability over the whole value chain
- Improved electrochemical sensors for natural resources quality monitoring

- Improved Human-Machine Interfaces
- Time critical functions moved to cloud
- Multi-modal and multi-sensory interfaces in serious gaming (beyond single games)

*Figure 0.5 - Global Timeline: Medium term 2029–2033*



## GLOBAL TIMELINE: LONG TERM 2034 AND BEYOND

- Policy based autonomous System of Systems engineering and evolution

- Programming and modelling languages to develop large scale applications for embedded system of systems
- Embedded software for trusted (secure and safe) autonomous systems

- Convergence of sensing principles
- Integration methods for quantum computing, communication and sensing
- Zero defect manufacturing and circular economy for ECS

- Gallium Oxide and/or Diamond based power devices
- Equipment for sub-1nm node for logic and memory including 3D monolithic integration
- Novel computing paradigm concepts (optical/quantum) including packaging platforms

- Integration and orchestration of multiple computing paradigms into AI-based embedded systems
- Global and local reconfiguration of resources to satisfy functional and non-functional requirements
- Certifiable and Explainable AI

- Autonomous interoperability: from physical layer to instant information understanding.

- Certification at run-time (for known environments and for restricted classes of updates)
- AI-based design processes and tools
- Architectures and tools for new technologies, e.g., non von-Neumann, Neuromorphic Computing, Quantum Technologies

- EU ecosystems for dependable SW
- AI/ML enable to shorten development cycle & deploy PHM for the ECS's
- Liability & Safely manage human interactions in complex systems

- Fully automated mobility
- True multi modal mobility
- Approach to $CO_2$-neutral (from cradle to grave) mobility

- Life-cycle assessment as integral part of design-time and operative decision making

- Close to zero emission (due 2050):
- Emission free cities with electrification, renewable energy sources and decentralised storages to improve reliability and efficiency (energy distribution, storage, and usage)

- Organ-on-chip developments addressing rare diseases

- AI-powered robots ensuring plant health care
- Water distribution mgt. based on advanced IoT
- Reduction of cumulated carbon and cropland footprint by 20% in the next 20 years

- Trustable AI-based IoT systems for increased situational awareness in surveillance and emergency response support
- No bandwidth and QoS limitation for video applications
- Real time emotion sensing

*Figure 0.6 - Global Timeline: Long term 2034 and beyond*

## 0.5 ECS-SRIA and its position in the technology landscape

Electronics components and systems are key digital technologies enabling the development of numerous applications. As such, the ECS research and innovation priorities are significantly driven by application roadmaps and needs. To that effect, the **Key Application Areas** part of the ECS-SRIA translates application roadmaps into requirements for ECS. Conversely, the **Foundational Technology Layers** part maps out future advances and potential new breakthroughs in applications. The ECS-SRIA therefore promotes synergies with many neighbouring application-oriented communities. For example, the **Mobility** Chapter ( 3.1) has strong links with ERTRAC; the **Digital Industry** Chapter (3.3) with EFFRA; and the **Agrifood and Natural Resources** Chapter (3.5) with the working group of the Alliance for the Internet of Things Innovation (AIOTI) in Smart Farming and Food Security, and with Water Europe[4]. In each case, experts participated in the work of both groups. There are also close interactions and alignments with European PPP initiatives, such as 2Zero and CCAM, IHI, etc.

The **Cross-Sectional Technologies** part also leverages the links of the ECS community with other technology-oriented domains, such as the European Technology Platform for High Performance Computing (ETP4HPC), EuroHPC, the European Working Group on High-Performance RISC-V based reference processing architectures, and Big Data Value Association (BDVA), with strong relations with the **Edge Computing and Embedded Artificial Intelligence** Chapter (2.1). Likewise, the **Connectivity** Chapter (2.2) benefited from fruitful exchanges with the 5G Infrastructure Association, SNS and inputs from the European Cyber Security Organisation (ECSO), as reflected in Chapter 2.4.

Several contributors of the **Technology** parts are also actively involved in the elaboration of international roadmaps (e.g. the Heterogeneous Integration Roadmap (HIR)[5] in electronic packaging and integration, the IEEE International Roadmap for Devices and Systems (IRDS)[6] for the semiconductor industry), and the RISC-V Roadmap of RISC-V International[7] and the European Working Group[8].

To summarise, this ECS-SRIA combines application-pull and technology-push with the objective of enhancing the fertile dialogue between technologists and technology users, and strives to include discussions of upcoming strategic value chains.

## 0.6 The ECS-SRIA outline

The following diagram provides an outline of the entire ECS-SRIA to clarify the roles of the chapters, the technology domains they cover and the synergies between them, simplifying the comprehension of the ECS-SRIA and its “navigation”.

# THE ECS-SRIA OUTLINE

**FOUNDATIONAL TECHNOLOGY LAYERS**

| | | 2.1 - EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE |
|---|---|---|
| | | Hardware architectures and their implementation (Systems of Chips, Embedded architectures), for edge and "near the user" devices. Generic technologies for compute, storage and communication (generic embedded architectures) and technologies that are more focused towards edge computing. Technologies for devices using Artificial Intelligence at the edge. |
| 1.4 - SYSTEM OF SYSTEMS | System of Systems (SoS) enable the cooperation, orchestration, management, control and evolution of an entire system composed of embedded and cyber-physical systems (ECPS). This layer covers SoS architecture, technologies to securely and safely compose ECPS in SoS, ECPS and SoS interoperability, advanced control, and open, secure and interoperable SoS platforms, supported by SoS full lifecycle automated engineering. | Artificial intelligence to automatically manage the composition of ECPS in SoS and control their evolution. Artificial intelligence to improve/automate interoperability. Distributed artificial intelligence to provide the level of automation required to monitor, to support decision making and to control the complexity of SoS. |
| 1.3 - EMBEDDED SOFTWARE AND BEYOND | Facilitate engineering of embedded and cyber physical systems (ECPS), enabling digitalisation through the feasible and economically accountable building of larger software-enabled systems with desired quality. This layer covers new applications of ECPS, continuous integration and deployment, ECPS engineering and management across their lifecycle, including sustainability aspects. Starting from integrated hardware systems, this layer provides the embedded software (OS, libraries, virtualisation, middleware, etc.) required to produce fully functioning embedded and cyber physical systems. | Embedded software represents one of the key enablers of embedded intelligence. Embedding data analytics and artificial intelligence in devices allow to process data on the edge, take decision on the edge, optimise operations, dynamically adapt, and improve the cooperation between ECPS and sustainability. This layer also provides software support for AI-specific hardware, machine learning and federated intelligence on the edge. |
| 1.2 - COMPONENTS, MODULES AND SYSTEMS INTEGRATION | Multidomain engineering for physical and functional heterogeneous integration of several functionalities into new physical entities at components, modules and system levels. Heterogeneous integration spans SoC, System-in-Package and larger modules and systems, including flexible electronics and photonics solutions. This layer generates hardware integrated systems including low level software (e.g. firmware and operating system drivers). | Smart components, modules and systems are the hardware key enablers for the embedded intelligence. The focus is on integrating machine learning and artificial intelligence on the sensor, module and systems level. New advanced, efficient and specialized processing architectures (based on CPU, embedded GPU, accelerators, neuromorphic computing, FPGA and ASICs) to increase the edge computing performances and reduce power consumption. Low level software support to enable AI-based data analytics is provided. |
| 1.1 - PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURIN | Semiconductor process technology, equipment, materials and manufacturing form the base of the ECS value chain and, from Single chip (e.g. Si, more Moore), more than Moore technologies (photonics, MEMS/Sens, Bio, etc.) and System on a Chip, they produce the chips (Packaged Single Chip, System in a Package, Packaged SoC) and packaged chip-level building blocks (SoC and Single Chip, Packaged Devices in Board) for all digital applications. | AI adoption covers both the electronic components and their manufacturing process. Add intelligence close to the sensors (Intelligence at the edge) and/or to the data sources (IoT), and integrate the components in a form factor that perfectly suits their applications. Use AI in the operation of semiconductor fabrication, to master complexity, increase reliability, shorten time to stable yield, improve quality, productivity, sustainability, resource saving volume production of semiconductors |

## CROSS-SECTIONAL TECHNOLOGIES

| 2.2 - CONNECTIVITY | 2.3 - ARCHITECTURE AND DESIGN: METHODS AND TOOLS | 2.4 - QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY |
|---|---|---|
| The connectivity and interoperability technology is focused on enabling the projected commercial and societal benefits that are related to the OSI model layers 1, 5 and 6. | Innovations, advancements and extensions in architectures, design processes and methods, and in corresponding tools and frameworks, that are enabling engineers to design and build innovative ECS-based applications with the desired quality properties, efficiently and cost effectively. | Ensure quality, reliability, safety, dependability, privacy and security of ECS as a part of the Design, Implementation, and Validation/ Testing process of complex, heterogeneous and intelligent ECS, including human-systems interaction. |
| Connectivity is a key enabler for SoS which, by definition, are composed of connected and distributed ECPS. Connectivity channels and their interfaces are at the base of the composition process from which SoS originate. | Engineering methodologies, tool chains and tools interoperability are fundamental to enable the definition of SoS architectures, the implementation of SoS platform and SoS management across their lifecycle. The heterogeneity of SoS requires automated engineering processes and toolchains, integrated between multiple stakeholders, brands and technologies, supporting efficiency, quality and sustainability. | End-to-end trust (security, privacy, reliability, etc.) covering the entire edge to cloud continuum (trust continuum) is a key factor for SoS. Trust must be preserved during the composition of ECPS in SoS and must be ensured during their evolution. Security, privacy, reliability, etc. must scale following the complexity of SoS, which requires automation to efficiently manage trust. |
| ECPS are, for the vast majority, connected and this layer provides them with all the elements required to ensure field connectivity, inter-system communications, and the capability to interact with cloud platforms. These elements are key to enable the composition of ECPS in SoS and also for the inclusion of legacy systems. | Software engineering is exceeding the human scale, meaning it can no longer be overseen by a human without supporting tools: current and future ECPS, due to their complexity, require continuous hardware-software integration, both at component and system level. Continuous and automated engineering extends also to ECPS deployment and to their entire lifecycle. These necessities increase when considering embedded AI and new computing paradigms (e.g., neuromorphic). | Trust represents one the strongest barriers for the acceptance of ECPS and it must be ensured in embedded software, in particular for embedded AI. Trust should be ensured by design, and by ensuring it becomes an interdisciplinary solution because, at this level, many technology aspects converge in a single system: hardware, different layers of software, connectivity, development tools, etc. The quality of embedded software also plays a key role in ECPS. |
| Connectivity solutions (communication modules & interfaces) that are needed in networked embedded and cyber physical systems (ECPS). Focus is on providing real-time, low-latency, low-power for edge and IoT devices, photonics communications, high-speed 5G and beyond 5G/6G connectivity, and quantum technology preparing the path towards the quantum internet. | Design and simulation methods that enable and support multi-physics and multimodal design, simulation, manufacturing and testing must be addressed (e.g. modelling and design tools for thermal, mechanical and electrical characteristics in small 3D packages). Focus cover also lifecycle engineering for optimized use for materials, for components, modules and systems condition monitoring, predictive maintenance, and to improve their recyclability. | Growing complexity of smart components, modules and systems represents a reliability challenge which requires the continuous improvement of existing methods (e.g. design for reliability) and development of new techniques (e.g. prognostic health management) for reliable ECS.<br>The area also focuses on solutions for ensuring secure integration of systems, sensor level hardware and software security, privacy and data trustworthiness and AI Hardware safety. |
| Provide process technologies and electronic components required for ECS hyper-connectivity, including 5G/6G communications, advanced RF and photonics communication technologies to interface between semiconductors components, subsystems and systems. | Electronic design and automation methods and tools required to support the use of nanomaterials and metamaterials, the design and manufacturing process of future nano-scale semiconductors and electronic components, including assembly and packaging of electronics on flexible substrates. Production tools for heterogeneous integration and to support flexible, sustainable, agile and competitive high-volume high- quality semiconductor manufacturing are also considered. | End to end security starts from semiconductors. New technologies to address security at silicon level are considered, including application-specific logic, heterogeneous SoC, security by design, etc. Quality and reliability in the semiconductor production are also considered, focusing on maximising quality KPIs, monitor the process with AI, early detect yield/reliability issues, qualify the parameters that influence HW reliability, adopt design for reliability, prognostics health management of ECS etc. |

# KEY APPLICATION AREAS

## 3.1 - MOBILITY

Mobility is a basic human need and Europe's mobility industry is a key contributor to it, with a significant share in the global market in all mobility sectors (automotive, aerospace, maritime and rail). ECS take a fundamental role in mobility innovation for the final user, the society, the ecosystem and for European companies. The Green Deal and digitalisation are significantly influencing mobility, oriented to the reduction of $CO_2$ and other emissions (with electrification, alternative fuels but also more energy- and cost-efficient electronic and optoelectronic components, interconnected intelligent systems and AI-based embedded software), and to ensure an inclusive safe and secure mobility (e.g. with smart perception, affordable, safe and environmentally neutral light mobility, automated on- and off-road vehicles, and smart mobile machinery). The mobility market is increasing integration of automation functions, to evolve towards connected, cooperative and automated mobility, where ECS are essential building blocks, bringing to partial or fully automated vehicles: the focus is on affordable, automated and connected mobility for passengers and freight on road, rail, air and water, on tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility, and on real-time data handling for multimodal mobility and related services.

## 3.2 - ENERGY

The Energy chapter focuses on the challenges of a society and industry more and more based on electrical energy, addressing energy generation, supply, conversion, and use, aiming at developing highly efficient, reliable and secure solutions to achieve a carbon neutral society by 2050. The chapters cover smart and efficient solutions to manage energy generation, conversion, and storage systems, solutions for the energy management from on-site to distribution systems, for future transmission grids, for a clean, efficient and resilient local energy supply and for energy systems monitoring and control. ECS play a central role for these solutions and, in conjunction with 5G, IoT, AI, and cloud-edge computing, will strengthen the position of leading European companies in smart energy related markets (e.g. for electrical drives, grid technologies, and decentralised renewable energy sources). ECS increase also sustainability, improving the smooth implementation, integration and use of renewable energy resources and lowering the costs through new materials and semiconductors, new device architectures, innovative new circuit topologies, architectures, and algorithms, the total system cost can be lowered. ECS ensure a competitive, self-sufficient and efficient energy transmission and consumption in the EU, supporting decentralized intermittent energy sources, bi-directional grid and storage systems, and distributed AC/DC network and grid technologies.

## 3.3 - DIGITAL INDUSTRY

The Industry 4.0 have a profound impact on how factories, construction zones and processes are managed and operated. Powerful networked digital solutions are needed to support discrete manufacturing (e.g. manufacturing of automobiles, trains, airplanes, satellites, white goods, furniture, toys and smartphones), process industries (e.g. chemical, petrochemical, food, pharmaceuticals, pulp and paper, and steel), provisioning, and also production services, connected machines and robots. Emphasis is also given to any type of factories, productive plants and operating sites, value chains, supply chains and lifecycles. ECS and digitalisation represent a key enabler for the future success of European industry sector and this chapter focuses on their adoption for the development of responsive, smart and sustainable production, artificial intelligence in digital industry, industrial services, digital twins and autonomous systems and robotics. The objective is to increase the level of automation, digitisation and decision making, to support demand-driven and agile production, condition monitoring and maintenance, to improve sustainability through energy, waste, material, recycling optimisation, to improve production and supply chains resilience and responsivness, and to strengthen key European value chains with digital infrastructures and added value services based on ECS.

## 3.4 - HEALTH AND WELLBEING

The healthcare industry is facing a radical change, enabled by its current digital transformation in combination with a change towards a personalized medicine, the so called P4 healthcare (predictive, preventive, personalised, participatory). Related developments in healthcare electronics, healthcare data and healthcare technologies will progressively generate a new ecosystem positioning the "healthcare consumer" at the centre of the value chain. The ecosystem will rely on digital instruments, advanced electronic sensors and photonics, micro-electromechanical systems (MEMS), and the large volume, high-quality, low-cost production capabilities of the ECS industry. ECS will play a key role to enable the development of tools, data, platforms, technologies and processes for improved prediction, prevention, interception, diagnosis, treatment and management of diseases. The objectives include a better understanding of the determinants of health and priority disease areas, a reduction of the fragmentation of health R&I efforts bringing together health industry sectors and other stakeholders, the creation of people-centred digital health platforms based upon P4 healthcare, the exploitation of digitalisation and data exchange in health care, the development of the home as the central location of the patient, the development of a more integrated care delivery system and the creation of solutions to ensure more healthy life years for an ageing population.

## 3.5 - AGRIFOOD AND NATURAL RESOURCES

Electronic components and smart systems are vital for the sustainable production and consumption of safe and healthy food, for sustainable practices in agriculture, livestock, aquaculture, fisheries and forestry, access to clean water, fertile soil and healthy air for all, and also to preserve biodiversity and protect the planet's ecosystems. This chapter focuses on ECS-based technologies (e.g smart IoT solutions, traceability frameworks, robots, drones, AI) to ensure livestock and crop health, and also to farming systems and food supply chain assurance, food production and management. ECS are also at the base of soil health, air quality and environment smart integrated monitoring solutions, as well as of smart waste management systems and remediation methodologies. Moreover, the chapter focuses on the key role that IoT systems can play in water quality monitoring, manage and access to clean water, including the smart treatments of wastewater, rainwater and storms/floods. Finally, the chapter covers ECS-based solutions for biodiversity restoration and ecosystem resilience, conservation and preservation, to ensure the natural sustainability of healthy ecosystems and their resources (agriculture, aquaculture, fisheries and forestry). The objectives of the chapter are aligned with the key Horizon Europe missions and with the European Green Deal.

## 3.6 - DIGITAL SOCIETY

Digital Society chapter covers digital innovations that are essential to stimulate an inclusive and healthy society, contributing to solutions for European challenges in the fields of health, mobility, security, energy and the climate, and consequently to European economic prosperity. Europe needs digital solutions that support the individual, and at the collective level to empower society as a whole. These (smart) digital solutions will be driven by new technologies such as 5G, Artificial Intelligence with deep learning, virtual and augmented reality, brain–computer interfaces and robotics. They will shape new ways of how people use and interact with these technological solutions, with each other, and with society and the environment. Digital innovations should facilitate individual self-fulfilment, empowerment and resilience, collective "inclusion" and safety, as well as supportive infrastructure and sustainable environment. The ethical aspects of the digital transformation are also considered, trying to address societal concerns in a sustainable way, guaranteeing participation and reducing inequality. A human-centred approach is therefore a key aspect of the EU's approach to technology development. It is part of European social and ethical values, (social) inclusiveness, and the creation of sustainable, high-quality jobs through social innovation.

# LONG TERM VISION

The Long Term Vision chapter addresses research subjects to enable and support effective development of European industry in about a decade from today. The chapter build upon the challenges identified by the ECS-SRIA and specify long-term industrial needs. These needs are the basis for research programs for effective research and development in appropriate technological and/or application domains, so that European technological strength increases continuously in time and at the appropriate pace. Since lead-time from a first scientific breakthrough (TRL1) to market presence of related products (TRL9) is about 10 years, the effective identification of the future industrial needs is a determining factor for the success and speed of innovation. The Long Term Vision is shaped by three main factors: technology, application domains and policies. Clearly, all factors are drivers of innovation, because (i) anticipated technological advances lead to innovative applications of these advances and (ii) user needs lead to technological innovations that enable these needs. At the same time, policies and politically established goals and processes lead technologies and applications towards common goals and targets such as the goals of the Green Deal and the European industrial competitiveness. It is apparent that, each of these factors motivates, shapes and initiates innovation efforts at many levels.

## 0.7 Make it happen

By themselves research projects contribute partially to resolve societal challenges and to create economic value for Europe. The full leverage of several research projects with significant impact for EU regarding societal and economic impact will happen only if several "innovation accelerators" are in place, which will bring the research results to market. Standardisation and regulation, education and training, international cooperation, and research infrastructures are a few of these accelerators.

Discussing those topics is beyond the scope of the ECS SRIA, which is the expression by the industry of its Research and Innovation vision. In essence, the SRIA is designed to be funding instrument agnostic, so that it can constitute the basis of calls for various programmes, such as Horizon Europe, Eureka, or national initiatives. That being said, some of the accelerators listed above are being set up in the frame of the Chips Act, and we cannot ignore that context. We refer here specifically to the Design Platform and the Pilot Lines included in the Chips for Europe Initiative, which has the objective of supporting and accelerating technological capacity building and innovation in the Union by bridging the gap between the Union's advanced research and innovation capabilities and their industrial exploitation.

The pilot lines are intended to allow companies and academic institutions to perform research on future technologies. By having prototyping capabilities, they allow to assess the feasibility, performance, and reliability of their novel electronic devices, components and modules, or of new manufacturing processes, without affecting ongoing production – in case of industrial pilot lines, or enabling research institutes to showcase their innovations and speed up the time-to-acceptance into the market. SME support via low-volume prototyping is another potential benefit of pilot lines.

Moreover, as pilot lines often involve collaborations between industry partners, research institutions, and academia, they will be fostering the exchange of knowledge, expertise, and best practices in electronics manufacturing to tie these stakeholders more closely together. In this context, pilot lines will also contribute to workforce training, as they will offer hands-on experience and exposure to state-of-the-art technologies and practices. Those collaborations will also pave the way for fast transfer to volume manufacturing ensuring European competitiveness and growth in EU-based share in microelectronics.

While it is outside of the SRIA scope to indicate how these research infrastructures and services should be run, it is important to ensure that their implementation most effectively supports the research needs exposed in the SRIA. To that effect, the following table identifies, for the Design Platform and for the Pilot Lines most likely to be launched in a first batch (as of the time of writing of this addendum to the 2023 ECS SRIA edition), research topics which are expected to be supported by those instruments. Note that the pilot line mechanism is meant to support a large variety of developments, from device manufacturing in semiconductor processes, MEMS, packaging and hybrid integration (SiP), as well as module and system level development. It is therefore expected that other pilot lines, beyond the ones considered here, and focusing on different technologies and different steps in the value chain, could be implemented in later phases.

|  | Design platform | Advanced 2nm and beyond | FD-SOI | Advanced Packaging and Heterogeneous Integration | Other pilot lines |
|---|---|---|---|---|---|
| **1.1 Process Technology, Equipment, Materials and Manufacturing** |  | Launching ground for new processes, equipment technologies and materials | Low-power consumption, radiation hardness, More than Moore app. | Introduce materials and process innovations as well as advanced manufacturing, test and inspection equipment for future AP/HI systems. |  |
| **1.2 Components, Modules and Systems Integration** | Improve design capabilites to become a closed loop (i.e., to include feedbacks from the production process and from the field use, respectively) as well as define the new sets of interfaces for the complex integration solutions at die / module / system levels as needed for implementing heterogeneous and chiplet approaches - in particular for ECS applications that will be exposed to demanding and harsh environments (as these ECS are essential for our European backbone industry -automotive, energy, industry, health, …- and not sufficiently and securely addressed by the worldwide leading players). | Impact of advanced node inflections like backside power distribution networks, forksheet, CFET and 2D material channels<br>3D heterogeneous integration in chiplet implementation |  | Enable enhanced and diversified functionalities (e.g. combined sensing, processing, communication, …) in small form factor electronic components and systems. | Platforms leading to the scalability of elements enabling connection between the digital and physical worlds (e.g. MEMS, integrated photonics, power electronics, quantum approaches…) in silicon or silicon alternative technologies will provide, together with logical circuitry, additional essential building blocks to be integrated in full fledged electronic systems |
| **1.3 Embedded software and Beyond** |  | Design Technology Co-Optimisation | Design Technology Co-Optimisation |  |  |
| **1.4 System of Systems** |  | System Technology Co-Optimisation | System Technology Co-Optimisation |  |  |
| **2.1 Edge Computing and Embedded Artificial Intelligence** | Provide non-differentiating IPs (I/Os, memory interfaces, etc)<br>Support the Open Source Hardware community in Europe<br>Provide tools for embedded AI, such as tools allowing to quantize and decrease the size of Neural Networks for embedded accelerators | Drive PPACE (Power - Performance - Area - Cost - Efficiency) improvements for advanced nodes to increase the energy efficiency of computing systems<br>Research PDK's to support managing the increasing complexity of systems | Energy efficiency, embedded non-volatile memories | Advanced packaging technologies allow the integration of diverse and specialized components such as processors, GPU/FPGA, memory, sensors and communication chips in a single package. This enables new, more powerful and energy-efficient edge computing, AI and communication solutions in small form factors. |  |
| **2.2 Connectivity** |  |  | * Enable the development of power efficient connectivity solution leveraging European-based semiconductor technology<br>* Enable the development of innovative connectivity solution at mmW and THz frequencies | * Enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc.) to help European players capture higher value in the connectivity market.<br>* Enable the development of innovative Antenna in package solution at mm-wave and THz frequencies<br>* Enable a sovereign European packaging ecosystem to secure the supply chain of European semiconductor players |  |

| | Design platform | Advanced 2nm and beyond | FD-SOI | Advanced Packaging and Heterogeneous Integration | Other pilot lines |
|---|---|---|---|---|---|
| | | | | (especially in key areas such as space were required manufacturing scale limits the possibility to have access to Asian OSAT) | |
| **2.3 Architecture and Design : Methods and Tools** | Support EDA research and innovation, in particular:<br>- Exponentially increasing design complexity (MC 3) and Increasing Diversity (MC 4)<br>- Sustainability (MC1)<br>- Emerging technologies (MC1)<br>- Increased automation and operability (MC1, MC2, MC3)<br>- Multidisciplinary design (MC4) | | Automated application of back-biasing for adjusting power and performance | Proving ground for new design methods mastering the differences in materials, technologies, and processes that are heterointegrated into a single package. | |
| **2.4 Quality, Reliability, Safety and Cybersecurity** | Widen the implementation of Design for X (DfX) besides the design for functionality and performance - in particular for the heterogeneous and chiplet implementations to be used in demanding and harsh environments. Implement 'closed loop design' approaches (= with feedbacks from manufacturing, testing, ... field use)<br>X ... manufacturing, testing, reliabiltiy, safety, security, repairability, disassembly+reuse, sustainability, ... | | Develop new processes ensuring quality, reliability and safety of heterotintegrated chips and systems. | | |
| **3.1 Mobility** | High Performance automotive SOC for Software Defined Vehicles based on RISC-V (including necessary accelerators and support for automotive bus systems as well as automotive trust-ability concepts) | | | New generation of environmental sensors (or combined sensors), which simplify and improve object and lane detection, work in difficult (severe) weather conditions and situations (as tunnel exit). Can be supported via Heterogenous integration pilot line, but also via other PL on photonics, quantum sensors.<br>Chiplets will allow for higher functionality and future capabilities to combine processing, sensing, and memory out of different nodes | |
| **3.2 Energy** | Energy efficiency is one of the major factors to reduce energy consumption - design for energy efficient devices, process technologies for energy efficient operation and integration and packaging technologies for all the advanced technologies, either logic or power electronics.<br>To manage the demand of the interlinked society for more and more communication and in parallel a sustainable way of operation including fulfilling the transition towards the Green Deal objectives plenty of control and forecasting systems will be required in addition to highly miniaturized, safe, connected and efficient power conversion and distribution systems. | | | | |
| **3.3 Digital Industry** | | | | Facilitate advanced, cost- and energy-efficient integrated systems for key application areas. | |
| **3.4 Health** | | | | | |
| **3.5 Agrifood and Natural Resources** | New advanced circuits needed to develop innovative and cost-effective solutions related to the chapter challenges could be designed (through the Design platform programme) and fabricated (through the Pilot lines | In agriculture, low cost, highly energy-efficient and self-contained components are essential. They include highly innovative types of sensors related to agriculture and intended to preserve natural resources, highly efficient processors | In agricultural devices with a minimal form factor, low power consumption and low cost are essential. The wide variety of devices, related to the multiple applications, requires modular and heterogeneous integration including multiple sensors, | | |

|  | Design platform | Advanced 2nm and beyond | FD-SOI | Advanced Packaging and Heterogeneous Integration | Other pilot lines |
|---|---|---|---|---|---|
|  | programme). Examples include sensors for water quality monitoring, GHG emission measurement, plant and soil health. | including AI capabilities and long-range RF solutions. | advanced processors and multiple RF protocols. |  |  |
| **3.6 Digital Society** |  |  |  | Facilitate advanced, cost- and energy-efficient integrated systems for key application areas. |  |
| **Long Term Vision** |  | Foundational studies for new processes, equipment technologies and materials |  | Establish and nurture advanced packaging and heterointegration expertise in EU. Facilitate and promote AP/HI technology and infrastructure access to foster electronics device and systems innovations. |  |

The Design Platform, as proposed in the European Chips Act, should also support research in several cross-sectional technologies:

- On the one hand, the development of edge AI and embedded computing chips (research areas identified in Chapter 2.1) will be facilitated if the Design Platform covers the following aspects:
    - Providing as many non-differentiating IPs (for instance I/O's, memory and communication interfaces, etc.) as possible, allowing to have a one-shop entry for start-up/SMEs and academia to validate into silicon their new architecture ideas in the field of accelerator for IA (at the edge) and embedded systems.
    - Supporting the Open Source Hardware community in Europe (e.g. RISC V), where the Design Platform could be linked with Open Source repositories and allowing access of the instances (and the tools to use them, such as compilers, OS and basic middleware).
    - One specific topic that the Design Platform should add is to give access to the tools specific for embedded AI, such as tools allowing to quantise and decrease the size of Neural Networks for embedded accelerators (and perhaps to learning databases) so that it will be a single entry for using all those tools in a coherent environment. That will imply certainly to bridge to other platforms either from European projects (NeuroKit2E for example), but perhaps also with non-European repositories such as HuggingFace.
- On the other hand, the design platform could be used to investigate many EDA challenges (research areas identified in Chapter 2.3), such as:
    - Exponentially increasing design complexity (Major Challenge 3) and diversity (Major Challenge 4):
        - Developing highly complex and heterogeneous systems-on-chip (SoCs) that integrate diverse functionalities.
        - Supporting the design and optimisation of new advanced packaging solutions for complex heterogeneous systems, addressing challenges related to power delivery, thermal management, signal integrity, and testing, etc.
        - Being able to handle the impact of increasing complexity on security, safety, reliability, …: design for trustworthiness.
        - Design verification: as designs grow larger and more intricate, exhaustive verification becomes increasingly time-consuming and resource-intensive.
        - Design for manufacturability and short time-to-market: EDA tools must evolve to improved yield, reduced variability, and better reliability, to reduce design cycles and facilitate faster design iterations, verification, and optimization, etc.
    - Sustainability (Major Challenge 1): EDA tools will need to enable designers to optimise designs for lower power consumption, reduced carbon footprint, and efficient resource utilization.
    - Emerging technologies (Major Challenge 1): quantum computing, neuromorphic, edge AI, … e.g. EDA tools need to evolve to support quantum circuit design, verification, and optimisation.
    - Increased automation and interoperability in the design flow, including for multi-vendor solutions (Major Challenges 1, 2, and 3): increasing complexity has a direct impact on the human effort required to design, validate, test, etc.
    - Multidisciplinary design (Major Challenge 4): ECS require and will require collaboration across various engineering domains, including electrical, mechanical, thermal, and materials engineering. EDA tools must support seamless integration between different design disciplines.

In a nutshell, the Design Platform and the Pilot Lines included in the Chips for Europe Initiative have the potential to offer a valuable research, development and testing ground, a learning environment to advance innovation, enhance manufacturing capabilities, and accelerate the development of cutting-edge electronic products. To make that promise come true, it is of utmost importance that their research roadmaps are established in strong synergy with the contents of the ECS SRIA and that the results are prepared for transfer into volume manufacturing.

The ECS community is positive toward those two new instruments under the pre-condition of appropriate involvement of industrial stakeholders in advisory bodies of these two instruments. For the Pilot lines the projects have to be designed to explore new technologies with clear outcome for the European industry at large, and with feedback mechanisms ensuring this is implemented and established over time. For the Design Platform the rules of access and use of the resulting designs (Silicon IP) or chips for companies or laboratories will have to be clearly and carefully crafted to avoid competition distortion.

## 0.8 References

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**1.1**

PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING

**1.2**

COMPONENTS, MODULES AND SYSTEMS INTEGRATION

**1.3**

EMBEDDED SOFTWARE AND BEYOND

**1.4**

SYSTEM OF SYSTEMS

# 1

*Strategic Research and Innovation Agenda 2024*

# FOUNDATIONAL TECHNOLOGY LAYERS

# 1.1

# PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING

# 1 Foundational Technology Layers

1.1

## Process Technology, Equipment, Materials And Manufacturing

Semiconductor process technology, equipment, materials and manufacturing form the foundation of the ECS value chain producing the chip and packaged chip-level building blocks for all digital applications.

Nano- and microelectronics are key to achieving digital sovereignty in Europe, and they offer a range of solutions for a green and sustainable society. If Europe wants to control the development of a digital future fitted to its citizens and their requirements, as well as its social, economic, industrial and environmental goals, it needs continuous innovation in the field of semiconductor technology.

### 1.1.1 Scope

The key scope of this section is to cover all process technologies, equipment and materials' research and innovation to enable CMOS compatible semiconductor chip and packaged chip manufacturing inside a cleanroom environment. This includes:

- New materials and engineered substrates to improve device performance,
- process technologies, equipment and manufacturing technology to advance integrated circuit (IC) functionality and/or systems on chips,
- packaging and integration technologies for chips, chiplets, system on a chip (SoC) and system in a package (SiP).

Clearly, the scope of this section involves synergies with other sections in this ECS-SRIA. First and foremost, the section links with Components, Modules and System Integration in Chapter 1.2. In addition, this section also links with Embedded Software and System of Systems (SoS) to allow for an integral system technology co-optimisation approach to deliver application-driven solutions. More details about the synergies with other sections are described in Sub-section 1.1.6.

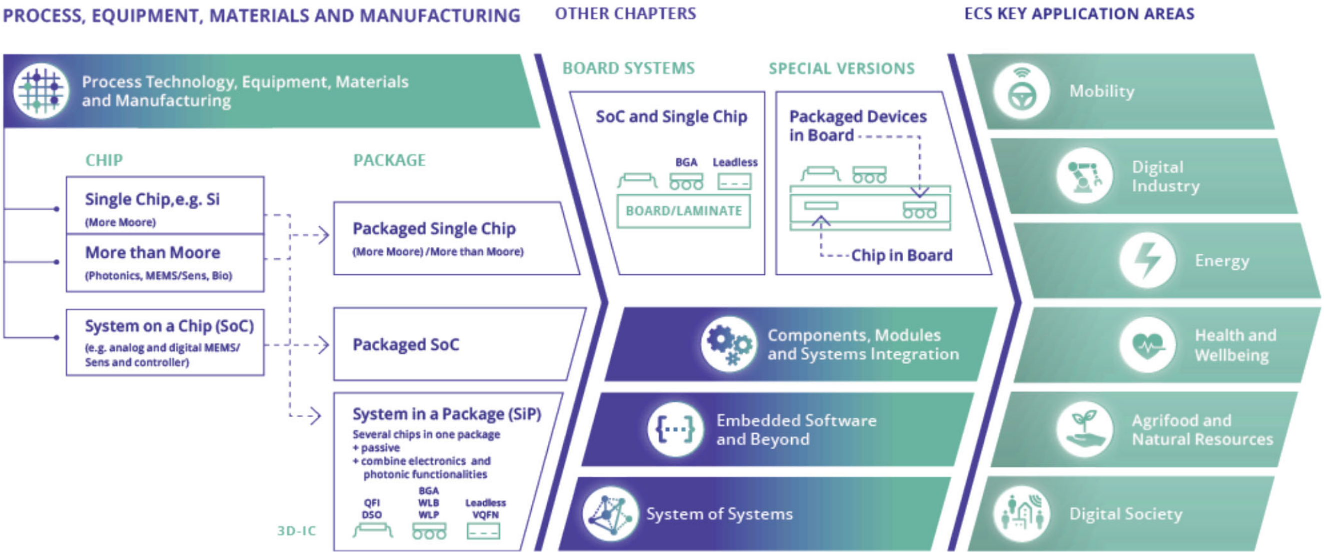

*Figure 1.1.1 - The chip and packaged chip-level building blocks are the starting point for the other ECS-SRIA chapters*

### 1.1.2 Technology Enabled Benefits

Technological challenges arise from evolving and future technologies such as the Internet of Things (IoT), artificial intelligence (AI), edge computing, autonomous driving, high-speed mobile connectivity networks (5G and beyond), image/sound-driven immersive computing (augmented reality) and quantum information processing (QIP). These challenges require advances in: Moore's law; functional building blocks; ICs; electronics performance; more-than-Moore devices; heterogeneous integration of functionality; and the development of novel computing paradigms and their applicability to "extreme" (e.g. cryogenic or high temperature) environments. Likewise, Industry 4.0 and the sustainable manufacturing of semiconductors require new processes, manufacturing techniques, equipment and materials.

European industry in sectors such as healthcare, automotive, energy, smart cities and manufacturing strongly depends on the timely availability of highly specialised electronics devices enabling added value and new functionalities in their products. Moreover, the advances in chips and packaged chips will strongly contribute to Europe's ambition to become climate-neutral by 2050, as promoted by the European Green Deal[1].

First, across the electronics value chain, the aim is to minimise waste and maximise circular resource usage by extracting the most value from the materials used and repurposing products across their lifecycles. This includes moving towards zero emissions for the direct operation, as well as enhancing the energy efficiency, of electronics manufacturing processes while increasing their productive output.

Second, improving process and manufacturing technologies of semiconductor components, developing new more adequate materials and substrates will allow a more efficient device and system-level use of the energy resources. For instance:

- Device scaling by moving into 3D for sub-3 nm node memory and computing technologies will also drive down energy consumption following the power, performance, area and cost (PPAC) scaling roadmaps.
- New embedded non-volatile memory technologies enable local processing and storage of configuration data, decreasing data transmission and energy needs for a wide range of automotive and IoT applications.
- New power electronics devices, either based on silicon or new (GaN, SiC) materials, will increase the energy efficiency of electric powertrains, energy storage, lighting systems, etc.
- Improved radio frequency (RF) and Mixed-Signal (MS) device technologies based on new materials such as GaN or other compound materials, new switches, and passives enable increased output power and efficiency towards higher frequencies, as well as improved control of the transmission and reception channels with more energy efficiency due to finer RF band control and better directionality.
- New hybrid and heterogeneous combinations between photonic ICs and electronics enable microwave photonic modules – for example, for wideband millimeter-wave processing, and high-bandwidth off-chip and on-chip communications RF filtering.
- New sensor technologies and devices enable better control of processes (e.g. industrial processes, lighting), which contributes to energy saving.
- New (quantum) sensor and (quantum) information processing units that can operate at and near the theoretical limits allowed by nature.

## 1.1.3 Applications Breakthrough

The main breakthrough enabled by the technological advances discussed in this section concerns the reduction of energy consumption in the various electronic components without any decrease in their performance.

In 2022, the globally consumed power of data centres alone was 240-340 TWh[2], which represents between 1-1.3% of global final electricity demand. This excludes energy used for cryptocurrency mining, which was estimated to be around 110 TWh in 2022, accounting for 0.4% of annual global electricity demand. Investing in more efficient IT hardware including microchips will provide the means to flatten this curve whilst data centre workloads are expected to increase[3].

Reducing the energy consumption of electronic components is essential for improving the autonomy of electric and hybrid vehicles, the lifetime of battery-powered sensors (for health monitoring, preserving natural resources such as water through more efficient irrigation, etc.), as well as for the development of autonomous sensors with energy harvesters and energy storage.

Since moving data from the logic cores to the adjacent memories is the main contributor to the energy consumption of logic devices (microprocessing units (MPUs), microcontroller units (MCUs), etc), their conventional von Neumann architecture must be drastically changed in close co-optimisation with other technology innovations. Near-memory or in-memory computing and neuromorphic computing are new architecture paradigms that strongly reduce the movement of data, and accordingly allow decreased overall energy consumption. Specific low- power transistors, memory and 3D-integration technologies need to be developed to ensure close coupling between computer and memory blocks.

The adoption of wide bandgap materials such as GaN and SiC is crucial for allowing higher operating temperatures and reducing the switching losses in power electronics for a broad range of power systems, such as smart phone/tablet chargers, industrial power supplies, power supplies for servers, etc., and very important, electric vehicles, as well as to increase their range. GaN/SiC is also important for increasing the power efficiency of 5G RF base stations. In addition, GaN/Si and GaN/SOI can induce the same effect in RF front-end modules when combined with high thermally conductive materials.

New architectures and technologies will be also essential for the future development of 6G communications for improving the bandwidth and data transmission rate, while exhibiting lower latency and lower power consumption.

The exponential increase in internet traffic (with a CAGR at 24% from 2021 to 2026[4]) sets demanding requirements on data communication technologies. Optical interconnects enable higher bandwidth- distance products, higher bandwidth density, lower electromagnetic interference, and potentially lower power consumption than electrical interconnects. They are being deployed at increasingly shorter distances – for example, within and between data centres. In the longer term, chip-to-chip and even intra-chip communication may be performed with CMOS-compatible photonics. Beyond these applications, emerging precision applications – including atomic clocks, precision metrology, and transformative applications such as quantum communications and information processing – will also benefit from photonic capabilities integrated with electronics, such as silicon and heterogeneous III/V (membrane) photonics, and potentially disruptive technologies such as nanophotonics, - and 2-D materials or graphene based photonics. At the same time, the potential (even remote) of novel computing paradigms such as quantum computing making current security protocols insecure will require development of novel, future proof cryptographic methods.

Other breakthroughs will concern adding intelligence close to the sensors (Intelligence at the edge) and/or to the data sources (IoT), and to integrate the components in a form factor that perfectly suits their applications. The initial generation of "Internet-of-Things" management was cloud-centric, where sensor data were collected from the periphery (or "edge"), then processed and analysed at the enterprise or platform tier. However, in that case, a tremendous amount of data needs to flow to the cloud and back, and a large amount of data processing power is required to structure and analyse it. In such a cloud-focused solution, latency and privacy concerns are often worrisome, or even prohibitive.

The term “embedded AI” or “edge AI” denotes how AI algorithms can be processed locally on a hardware device (e.g. a sensor) close to where the data is generated, and an action may then be required. A device using edge AI can process data it has collected and subsequently take decisions independently, without connecting to a central processing unit (CPU). Where initially local decisions will be supported by inference actions, there will be an evolution to training on the edge devices. Edge AI extends embedded computing, and contributes to economically effective solutions for the societal challenges we are facing in terms of:

- Reducing the energy consumption of the data infrastructure by transmitting only relevant data or pre-treated information (countering the unsustainable explosion of the energy demand by data centres and by telecommunication systems requiring higher bandwidths).
- Protecting personal data (GDPR compliance) by local processing and anonymisation of transmitted information.
- Increasing security and resilience due to a reduced reliance on telecommunication links as a result of local decision-making.
- Reducing latency by reducing the quantity of data needed to be transferred to and from a cloud, which is particularly important for automotive, digital society (real-time control of power distribution, for instance) and manufacturing applications, as well as some health applications.

Rethinking human activities to take advantage of the innovation opportunities offered by hyper-connectivity, AI solutions and new kinds of sensors based on miniaturised technologies will create numerous benefits for every new market, ranging from connected cars and digital health to smart home and smart living, and factories of the future. This should include lessons learned from the COVID-19 pandemic like the sudden increase in remote-working.

Sensors and biosensors will be an extensively studied discipline since their rapid, low-cost and highly sensitive features contribute to tremendous advances in many domains. Visible light, IR or multispectral imagers, lidar, radar and ultrasonic sensors, in combination with high-precision inertial sensors, will be essential for the deployment of advanced driver assistance systems (ADAS), augmented reality devices, and industrial automation for instance. Advancements in chemical-sensing technologies also open the door for multiple new markets. Gas sensors are increasingly integrated into IoT ecosystems to monitor air quality indoors and outdoors – for instance, wearable devices, smart city projects, sensor networks for pollution mapping, smart home electronics and automotive technology. Another key trend to utilise advanced gas-sensing technology is breath analysis, which aims at non-invasive diagnostics via detecting biomarkers from exhaled breath. Furthermore, pressure sensors in human and robot assisted minimally invasive surgery catheters are required to give haptic feedback to the surgeon. Miniaturized ultrasonic sensors open possibilities for minimally invasive medical imaging. However, to access the brain and smaller arteries in the body further miniaturization is required, posing a challenge for current pressure sensor technology.

R&D on highly selective biosensors will contribute to advances in next-generation healthcare, including personalised medicine and the ultrasensitive point-of-care detection of markers for diseases.

Next-generation electronic products are pushing the semiconductor industry to integrate more ultra-thin and flexible ICs. The combination of flexibility and processing capability is very desirable since it reduces weight and enables new form factors, while maintaining desirable functionality such as data logging and RF connectivity. Ultra-thin and flexible ICs enable more efficient and cost-effective solutions that will affect many applications, such as wireless communications, wearable electronics, implantable biomedical devices and the IoT.

The field of quantum sensing is rapidly expanding because quantum phenomena are extremely sensitive to their environment and thus can be used to measure physical properties with unprecedented precision. Quantum sensing refers to the process of employing an individual or an ensemble of quantum systems, often a quantum coherence and/or a quantum entanglement, to measure a physical quantity – ideally with improved accuracy, stability, sensitivity, sensitivity, precision, or spatial resolution compared to conventional measurements.

Quantum sensing usually describes one of the following:

1. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized discrete and resolvable energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, cold atoms, trapped ions, or photons.
2. Use of quantum coherence (i.e., wavelike spatial or temporal superposition of states) to measure a physical quantity.
3. Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

There are two generations of quantum sensors. The first, which includes devices such as microwave atomic clocks and superconducting quantum interference devices (SQUIDs), has been available for decades. The second generation, which includes atomic clocks, gravity sensors, magnetometers, gravimeters, gyroscopes, nitrogen-vacancy (NV) sensors, and other innovations, is just emerging. Second-generation quantum sensor applications may enable various domains:

- **Biomedical imaging**: neural sensing and heart imaging.
- **Spectroscopy**: imaging of molecular structure such as proteins.
- **Communications**: Signal receiving and amplification for radar communication; calibrating electrical standards to support 5G/6G.
- **Navigation**: Providing high-accuracy GPS; assisting with navigation inside buildings and underground.
- **Environmental monitoring**: Predicting volcanic disruption and measuring $CO_2$ emissions.

- **Infrastructure monitoring**: Monitoring mechanical stability and detecting leaks.
- **Geographical surveying**: Assisting with the location of oil and gas.

### 1.1.4 Strategic Advantage for the EU

The European Chips Act aims to bolster Europe’s competitiveness and resilience in semiconductor technologies and applications, and help achieve both the digital and green transition. Strengthening Europe’s technological leadership in the field is essential to achieve this goal[5].

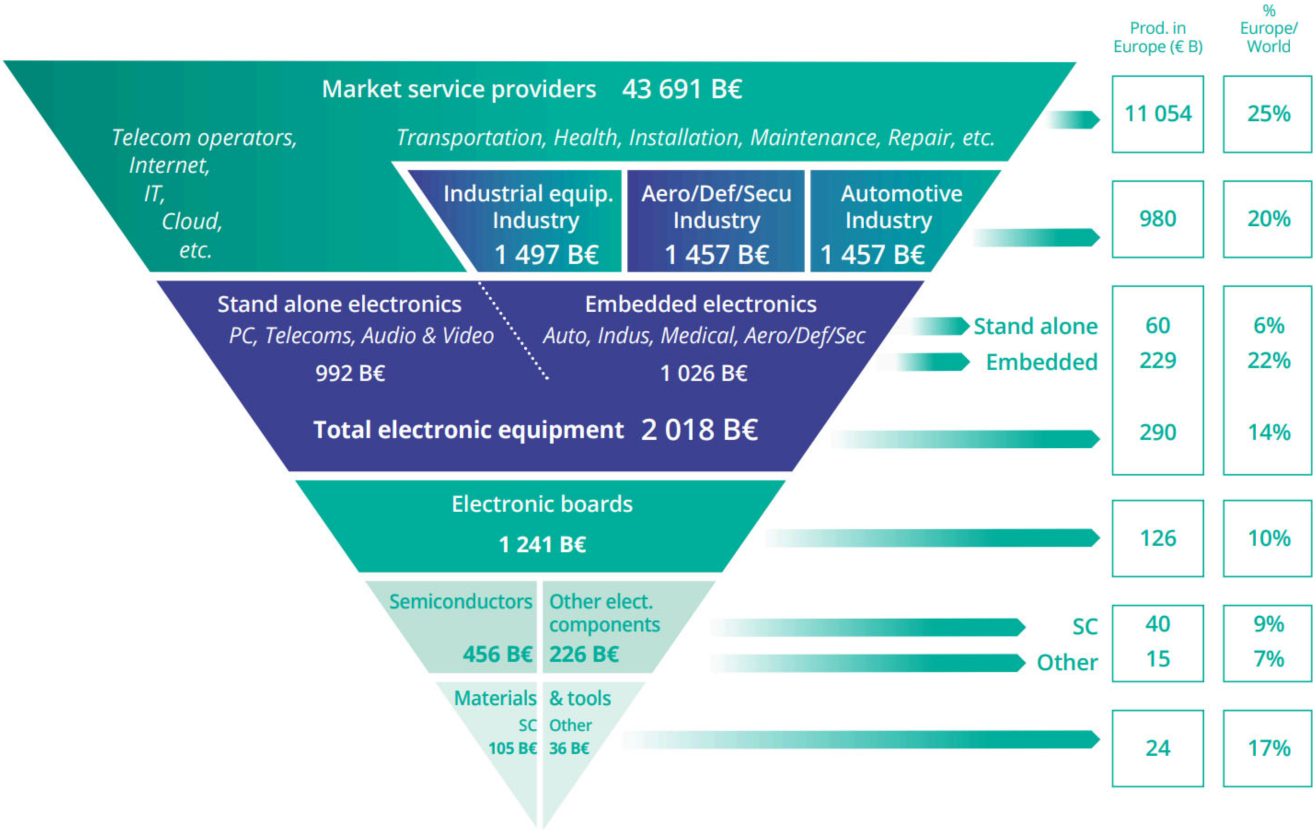

*Figure 1.1.2 Process technology, equipment, materials and manufacturing is at the base of the digital value chain (Source: DECISION Etudes & Conseil) – 2018 market size numbers*

Globally, the long-term market trend for electronic components is expected to exceed US $1,000 billion by 2030[6]. In Europe, the semiconductor ecosystem employs some 250,000 people, with 2.5 million in the overall value chain of equipment, materials, semiconductors components, system integration, applications and services – mostly in jobs requiring a high level of education.

In the past, the semiconductor market has been extremely volatile, and R&D investments have been high (up to 10–20% of total revenue). Nonetheless, public/private funding has enabled Europe to lead the world in dedicated semiconductor devices, semiconductor equipment, materials and manufacturing solutions.

Continued investment is vital not only for the ECS industry, but also for the downstream industries that depend on it, including automotive, aviation, space, healthcare, energy, security and telecommunications.

Under Horizon 2020, Future and emerging technologies (FET) flagship initiatives, such as those on graphene and quantum technologies, have been shown to have significant impact on European R&D landscape in these areas. To ensure European leadership in this highly challenging discipline, early involvement of equipment and material suppliers will bring these activities to the next level in parallel with identifying the best application areas. Importantly, the functionality of several current ECS technologies needs to be updated to respond to the challenges that new materials and Quantum Information Processing (QIP) are raising. Advanced materials and computational paradigms require not only the development of new scalable platforms, but also non-trivial adaptations and extensions of existing technologies as enablers of such functionalities. For example, any solid state-based quantum computer will need efficient “classical” low-power cryogenic electronics to enable operation of its computing circuit. Both the cryogenic electronics itself (performance, power consumption, noise-compatibility with the fragile qubit layers, 3D integration, packaging...) as the (novel, scalable, efficient) cooling solutions themselves therefore require focused attention.

The creation of manufacturing pilot lines is key to impact industry, as already demonstrated by successful European projects to date. Pilot lines are a launching ground for new processes, equipment technologies and materials, allowing for early validation of new concepts in support of industrial introduction, and fostering collaboration between industry, research institutes and academia. In addition, they constitute valuable technology platforms based on advanced sub-2nm CMOS nodes, FD-SOI, heterogeneous integration and advanced packaging or a wide range of applications. Future technology platforms addressed through pilot lines may include wide bandgap for power and RF applications, integration of photonics and sensors and more advanced technologies like quantum.

Pilot lines are important drivers to advance an understanding of application needs, cut products' time to market, and showcase European capabilities to potential customers worldwide. Pilot lines provide excellent opportunities for advanced education and training to skilled engineers and scientists. Early availability of innovative semiconductor, sensor and packaging technologies will pave the way to cyber-physical production systems. Having a strong semiconductor portfolio "made in Europe", with early access for lead system suppliers, is a winning competitive asset for Europe. Such semiconductor manufacturing requires access to advanced materials and characterisation equipment, and competitive manufacturing techniques at the current base of the European value chain. In future, the complete value chain must be covered to promote the competitive situation of the European semiconductor process and integration technology, and to ensure European independence in this field.

Given that in the next decade, 85% of overall global growth is projected to take place outside the EU[7], it is essential that strategic industrial ecosystems receive the backing to ensure the robustness that is needed to continue competing globally and to reduce the potential disruptive impact of disasters such as pandemics and climate-related effects. Foreign and domestic investments leveraged by government subsidies have enabled many of these regions to take on a leadership role in several areas of semiconductor manufacturing. Despite competition from East Asia and the US, Europe can reinforce its lead in semiconductor processing and packaging, equipment and smart systems based on the priorities set out in this ECS-SRIA. The first Important Project of Common European Interest (IPCEI) on microelectronics, for example, was a successful step towards strengthening European semiconductor manufacturing in strategic areas where large-scale subsidies in other regions have started to threaten the position of European players. The European Commission has set ambitious targets[8] in its 'Digital Compass' to double 'cutting-edge semiconductor' manufacturing share in Europe in 2030 – to maintain strategic autonomy, and to be involved in AI and other key technologies of the digital world. In line with this initiative, the EU Chips Act and a second IPCEI on Microelectronics and Communications Technologies is being set-up to achieve digital leadership in Europe.

Furthermore, through a traditionally strong and advanced educational system, and the presence of world- leading research associations, Europe's R&D position throughout the whole stack of competencies (also industry-driven) is a unique asset. Continued investment in semiconductor-related studies is crucial to reversing the current trend of declining numbers of students as intended under the Pact for Skills[9].

## 1.1.5 Major Challenges

To achieve application breakthroughs and strategic advantage, the European position must be reinforced through leadership in all relevant equipment, materials, processes and manufacturing technologies by driving the following Major Challenges:

- **Major Challenge 1:** Advanced computing, memory and in-memory computing concepts.

  Materials and substrates, process modules and integration technology for novel devices and circuits for advanced computing, memory and in-memory computing concepts based on nano-electronic, photonic or quantum technology.

- **Major Challenge 2:** Novel devices and circuits that enable advanced functionality.

  Materials, process modules and integration technology for novel devices and circuits that enable advanced functionality (sensing including quantum sensing, actuating, power, connectivity, biomedical, cryogenic operation, etc.).

- **Major Challenge 3:** Advanced heterogeneous integration and packaging solutions.

  Advanced heterogeneous integration and packaging solutions for system on a chip (SoC), 2.5 and 3D stacking (including chiplet technology), and smart SiP, off-chip high-density embedded memory technology, (quantum) sensor integration, photonics, power electronics, and other functionalities required for application domains (such as augmented reality/virtual reality (AR/VR), automotive, (bio)chemical, biomedical, aerospace, etc.).

- **Major Challenge 4:** World-leading and sustainable semiconductor manufacturing equipment and technologies.

  World-leading and sustainable semiconductor manufacturing equipment and technologies for the realisation of sub-2 nm node logic and compatible on and off-chip memory solution according to PPAC roadmap requirements, chips/chiplets with single and/or multi-node layers, advanced functionality devices and heterogeneous integration technology options, as described under Major Challenges 1–3.

### 1.1.5.1 Major Challenge 1: Advanced computing, memory and in-memory computing concepts

Semiconductor process technology and integration actions will focus on the introduction of new materials, devices and concepts, in close collaboration with the equipment, materials, modelling/simulation and embedded software communities, to allow for the necessary diversity in computing infrastructure. The applications range from high-performance cloud/edge computing in servers, office/home computing, mobile computing, and ultra-low power data processing at the IoT node level up to the highest possible performance.

#### 1.1.5.1.1 State of the art

The obvious solution for transistors with increased electrical performances is the use of fully depleted devices. The industry has adopted two integration methods: FDSOI CMOS and FinFET-style CMOS devices. Chip designers have now embraced the idea that FDSOI and FinFETs can play complementary roles depending on the system requirements (cloud-based services, edge computing or extreme-edge device functionality).

3D FinFET-style CMOS devices provide high current drive, and hence higher speed, low leakage and, most importantly, less wafer area per transistor than 2D metal–oxide–semiconductor field effect transistor (MOSFET) technology. These devices are designed and processed to deliver better performance for applications in high- growth markets such as hyperscale data centres, autonomous vehicles and power-efficient SoCs for the most demanding computer applications. Extreme ultraviolet (EUV) lithography has also made its way into high-volume manufacturing. The international industry value chain is pushing production beyond the 3 nm node by moving towards Gate-All-Around (GAA) architecture[10], and requires solutions in materials and process integration challenges to realise these novel devices.

Scaling further has recently been demonstrated being possible via the introduction of CFET devices (complementary FET). A future sub-2nm advanced System-on-Chip pilot line will enable bringing R&D of this technology to higher maturity including design enablement that will offer **access to** European manufacturing and design Industry. This allows **SME's and start-ups** to **be** competitive and **strengthen EU's position in the value chain, increasing the resilience and** maintain **relevance** in the world race of addressing the ever-increasing user needs and societal challenges.

FDSOI is a 2D technology based on a thin buried oxide (BOX) layer under the CMOS channel. FDSOI exhibits several advantages, such as reducing the leakage current at standby mode and its higher tolerance against soft errors compared to traditional structures. FDSOI is perfectly suited for ultra-low-power IoT automotive, edge AI and 5G devices. The leading companies produce 18 nm and 22nm FDSOI-based chips. The future pilot line on FDSOI will develop 10nm and 7nm FDSOI technology nodes to allow a further reduction in energy consumption, while increasing its information processing performances.

A clear differentiation between logic, memory and process information in conventional von Neumann computing schemes necessitates the frequent movement of data between the memory and processor. Thus, much of the execution time and energy consumption is spent in the movement of data, a barrier referred to as the "von Neumann bottleneck", or "memory wall". This obstacle has been greatly exacerbated since the advent of data-intensive computing applications, such as AI. Near-memory and in-memory computing are emerging paradigms, wherein the computing system is redesigned to process data at its storage – in the memory – thereby minimising the expensive movement of data.

Near-memory computing involves adding or integrating logic (e.g. accelerators, very small cores, reconfigurable logic) close to or inside the memory. Logic cores are usually placed inside the logic layer of 3D-stacked memories or at the memory controller.

Silicon interposers allow for separate logic chips to be placed in the same die package as a 3D-stacked memory while still taking advantage of the through-silicon via (TSV) bandwidth. Some foundries (Intel, Samsung, TSMC, etc.) offer this kind of heterogeneous integration.

Recent advances in heterogeneous integration technology focus on integrating Si-bridges to connect dies together over very short distances along the die perimeter (e.g. Intel EMIB technology, TSMC implementation of Si-bridge and "InFo" technology for the Apple M1 Ultra computer). Currently, several initiatives have been taken by industry groups to attempt to create standards for these "chiplet" interconnect schemes (HBM by JDEC, BOW by OPC, AIB by the "CHIPS" alliance which is further developed to "the Universal Chiplet Interconnect Express", UCIe).

These heterogeneous integration technologies (Interposers, bridges, chiplets) are often referred to as 2.5D as they still place active die next to each other in a 2D plane. Through 3D integration technology stack active devices are placed vertically on top of each other. This is commonly done in the field of CMOS image sensors and HBM DRAM memory stacks. These 3D integration technologies use TSV technology in the active die, in combination with high density die-to-die or wafer-to-wafer interconnect technologies. This greatly increases the number of functional interconnects per die area on the functional chips. 3D-Interconnect pitch below 10 µm and even down to 1 µm pitch have already been demonstrated.

An even denser 3D interconnect technology could be achieved by so-called "monolithic" 3D integration, a technique using sequential manufacturing of multiple layers of active devices and high density (Back-end of line) interconnect layers. Such monolithic integration is not currently available in foundries. In-memory computing also uses the intrinsic properties and operational principles of the memory cells and cell arrays, by inducing interactions between cells such that the cells and/ or cell arrays can perform computations themselves.

Due to the increasing need for large memory systems by modern applications (big data analytics, AI, etc.), dynamic random access memory (DRAM) and Flash memory scaling is being pushed to its practical limits. It is becoming more difficult to increase the density, reduce the latency and decrease the energy consumption of conventional DRAM and Flash memory architectures. 2D-NAND became monolithically integrated 3D-NAND, found the 3rd dimension for scaling, DRAM may follow the same path in near future. This will seek innovation in DRAM select transistor channel material (ALD $MX_2$, ALD Oxide Semiconductor etc.), capacitor dielectric, new cell architecture, new process steps etc. Alternative approaches are also being developed to overcome these barriers for implementing near- or in-memory computing.

The first key approach consists of stacking multiple layers of memories (DRAM, Flash). With current manufacturing process technologies, thousands of TSVs can be placed within a single 3D-stacked memory chip. The TSV provide much greater internal memory bandwidth than the narrow memory channel. 3D-stacked DRAM and Flash are also commercially available.

The second major innovation is the use of emerging non-volatile memory (NVM) as parts of the main memory subsystem, and as embedded memories. To avoid DRAM scaling limitations, new memory devices and technologies that can store data at much higher densities, longer retention, and cheaper than the typical density available in existing DRAM manufacturing process technologies are currently being investigated. The main emerging NVM technologies to augment or replace some DRAM tasks at the main memory layer, and as embedded memories: (i) phase-change memory (PCM); (ii) magnetic RAM or spin-transfer or spin-orbit torque, or voltage-controlled magnetic anisotropy magnetic RAM (MRAM, STT-MRAM, SOT-MRAM, VCMA- MRAM); (iii) metal-oxide resistive RAM (RRAM or ReRAM) and conductive-bridge RAM (CBRAM) or memristors; (iv) ferroelectric FET (FeFET) and RAM (FeRAM); (v) Electrochemical RAM (ECRAM). and (vi) Oxide Semiconductor (OSC) channel gain cell (2TnC, n=0 or 1) All these NVM types are expected to provide memory access latencies and energy usage that are competitive with, or close enough to, DRAM while potentially enabling much larger capacities per chip and non-volatility in main memory.

#### 1.1.5.1.2 Vision and expected outcome

Driven by market demand on the one hand for advanced high-performance computing devices, and on the other hand for mobility and IoT devices, the advanced Si technology roadmaps for both FinFET and FDSOI will need to be pushed further. To enable this, a wealth of explorations into novel low-thermal-budget-processing 2D materials, nanowires, nanosheets or nanoribbons and quantum dots needs to be combined with significant developments in advanced 3D integration schemes of materials and devices. In parallel, to overcome the von Neumann bottleneck, development of new computing paradigms such as neuromorphic, in-memory and quantum computing is essential.

New memory concepts will support the correct memory hierarchy in various applications. An example here is the opportunity to push new memory concepts (resistive RAM (RRAM), phase-change RAM (PCRAM), STT- MRAM, FeFET, FeRAM, Electro-Chemical RAM (EC-RAM)) to the demonstration level in the IoT infrastructure (from server, over edge to nodes). These alternative memories require the development of advanced novel materials (magnetic, phase-change, nanofilament, ferroelectric, electrochemical). A much closer collaboration between new material innovation, process, device integration, device teams and system architects is indispensable in the future. New markets will require storage class memory to bridge the performance gap between DRAM and NAND Flash. IoT applications will require low-power embedded devices and cloud computing with more mass-storage space. The standard memory hierarchy is challenged. Simultaneously, advanced interconnect, SoC integration and packaging issues will need to be addressed (cf. also Major challenges 2 and 3), with innovative solutions to reduce costs being required. The option to use advanced 3D and optical input/output (I/O) technological solutions to circumvent limitations of traditional I/O's architectures are strengths to foster and build upon in Europe.

To maintain the European competencies in advanced design for integrated circuits and systems, a close link with a strong effort in semiconductor process technology and integration has to be maintained. Issues such as the creation of standards for the IoT, reliability for safety or mission-critical applications, security and privacy requirements need close collaboration among all players to build leadership going forward in this coming generation of advanced and distributed computing infrastructure and diversified system performance.

**Expected achievements**

Maintaining competence on advanced logic and memory technology in Europe is key to maintaining strategic autonomy and supporting societal benefits from the core technology base. Implementation of dedicated and sustainable pilot lines for specialised logic processes and devices supporting European critical applications is also a major objective, as is the exploration of new devices and architectures for low-power or harsh environment applications.

#### 1.1.5.1.3 Key focus areas

This challenge includes the following key focus areas:

- Explorations of the scaled Si technology roadmaps of the 2 nm node and beyond including FinFET/Trigate and stacked gate-all-around horizontal or vertical nanowires, Forksheet-, complementary FET architectures, next generations FDSOI, 3D integration, and further device and pitch scaling where parallel conduction paths (nanowires, nanosheets, nanoribbons, etc.) are brought even closer together. It includes novel device-interconnect technology such as but not limited to contact from wafer backside.
- Exploration and implementation of materials beyond Si (SiGe, SiC, GaN, Ge, InGaAs, InP, functional oxides, 2D material heterostructures, CNT and nanowires).
- Novel device, circuit and systems concepts for optimum PPAC specifications, high-energy efficiency and novel paradigms such as for near/in-memory, neuromorphic, optical and quantum computing.
- Long-term challenges such as steep slope switches (tunnel FET, negative capacitance FET, nanoelectromechanical systems, NEMS), spin-based transistors, and alternative high- performance switches.
- Unconventional devices and materials, such as 2D and III-V materials, oxide-semiconductors, metamaterials, metasurfaces, nanowires, CNTs, nanosheets, nanoribbons, nanoparticles, quantum dots, spin effects, functional oxides, ferroelectric and magnetic, which are being investigated to overcome the limits of conventional CMOS logic and memories.
- New embedded non-volatile memory (eNVM) technologies to enable local AI processing and storage of configuration data, which decrease data transmission volume, energy needs and allow for more efficient control of electric powertrains and batteries, along with many other applications in the IoT and secure devices domains.

### 1.1.5.2 Major Challenge 2: Novel devices and circuits that enable advanced functionality

These are materials, process modules and integration technology for novel devices and circuits that enable advanced functionality (sensing, actuating, energy harvesting and storage, connectivity, biomedical, etc.), including wafer or substrate technologies.

This section covers the integration of the logic/memory building blocks (of Major Challenge 1) with other logic/memory building blocks and/or with the non-logic/non-memory building blocks on a single chip (power chips, sensors, NEMS/MEMS (nano-and microelectromechanical systems), energy harvesting and storage devices, RF chips such as SiGe or the GaN and other compound semiconductors, passive and active photonic functionalities). The resulting multiple (sub)systems on a chip should enable heterogeneous SiP integration of Major Challenge 3.

## 1.1.5.2.1 State of the art

Besides the highly integrated chips necessary to overcome Major Challenge 1 on advanced computing, memory and in-memory computing concepts, many more devices are needed to achieve advanced functionalities – such as sensing and actuating, power management, and interfaces to other systems. This is what has also been named “more than Moore” in recent years, and is an integral part of all systems, as well as one of the strengths of European microelectronics. Given the inherently diverse nature of this sector, the state of the art will be captured by providing a few snapshots of key technologies.

In application-specific logic, the architectures of the embedded NVM implementations are well adapted to current applications, such as flash-based generic or secure micro-controllers, but still lack optimisation to new schemes such as true neuromorphic processors. For IoT applications, logic and RF functions are combined, but not with the highest efficiency required by the ultra-long lifetime. Energy harvesting schemes, often based on photovoltaics, do exist, yet are not always able to provide the requested energy supplement of self-contained low volume and low-cost sensor nodes.

Smart optical, mechanical and magnetic sensors are already able to provide a wealth of information for complex systems. Nevertheless, there are current limits to integrating various types of sensors monolithically. In the field of optical sensors, for instance, depth mapping requires complex scanning schemes using either mechanical systems or large volume and poorly integrated light sources. Devices based on rare or expensive materials, which are not compatible with standard CMOS technology, cover various useful zones of the electromagnetic spectrum. The same is true for chemical-sensing technologies, which are mostly based on metal oxides. While solutions for specific gases and applications are starting to emerge, sensitive and robust technologies using semiconductors still remain to be developed for a large number of applications and species. The situation is similar for many kinds of sensors and actuators. For instance, fine pitch displays are beginning to be possible, but will require new advances both in high brightness low variation sources and assembly methods.

Technologies used for the next generation of quantum sensing include neutral atoms, trapped ions, spin qubits, superconducting circuits, and photonics. They can be used to measure the magnetic field (B), the electric field (E), the rotation (θ), the acceleration (g), the time (t), the frequency (f), the temperature (T), the pressure (P), the force (F), the mass (m) and the voltage (V) (Table 1). Charged systems, like trapped ions, will be sensitive to electrical fields, while spin-based systems will mainly respond to magnetic fields. Some quantum sensors may respond to several physical parameters.In power technologies, recent years have seen the emergence of wide bandgap materials able to reduce the losses of power conversion, namely SiC and GaN, or other wide bandgap technologies. These technologies are making quick inroads as one of the cornerstones for the energy transition... However, they are still nascent, and the challenge is to develop low-cost (involving larger diameter, good quality and less-expensive substrates) and robust technologies. Today, SiC is produced mainly on 150 mm substrates, while GaN devices are produced on silicon substrates, but the technology and epitaxy techniques will still need further refinement (and even breakthroughs). Moreover, the development of disruptive substrate technologies as well as layer transfer will be key steps toward a cost effective, high performance solution linked with transition from 200 mm to 300 mm substrates, which is essential for future integrated logic and power management functions using technologies to combine logic and power transistors. Beside research on wide bandgap materials, the Si-based insulated-gate bipolar transistor (IGBT) technologies have further innovation potential in the area of cost-sensitive applications. Challenges are in the domain of high power and high voltage electronics with high junction temperatures processed on 300 mm substrates – leading to increased power densities and lower costs to support the transformation in the energy systems with Si-based power semiconductors.

For RF and communication technologies, recent advances in integrating RF technologies on low-loss substrates such as SOI have allowed the integration of switches as well as amplifiers on the same silicon substrates. This concept is in production in Europe on 200 mm and 300 mm wafer substrates. Further advances are on the way on 300 mm substrates and technologies, which will allow the integration of more functions and address the requirements of complex 5G systems below and beyond 6 GHz, up to the mm waveband. Synthetic antennae systems for radar or communications are emerging thanks to highly integrated RF technologies, including BiCMOS, but are often limited by power consumption and costs. New, RF technologies delivering high output power and efficiency like RF GaN (GaN-SiC as well as GaN-Si) and III-V could overcome these limitations. In the field of communications, the integration of photonics technologies with electronics is gaining commercial ground. Further advances in efficient source integration, and modulation and power efficiency, are still needed to use them more widely. New advances in fine photon handling can also open the way to innovative sensing techniques.

In optical communications, the industry trend is to adopt power-efficient, high-speed, silicon photonic links to help addressing the growing demand for data transmission bandwidth, increase computing capabilities and lower consumption. The intrinsic capability of light waves to transmit signals with low latency and power dissipation, at ultrahigh data rates, can be scaled from long-haul infrastructures to intra-datacenter optical links, down to chip-to-chip photonic interconnects. However, bulk silicon cannot meet the necessary requirements of these integrated optics applications which can be addressed with silicon-on-insulator (SOI) technology. SOI photonics is one route to enable the development of novel lidar systems as well as support advancements in quantum technologies. By leveraging mature semiconductor manufacturing methods, engineered wafers that incorporate SOI technology offer a powerful approach toward broader adoption of advanced chip-scale integrated optics.

In “traditional” polyimide (PI)-based flexible electronics, the continuing trend is towards more complex designs and large-area processing, especially in displays and sensor arrays. Since the achievement of high-performing flexible electronics by monolithic approaches is limited, hybrid approaches are used when conventional electronics (such as thinned chips) is assembled on flexible electronic substrates. For more complex devices, the reliability and performance of organic materials or mechanical and processing properties of inorganic materials are still a focus of research activities in addition to adapted and optimised assembly techniques. In general, current R&D activities indicate that technical spots can be identified where a merging of novel flexible devices and adapted Si electronics create progress beyond the state of the art.

## 1.1.5.2.2 Vision and expected outcome

Depending on the application, the advantages of heterogeneous SoC technology are size, performance, cost, reliability, security and simpler logistics. Therefore, this technology is a key enabler for European industry. To maintain and strengthen Europe's position, it is necessary to improve existing technologies, and to seamlessly integrate emerging technologies in a reliable and competitive way. All application domains addressed by the ECS SRIA will benefit from components with very diverse functionalities.

Specific process technology platforms may be required, as in the case of biomedical devices for minimally invasive healthcare or point-of-care diagnosis, or mission-critical devices in automotive, avionics and space. Semiconductor process and integration technologies for enabling heterogeneous SoC functionality will focus on the introduction of advanced functional (nano-)materials providing additional functionalities and advanced device concepts.

Innovations for these domains require the exploration and functional integration, preferably in CMOS- compatible processing, of novel materials. A non-exhaustive materials list includes wide bandgap materials, III-V, 2D (e.g. graphene, $MoS_2$ and other transition metal dichalcogenides), 1D (e.g. nanowires, carbon nanotubes) and 0D (e.g. nanoparticles, quantum dots) materials, metal oxides, organic, ferro- and piezoelectric, thermoelectric and magnetic thin films materials, metamaterials and metasurfaces. Obviously, safety and environmental aspects should also be taken into consideration.

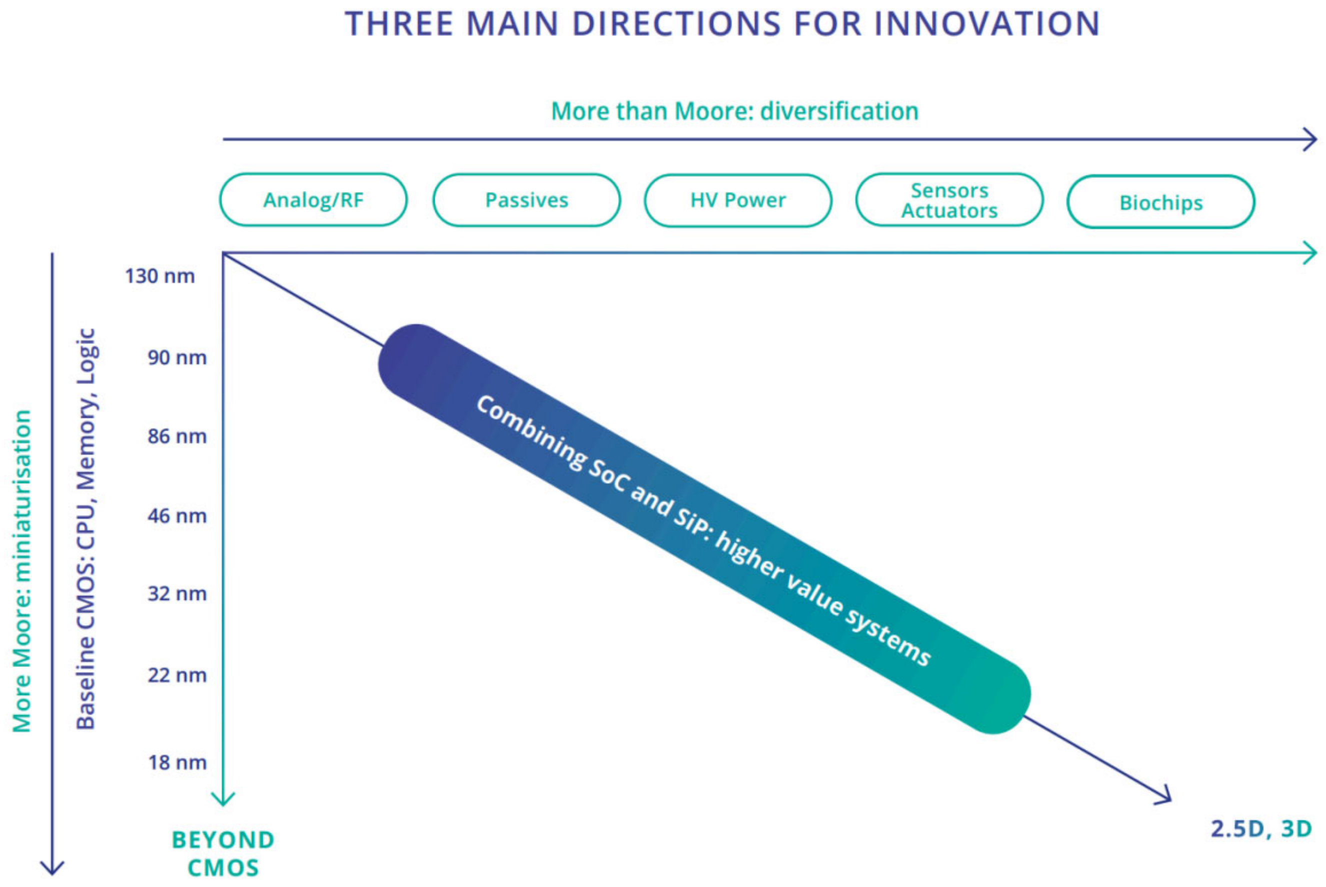

*Figure 1.1.3 Diversification of applications, continued miniaturisation and integration on chips and in package leads to higher value systems (Source: ST Microelectronics/IRDS)*

The driver for SoC integration is always a clear demand from the application domain. To maintain and push forward Europe's position, the focus should be on emerging technologies as they are introduced, as well as new developments in the equipment and materials industry, in which Europe has a leading position. Furthermore, the early generation of models and their initial validation for benchmarking and intellectual property (IP) generation are required to reinforce position of Europe in specific design concepts and architecture, especially when used in combination with re-use IP and third-party IP blocks to secure fast time to market.

For structural and flexible electronics, the most important development topics on building the active devices are thinning of Si components for flexibility in heterogenous integration approach, and the development of materials and fabrication methods for flexible active components (e.g. printed transistors). Materials development for active components includes stretchable, printable, conductive and insulative inks. The progress in material science with respect to organic materials, metal oxides, nanomaterials and low-thermal-budget-processing 2D materials will be used for flexible electronic devices to improve their performance. Although there are already many applications that can be addressed by flexible electronics, foldable and stretchable electronics is increasingly on the agenda of research and technology organisations (RTOs) and industry. The objective is to handle electronics like paper or to integrate flexible electronics on 3D-conformable surfaces. The first of these will be important for the display industry, for instance, and the second will be key for the automotive industry as it deals with 3D surfaces in the interior, and integrates electronic functionalities (sensors, displays, light sources, etc.) on complex surfaces. The requirement on materials and process techniques is much more challenging than for flexible devices since all components and materials have to provide elasticity (intrinsic stretchability).

## 1.1.5.2.3 Expected Achievements

This will involve the implementation of pilot lines for integrated application-defined sensors, novel IoT solutions, complex sensor systems and new (bio)medical devices, new RF and mm-wave device options (including radar), photonics options, electronics and packaging solutions. Key will be the initiation of process technology platforms for the exploration and exploitation of advanced functionalities through integration of novel reliable materials.

The exploration and implementation of materials beyond Si will require strategic collaborative EU projects for European industry to become more independent, and will result in the development of a EU-based supply chain for wide-bandgap materials, for example, including a move towards larger substrate sizes of 200 and 300 mm (i.e. SiC and GaN).

Improved materials and assembly techniques will result in more feasible applications for large-area, lightweight, robust and structurally integrated electronics. Hybrid approaches will be used more often, and the boundaries between µ-electronics, semiconductor electronics and flexible electronics will slowly disappear. Strategies to create stretchable electronics will also be developed.

## 1.1.5.2.4 Key focus areas

More specifically, the following challenges are identified (this is a non-exhaustive list).

Application-specific logic: as explicitly treated in sub-section 1.1.4.3, heterogeneous SoC integration can require specific solutions for logic to be integrated with more-than-Moore technologies such as the following:

- Tight logic/memory integration for new architectures for neuromorphic computing.
- Logic integration with RF, optical or sensor technologies.
- Ultra-low power (ULP) technology platform and design.
- Integration of lasers and detectors within silicon photonics platform.

Advanced sensor technologies:

- Mechanical sensors (e.g. acceleration, gyroscopes, microphones).
- Chemical sensor devices such as selective gas-sensing components for environmental monitoring or smart medicine and smart health (e.g. CO, $CO_2$, $NO_x$, $O_3$, toluene, VOCs, acetone, $H_2S$).
- Physical sensors (magnetic, optical, RF).
- Multispectral or highly sensitive optical sensors
- Transmitter/receiver technologies for applications such as lidar and active phased array imaging.
- Biomedical and biochemical sensors.

Quantum sensor technologies:

- Atomic vapor or cold atom (Bose-Einstein condensate) based sensors
- Trapped ion based quantum sensors
- Solid state spin based quantum sensors making use of Nitrogen-Vacancies or color centres as sensitive element
- Superconducting circuit sensors based on SQUIDS, flux qubits and charge qubits
- Sensors based on photon entanglement using nonlinear optical media

Advanced power electronics technologies (Si-based, BCD, SiC, GaN, $Ga_2O_3$, AlN etc.) to enhance the efficiency of motors, energy storage, lighting systems, etc. More specifically:

- Higher power density and frequency, wide-bandgap materials for high temperature electronics, new CMOS/IGBT processes, integrated logic, uni- and bipolar; high voltage classes, lateral to vertical architectures.
- Materials for energy harvesting (e.g. perovskite solar cells, piezoelectric ceramics and thin films) and storage (e.g. perovskites, ferroelectrics and relaxors), micro-batteries, supercapacitors and wireless power transfer.
- Power devices and modules for highly demanding automotive, industrial and energy infrastructure applications.

- Substrates towards larger diameters to serve future greater demand for cost-sensitive power solutions.

Advanced RF and photonics communication technologies to interface between semiconductors components, subsystems and systems. These technologies should enable better and more energy-efficient control of emission and reception channels (for example, for 5G connectivity and 6G preparations) via:

- New energy-efficient RF and mm-wave integrated device options, including radar (building on e.g. SiGe/BiCMOS, FD SOI, CMOS, GaN, III-V, PIC).
- Development and characterisation of new RF cryogenic electronics for QIP, as well as logic devices at quantum-enabling cryogenic temperatures taking into account the available cooling power of refrigerators and interfacing requirements at different operation temperatures.
- Energy-efficient computing and communication, including a focus on developing new technologies.
- Bringing MOEMS and micro-optics, nanophotonics, optical interconnections, photonics-enabled device and system options into a CMOS-compatible manufacturing and/or packaging flow.
- Integration of solid-state light emitters such as LED and laser with, or onto, a CMOS-compatible platform.

Electronics on flexible and structural substrates are to a large extent dealt with in the Chapter 1.2 on Components, Modules and Systems Integration. However, specific aspects related to process technology are also required:

- Development of new process capabilities for adapting to flexible, structurally integrated and stretchable electronics, which includes enabling large interconnection areas on substrates.
- Novel (semi)conducting, insulating and encapsulation materials for more reliable devices, and novel substrate materials that can deal with the challenges of flexible electronics.
- Flexible electronics is prone to be used as disposable electronics, and therefore biodegradable materials should be developed that can demonstrate the required performance.

### 1.1.5.3 Major Challenge 3: Advanced heterogeneous integration and packaging solutions

Advanced heterogeneous integration and packaging solutions for SoC, 2.5 and 3D stacking (including chiplet technology), smart SiP, photonics integration, sensor integration, power electronics, and other functionalities are required for application domains such as AR/VR, automotive, biomedical, avionics, space. Advanced packaging is also required to bridge the scale gap between wafer dies of various technologies and printed circuit boards (PCBs).

By splitting the packaged chip into smaller functional IP blocks, the overall system yield improves and system performance is enhanced. In addition, by using system-independent IP block design and verification, as well as common die-to-die interfaces (including IP re-use and use of third-party IP), a faster time to market can be achieved.

#### 1.1.5.3.1 State of the art

Over the last few years a huge variety of semiconductor products have emerged where several functions are added in one IC package, enabled by advances in integration and packaging technology.

To maximise the benefits from ICs made for IC-nodes of 7 nm and less, there has already been a move from simple wire bonding to more advanced methods such as ball grid arrays (BGAs), flip chips, wafer-level packaging, fan-out wafer-level packages without substrate interposers and complex 3D structures with TSVs, micro-bumps and thin dies.

The functional diversification of technologies, where digital electronics meets areas such as analogue, photonic and MEMS technologies, has been advanced through the assembly/packaging of heterogeneous elements. For example, in today’s power stages in automotive powertrain applications, there could be power modules that integrate several dies in parallel. Similarly, 5G networks are enabled by advanced RF functionality, often combining a photonic interface with in-package integrated logic and memory functionalities. Upscaling of capacity for photonic ICs may be kickstarted via microwave photonics as a new domain. Semiconductor materials in packaging technology have already moved from being largely silicon-based to more advanced SiC and GaN compounds, as well as towards environmentally friendly lead (Pb) and halogen-free mold compounds. For wire bonding, a similar move from aluminium and gold towards copper and silver wiring has been made. Furthermore, flip chip attach has made a transition to lead-free bumps and BGA using lead-free ball materials.

#### 1.1.5.3.2 Vision and expected outcome

This challenge covers the integration of new chip technologies in advanced low parasitic packages, as well as chips of different functionalities resulting from the previous two challenges – e.g. CMOS logic, NVM, NEMS/ MEMS, RF, analogue, sensing, actuating, energy harvesting and storage – into an SiP.

Advanced packaging technologies are required for mm-wave applications (> 30 GHz), both GaN/Si RF and other high-electron-mobility-transistor (HEMT) devices, or dedicated MEMS and sensor devices (e.g. electro-optics for lidar without moving parts). Depending on the application, heterogeneous SiP technology can provide a better compromise between available functions, performance, cost and time to market.

Assembly and packaging (A&P) technologies, especially those with a focus on system integration, are a key enabler for European industry, including the new field of cryogenic QIP, characterisation of logic devices at quantum-enabling cryogenic temperatures, and associated packaging challenges. To maintain and strengthen Europe's position, it is necessary to improve existing technologies and develop emerging technologies, as well as to integrate both to advanced electronic systems in a competitive and reliable way. All application domains addressed by the ECS agenda will benefit from innovative assembly and packaging, including SiP components.

Moreover, component carriers also known as Integrated Circuit (IC) Substrates represent a big portion of the package cost (up to 50%), excluding the semiconductor component itself. This is particularly true for Flip Chip Ball Grid Array (FC-BGA) Substrates, which are essential component carriers in high performance computing solutions. Due to the increase of functionality and driven by chiplets integration, FC-BGA substrates are facing many challenges not only in terms of miniaturization, but also they are becoming central elements for power management in advanced computing systems.

Integration of the above functionalities in miniaturised packages and (sub)SiP require fundamental insights into application needs and system architecture. Process and characterisation technology to realise this integration is part of this third Major Challenge, and is essential for ensuring Europe's prominent role in supplying novel solutions for the various existing and emerging application domains.

Compared to chip technology, assembly and packaging are becoming increasingly important. In many cases, assembly and packaging costs are becoming higher than the chip cost. To reverse this trend, we must focus on dedicated packaging and SiP process technologies that consider all the levels of chip, package and board/ system to identify the optimum trade-offs between function, cost, power, reliability, etc.

To remain economically sustainable and globally competitive, a toolbox must be set up, including evolution of current process technologies as well as new ones, aiming to provide cost-effective and outstanding system integration. Alternative low cost solutions are needed addressing 2.xD integration include interposers based on inorganic, e.g. Si and glass, as well as organic, e.g. FC-BGA and RDL-based, substrates. Furthermore, novel 3D interconnect solutions should be explored enabling new levels of integration for high performance and multifunctional electronic smart systems (ESS).

At the macro-scale level, a system consists of a collection of large functional blocks. These blocks have quite different performance requirements (analogue, high voltage, eNVM, advanced CMOS, fast static RAM (SRAM), multi-sensing capability, etc) and technology roadmaps. Therefore, for many applications it is of increasing interest to split the system into heterogeneous parts, each realised by optimum technologies at lower cost per function, and assembled with parts using high-density 3D interconnect processes.

It is clear that 3D integration in electronic systems can be realised at different levels of the interconnect hierarchy, each having a different vertical interconnect density. Different technologies are therefore required at different levels of this 3D hierarchy.

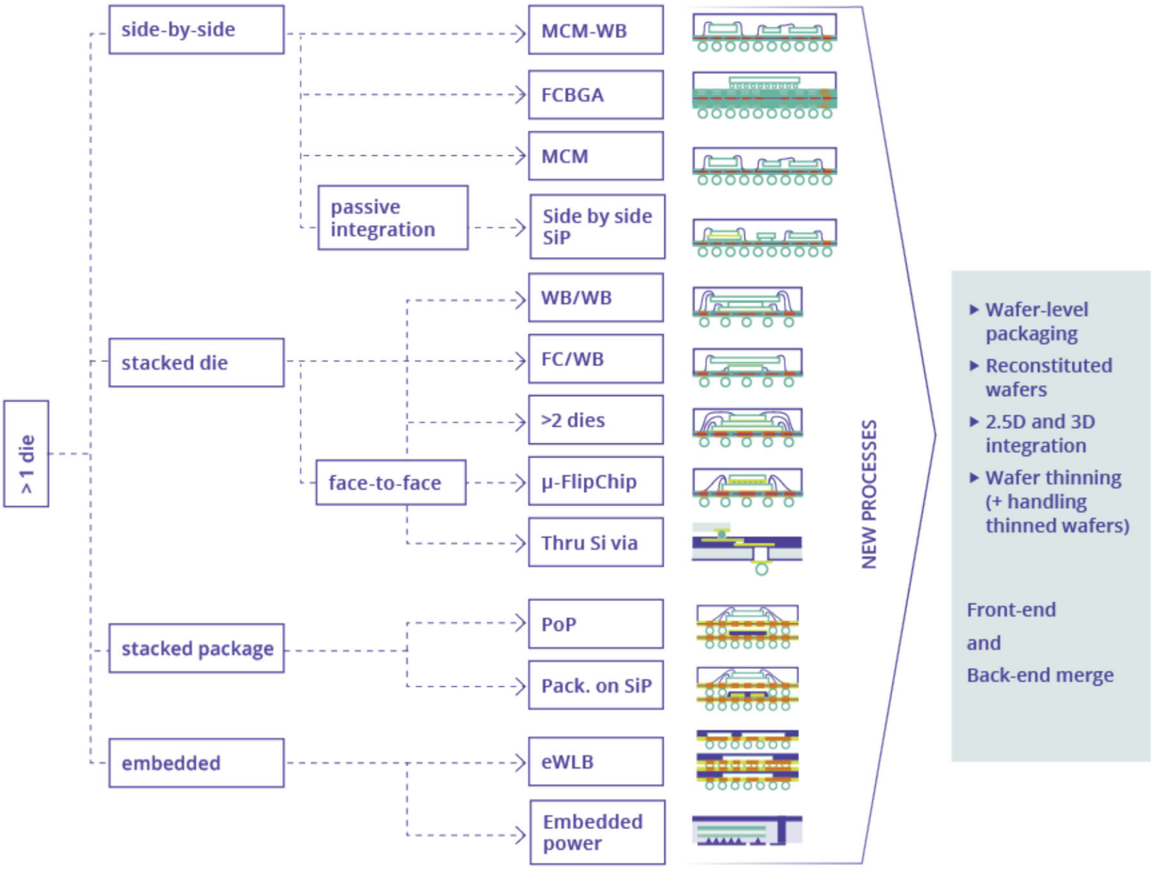

*Figure 1.1.4 - System in a package (SiP) examples. With merging of front-end and back-end, almost unlimited possibilities enabled (Source: Andreas Grassmann – Infineon – 3D Systems Summit*

### 1.1.5.3.3 Key focus areas

Research and development priorities are focused on innovative approaches, such as the following.

Advanced interconnect, encapsulation and packaging technologies:

- Interconnect technologies that allow vertical as well as horizontal integration: this includes process technologies for vertical interconnects, such as TSV, through-encapsulant via (TEV) technologies and microbumps, and copper/copper bonding, as well as process technologies for horizontal interconnects such as thin film technologies for redistribution both on chips and encapsulation materials. A technology base is needed for 3D stacking as well as horizontal interconnecting of dies and chiplets. This also includes interconnects through optical interfaces, most notably off-chip, but also within a package.
- Implementation of advanced nanomaterials and metamaterials, including low-thermal-budget-processing 2D materials, nanowires, nanoparticles and quantum dots with scalable logic and memory device technologies, which will be key for adding new functionalities and developing multifunctional smart systems.
- New materials like Al bumps from Electroplating could solve reliability issues and ensure advanced CMOS compatible packaging on Wafer level bonding and Chip Integration.
- Power electronic substrates will benefit from thick Al layers fabricated by novel electroplating technologies.
- Specific power and RF application technologies.
- Solutions for high-frequency miniaturisation, such as for mm-wave applications (> 60 GHz) and for > 100 GHz towards THz applications for which no package solutions currently exist.
- Increasing functionality in IC Substrates for high efficiency power delivery including voltage regulator circuitry and integrated capacitance. Additionally, fine structuring capability achieving high bandwidth interconnections has to be reached either sequentially (2.1D) or recombining separated manufactured carriers (2.3D and 2.5D).

3D integration technologies:

- High-integration density and performance-driven 3D integration (power/speed). For this category, denser 3D integration technologies are required: from the chip I/O-pad level 3D-SIP, to finer grain partitioning of the 3D-SOC and the ultimate transistor-level 3D-IC (see Sub-section 2.3.1 for the 3D landscape).
- Chip-package-board co-design. This will be of utmost importance for introducing innovative products efficiently with a short time to market (and which is closely linked to the work described in Section 2.2).
- System integration partitioning: the choice of 3D interconnect level(s) has a significant impact on system design and the required 3D technology, resulting in a strong interaction need between system design and technology with a significant impact on electronic design automation (EDA) tools.

Enhanced reliability, robustness and sustainability technologies:

- Solutions for high reliability, robustness and high quality. For this, a close consideration of the chip/package interaction, but also of the interaction of chip/package to the board, is required. R&D in this area requires a strong link, especially with materials and their compatibility, and also consideration of the heat dissipation challenges. In addition, variations and extremities in operating environmental conditions should be considered to ensure devices work seamlessly and operational life is not impaired. Avoiding (particle) contamination is another, increasingly critical, requirement. In the last decade nearly all assembly and packaging materials have changed; in the next 10 years, it is expected they will change again. Also, a close link with the Architecture and Design section is crucial here.
- Solutions to test separate components, before and after assembling these in a single package/ subsystem. Concepts like built-in self-test (BIST) and self-repair require some amount of logic integration, and a design providing access for die testing.

System requirements and semiconductor device technology (Major Challenges 1 and 2) will evolve at the same time, creating momentum for further interconnect pitch scaling for 3D integration technology platforms. Hence, the timelines of all four challenges of this section are strongly connected.

### 1.1.5.4 **Major Challenge 4: World-leading and sustainable semiconductor manufacturing equipment and technologies**

Semiconductor manufacturing equipment for the high volume production of sub-2 nm node logic and memory according to PPAC roadmap requirements, chips/chiplets with single and/or multi-node layers, advanced functionality devices and heterogeneous integration technology options as described under Major Challenges 1–3.

The semiconductor equipment and manufacturing sector in Europe provides the global market with best- in-class equipment and materials to enable the manufacturing of miniaturised electronic components. The European equipment industry, RTOs and small and medium-sized enterprises (SMEs) active in this sector have a long history of successful mechanical engineering, tailor-made machinery, optical equipment, metrology, inspection and testing equipment, and chemical processing tools. This history of success is prominent in several domains, foremost in lithography (in particular EUV) and metrology, but also in thermal processing, deposition, cleaning and wafer handling, as well as wafer assembly, packaging and in overall product reliability.

### 1.1.5.4.1 State of the art

At the forefront of semiconductor manufacturing equipment is the production of logic and high-performance memory, which are applied mainly in portable devices as well as advanced cloud computing and data storage facilities. The continuous increase of device density known as Moore's law is being driven by an ability to create ever-smaller features on wafers. The technology leaps required to keep up with Moore's law have already been achieved via additional roadmaps complementing ongoing 2D pattern size reductions. They are realised by combining various devices, materials, and 3D and system architecture aspects that required dedicated long-term investment in high-tech equipment solutions. Enabled by current deposition, lithography, etch, processing and metrology tools and their performance, the 5nm technology node is in production by market leaders, solutions for 3nm node has been taped out late 2021[11], and even Angstrom nodes[12] are being explored.

For the production of miniaturised and reliable more-than-Moore electronics components and systems, such as sensors and sensor systems, MEMS, advanced imagers, power electronics devices, automotive electronics, embedded memory devices, mm-wave technologies, and advanced low-power RF technology, many equipment and manufacturing solutions have been implemented. To a large extent, the equipment and manufacturing sector in Europe has developed a full replacement cycle of nearly all assembly and packaging materials by more advanced and sustainable materials over the last decade.

### 1.1.5.4.2 Vision and expected outcome

The ever-increasing demand for leading-edge logic and memory technology is driving the development of new equipment and material solutions for sub-2 nm node semiconductor technologies. Besides finding equipment solutions for further shrinking minimum feature sizes well below 10 nm, the alignment accuracy of successive layers, called "overlay" or in another definition type "Edge Placement Error", needs to move towards Angstrom levels in a process technology roadmap that combines complex materials in 3D structures and architectures. At the same time, productivity demands on the equipment continue to increase to maintain reduced overall production costs. Process yield also continues to be a challenge with shrinking feature size and the increasing impact of defects and contamination.

The overarching goal of equipment development is to lead the world in miniaturisation techniques by providing appropriate products two years ahead of the shrink roadmap of world's leading semiconductor device and components manufacturers[13]. Internationally developed roadmaps such as the International Roadmap for Devices and Systems (IRDS) will also be taken into consideration[14]. Currently, leading integrated device manufacturers (IDMs) are forecasting a continuation of the technology roadmap following Moore's law at least until 2029[15], which corresponds to at least four new generations after the current technology node.

These equipment solutions will enable high-volume manufacturing and fast prototyping of electronic devices in CMOS and beyond CMOS technologies, and therefore allow for supplying the world market with technology-leading, competitive products. Applying new skills and knowhow in areas such as 3D heterogeneous integration and advanced SoC solutions (covered in Major Challenges 2 and 3 of this section) will create and trigger new technological and business opportunities.

For another part of the semiconductor ecosystem, which is also a European strength, system integration equipment is required that can combine chips and wafer technologies of various wafer sizes. In the coming years, 3D integration and SOC manufacturing will add complexity to the global supply chain, and generalise the concept of distributed manufacturing. This will require the development of new concepts for information and control. The interfaces and handovers between wafer technologies and assembly and packaging need to be clearly defined, and will require innovative equipment. Such technologies will necessitate working more closely together, combining front-end wafer equipment, and assembly and packaging equipment. Technologies and methodologies that are well established for Si wafers will partially be reused and adapted for assembly and packaging.

Heterogeneous SoC and SiP integration will pose significant challenges and require R&D activities in a multitude of fields. Equipment and material research must drive the general technology trends in respect to miniaturisation and integration of more functionality into a smaller packaged IC volume, and with higher efficiency, lower power consumption and longer battery life. Processes, equipment and materials for heterogeneous integration can be partially sourced from previous-generation CMOS infrastructures. However, new technology generations will also require capabilities that are not yet available in advanced CMOS fabrication.

Today's equipment was typically designed for the high-volume continuous production of advanced logic and memory devices, which requires major modifications or re-design when used as production tools for heterogeneous integration. Extending the life of installed equipment to match requirements of this domain via proactive lifecycle management (refurbishment) of these products will provide cost-effective solutions for specific applications. The performance must be enhanced for smaller batch production providing high flexibility and productivity at low cost of ownership.

Furthermore, the trend in solutions of ever-decreasing feature size with an ever-increasing number of features, and interconnects packed onto an IC, puts strong demands on product validation and verification methodologies, as well as on test methodologies and respective equipment.

It is imperative that the equipment and manufacturing sector enables highly flexible, cost-competitive, "green" manufacturing of semiconductor products within the European environment that enables European manufacturers to lead the evolution toward sustainable electronics. To achieve this, semiconductor manufacturing should lead the way in terms of digitisation, with a focus on secure, flexible and sustainable manufacturing and a move from "advanced process control-enabled" equipment to cyber-physical systems. The developed solutions should include innovations for resource-saving and energy-efficiency improvement, with further enhancement of productivity, cycle time, quality and yield performance, at competitive production costs. Furthermore, it will be key to adapt workflows to new, data-driven manufacturing principles adopting digital twins, AI, machine-learning and deep-learning methods, as described in Section 3.3 Digital Industry of this document.

Equipment and equipment integration need to become even smarter than it already is, carrying out intelligent data processing based on enhanced sensors and AI assisted operating strategies, not only to guarantee stable processes but also to learn, adapt and improve from data gathered and pre-processed in real time.

While the chip advancements are contributing to the industries across verticals, the increased development of chips is also adding to environmental wastes. For instance, fabricating a small 2g microchip (≈ 14-10nm technology node) requires 32-35 kilograms of water, 1.6kg of petroleum and 72g of chemicals[16]. Since very advanced technology nodes will require more process steps, and since the chip production could nearly double for satisfying chip demand in the coming years, the environmental impact of the semiconductor industry on power/energy and water consumption, as well as on $CO_2$ and GHG emission will strongly increase up to unacceptable levels to cope with the Green Deal objectives.

Like for its energy consumption, the water and carbon footprints of the semiconductor industry can be classified in three groups or 'Scopes':

- Scope 1: Water consumption and $CO_2$ emission as a direct result of the wafer fab usage.
- Scope 2: Water consumption and $CO_2$ emission come from purchased energy powering semiconductor fabs and their associated offices.
- Scope 3: Water consumption and $CO_2$ emission come from all other activities, including the full upstream and downstream supply chain.

A 2011 study[17] unveils that the wafer consumption of semiconductor production lines mainly results from the wafer fab usage (Scope 1: 97.3%), while the contributions of scope 2 and 3 were minor: 2.5 and 0.2%, respectively. Each chip needs to be rinsed after many process steps with ultrapure water (UPW) to remove various debris (ions, particles, silica, etc.) from the manufacturing process and prevent the chips from becoming contaminated. It takes 1,400-1,600 litres of municipal water to make 1,000 litres of UPW. Accordingly, for economic rather than ecological reasons, the semiconductor industry has been working for more than twenty years to reduce the amount of water needed to manufacture a chip (Scope 1). To avoid discharges and possible pollution, the proportion of closed-circuit water networks in semiconductor manufacturing plants is increasing. However, the total volume of water consumed by the semiconductor industry has never decreased as the number of chips released from the plants has also exploded over time.

Nowadays, due to the more frequent occurrence of droughts, the water issue is high on the sustainable development plans of major semiconductor companies. Semiconductor manufacturers must focus their efforts on new ways to recycle, reduce, and reuse the water used in their production. Nevertheless new advancements in water treatment must emerge to allow semiconductor manufacturers to recover and reuse wastewater, remove targeted contaminants, and even reclaim valuable products from waste streams.

Indeed, the semiconductor manufacturing process uses a wide range of slurries and chemicals, including hydrofluoric acid for cleaning and etching photosensitive components following the photolithographic process. Other chemicals such as ammonium hydroxide, hydrogen peroxide, hydrochloric acid, sulfuric acid or phosphoric acid are commonly used in rinsing operations. The wastewater includes mixtures of these chemicals, together with other contaminants that result from the manufacturing processes, such as traces of nickel, copper, cobalt, titanium, fluoride, silica, ammonia, and many other organic and inorganic compounds. The complexity of the wafer fabrication processes leads to the generation of wastewater streams that are highly contaminated with chemicals and particles. The fabrication process also uses PFAs (for instance in resists, or CMP slurries). Successful treatment or reclamation of the waste streams will thus require robust effluent segregation systems, such as micro- or ultra-filtration, reverse osmosis, precipitation, flocculation, sludge and membrane bioreactor. New long-term approaches could deserve some R&D efforts for improving the effluent segregation systems and hence increasing the use of recycled water in semiconductor manufacturing lines. With about 80% of semiconductor manufacturing emissions falling into either scope 1 or scope 2 categories, fabs control a large portion of their $CO_2$ and Green House Gases (GHG) emission. Scope 2 emissions, which represent the highest proportion of GHG from semiconductor companies, are linked to the energy required to run their production facilities. The sources of these emissions include:

- Tool fleets containing hundreds of manufacturing tools, such as lithography equipment, ion implanters, high-temperature furnaces, deposition and etching tools, etc.
- Large clean rooms requiring climate and humidity control with overpressure and particle filtration.
- Extensive sub-fab facilities for gas abatement, exhaust pumps, water chillers, and water purification.

The energy invested in a completed device can be 5.4 MJ (1.5 kWh) or more per square centimetre[18]. Furthermore, the fab energy consumption is expected to rise with more advanced process technology nodes.

Compared with "brown" or fossil energy (e.g., coal, gas), "green" energy (e.g., solar, wind, hydropower, and other low carbon) produces up to 30x fewer GHG emissions[19]. To ensure that sufficient power is always available, fabs often source their electricity from a combination of on-grid and off-grid sources. Most current off-grid power comes from fab-owned fossil fuel power plants. Over the short term, fabs can significantly reduce the energy consumption of these plants by pursuing efficiency improvements by including battery storage or switching to alternative fuels such as biogas or green hydrogen. For on-grid power, fabs may be able to reduce emission by purchasing renewable electricity from utilities through green premium energy offerings, which are often available in Europe.

European semiconductor manufacturing lines must reduce their energy consumption for reducing their operational costs and increasing profitability, but also for decreasing their environmental impact. This can be achieved in the short or midterm by investigating, in collaboration with the equipment suppliers, the energy efficiency of each processing tool and/or by creating energy-efficient process recipes without affecting the overall equipment effectiveness.

Scope 1 emissions, which also significantly add to fab GHG emission profile, arise from process gases used during wafer etching, chamber cleaning, and other tasks. Furthermore, they rise as node size shrinks. These gases, which include PFCs, HFCs, $NF_3$, and $N_20$, have high global-warming potentials. For instance, PFC 14, PFC16, $CHF_3$, $NF_3$ and $SF_6$ respectively exhibit a global warning potential of 6,500x, 9,200x, 11,700x, 17,200x and 23,500x that of $CO_2$. Moreover, the lifetime of such gases in the atmosphere can be very long 50,000 years, 10,000 years and 3,200 years for PFC14, PFC16 and $SF_6$, respectively.

In the short-term, semiconductor companies must collaborate with equipment suppliers to decrease their GHG emission and their operational costs by adjusting process parameters, such as temperature and chamber pressure, cooling water temperatures and by simultaneously optimizing yield and energy consumption during cleaning protocols.

Since much of these GHG and $CO_2$ emissions come from burning perfluorocarbons (PFCs), chemicals, and gases, more efficient gas abatement systems will probably be the main lever to address GHG emissions from process gases over the short to midterm.

Gas recycling of unutilized process gases and by-products through various means, such as membrane separation, cryogenic recovery, adsorption, and desorption can be a long-term approach for reducing the GHG emission. In collaboration with equipment suppliers, semiconductor fab could then refine them into pure process gases that can be used again, potentially reducing process-gas emissions. For this lever to become economically viable, collaboration between semiconductor companies, equipment suppliers and researchers will be compulsory to address these major challenges related to the separation of process-gas outflows and purification.

Another long-term approach could consist in lowering GHG emissions by switching chemicals that have a lower environmental impact than the aforementioned fluoride gases, such as on-site generation of $F_2$ for replacing $NF_3$, since molecular $F_2$ has no global warming potential. Nevertheless, developing new solutions will require strong R&D efforts and will be both costly and time consuming, as is the process for qualifying new chemicals on existing processes and tools.

Since most of the aforementioned fluoride compounds are used for etching, another long-term approach could concern the replacement of some non-critical etching processes by additive manufacturing process steps. Such a replacement will require strong R&D efforts to develop strongly selective deposition processes and/or self-assembled molecules that can prohibit the deposition of metal and dielectrics.

For a single phone unit, the precious metal content (without battery) is 250 mg Ag, 24 mg Au, 9 mg Pd, and 9 g Cu on average. For a single PC or laptop, the precious metal content (without battery) is 1g Ag, 220 mg Au, 80 mg Pd, and 500 g Cu on average platinum[20]. Taking into account the average number of cell phone, and PC-laptops currently sold per year (1.5 billion and 350 million, respectively) the recycling of these electronic devices can yield to 725 tonnes Ag, 113 t Au, 42 t Pd and 189,000 t Cu per year. Increasing e-waste recycling in order to address the large environmental impact of mining the Earth for metals looks nowadays mandatory. For not wasting mineral resources in view of the limited extractable quantities of metals in the earth's crust, chipmakers will be more and more concerned with the potential scarcity of some ores that are compulsory for producing ultra-pure metals for the high-volume manufacturing of devices. One way should be to use recycled metals instead of premium metals. Another approach for preventing the use of natural resources consists in recovering the metals for the electronic wastes (e-wastes). Since the amount of precious metal contained in a single smartphone or tablet compared to the overall weight and size is small , and therefore extremely difficult to recover from a scrapped device, the recovery of scarce metals from microelectronic devices opens a wide research domain for material scientists. Their solutions are very much needed to ensure sustainable usage of scarce metals in chip production.

**Expected outcome**

The goal of the European equipment and manufacturing industry for advanced semiconductor technologies is to lead the world in miniaturisation and performance by supplying new equipment and new materials approximately two years ahead of the introduction schedules for volume production of advanced semiconductor manufacturers. The focus will be on equipment and manufacturing technologies for lithography, metrology and wafer processing, including the respective infrastructure for sub-3 nm node technologies. Further focus needs to be on innovative equipment and material technologies for heterogeneous SoC and SiP integration, enabling advanced packaging of single and/or multi-node chips/chiplets.

Moreover, European semiconductor equipment and manufacturing technologies will be innovation leaders in terms of the use of AI, machine learning in the operation of semiconductor fabrication, and in taking care of limited datasets for model training in a high-mix environment. Solutions for current and future factories will allow high-productivity manufacturing of variable volume, and the energy-efficient, sustainable, resource- saving volume production of semiconductors.

### 1.1.5.4.3 Key focus areas

The key focus areas for innovative semiconductor manufacturing equipment technologies are as follows.

Wafer fabrication equipment:

- Advanced patterning equipment for sub-2 nm node wafer processing using deep ultraviolet (DUV) and EUV lithography, and corresponding subsystems and infrastructure (e.g. pellicles, masks and resist).
- Mask manufacturing equipment for sub-2 nm node mask patterning and tuning, defect inspection and repair, metrology and cleaning.
- Advanced holistic lithography using DUV, EUV and next-generation lithography techniques, such as e-beam and mask-less lithography, directed self-assembly (DSA) and nano-imprinting.
- Multi-dimensional metrology (MDM) and inspection for sub-2 nm node devices that combine all the spectrum of physical tools and data processing techniques.

- Thin film processes including thin film and atomic layer deposition, doping and material modification, and corresponding equipment and materials, able to support the increase of binary, ternary and quaternary materials
- "Bottom up" technologies to selectively deposit materials on topography or on a selected material.
- Integrated surface preparation, deposition and etch process technologies for optimal interface engineering.
- Innovative equipment and process strategies for perfect gapfill of metals and dielectrics in decreasing feature sizes.
- Equipment and manufacturing technology for wet and dry processing, wet and dry etching, including (atomic layer) selective etch processing, thermal treatment, laser annealing and wafer preparation.
- Increased utilization of AI and modelling (e.g. computational chemistry) techniques for material and process development.
- Technologies and tools for the manufacturing and integration of semiconductor components made with advanced nanomaterials and metamaterials (low-thermal-budget-processing 2D materials, nanowires, nanoparticles, quantum dots, etc) with logic and memory technologies.
- High-volume manufacturing tools for the production of III-V, GaN, SiC or other exotic material substrates of up to 200 mm, or 300 mm in the future.
- Dedicated equipment for manufacturing of electronics on flexible, structural and/or bio- compatible substrates.
- New electroplating equipment for ionic liquids (i.e. for Al deposition).

Assembly equipment:

- Equipment and manufacturing technology supporting 3D integration and interconnect capabilities such as chip-to-wafer stacking, fan-out WLP, multi-die packaging, "2.5D" interposers, wafer-to-wafer sequential processing, TSVs and transistor stacking.
- Enhanced equipment optimised for high-volume manufacturing of large batches of the same package into efficient reconfigurable equipment for the manufacturing of different packages in smaller batches.
- New process tools for die separation, attachment, thinning, handling and encapsulation for reliable heterogeneous integration on chip and in package, as well as assembly and packaging of electronics on flexible substrates.
- Equipment development to suit the requirements of multi-component assembly on flexible and stretchable substrates, especially in roll-to-roll for both conductive adhesives and soldering.
- New selective bonding equipment based on inductive or reactive heating.

Test equipment:

- In-line and off-line technologies for the testing, validation and verification (TV&V) of heterogeneous chips and SiP with ever-increasing number of features and ever-decreasing feature size to tackle the challenge of failure localisation in these highly complex (packaged) chips.
- Characterisation equipment for quality control at multiple levels and different scales of semiconductor structures, films and components.

In addition, specific manufacturing technologies are required to enable IC-fabs with interconnected tools to support flexible, sustainable, agile and competitive high-volume semiconductor manufacturing of high- quality, advanced functionality devices and heterogeneous integration technology options in Europe. This leads to the following key focus areas:

- Enable flexible line management for high-mix and distributed manufacturing lines, including lines for fabrication and deposition of advanced functional (nano) materials.
- Enhance equipment optimised for high-volume manufacturing of large batches of the same chip into efficient reconfigurable equipment for the manufacturing of different chips in smaller batches.
- Enable productivity enhancements (e.g. wafer diameter conversions) for heterogeneous integration technologies to significantly improve cost-competitiveness.
- New manufacturing techniques combining chip and packaging technologies (e.g. chip embedding) will also require new manufacturing logistics and technologies (e.g. panel moulding).
- Adopt factory integration and control systems to address the digital industry challenge of the ECS-SRIA, and to apply fast (and deep) learning as well as semi-automated AI-based decision- making to control processes, to enhance quality, increase reliability, shorten time to stable yield, and preserve knowledge and master complexity in these innovative machine-to-machine domains.
- Apply PAD approaches with a focus on predictive maintenance, virtual metrology, factory simulation and scheduling, wafer-handling automation and the digitisation of the value chain for AI-based decision management. In addition, attention should be given to control system architecture based on machine learning: viz. predictive yield modelling, and holistic risk and decision-mastering (integrate control methods and tools and knowledge systems).
- Doubling semiconductor manufacturing in Europe in 2030 also means evolving and upgrading installed base through incremental approaches, which will necessary mean increased complexity. Managing such hybrid factories will require advanced decision support and diagnosis techniques leveraging

IA but also integrating existing human knowledge and know how.

- Develop comprehensive modelling and sharing techniques to enable seamless flow and utilization of information across the whole value chain will require significant evolution of the existing knowledge management techniques and technologies (NLP to exploit existing documentation, diffusion and sharing of cutting-edge or strategic knowledge).

- Future innovations should also address new environmentally friendly solutions for manufacturing (e.g. in terms of energy consumption, chemical usage) and environmentally friendly new materials (e.g. in terms of quality, functionality, defects) in parallel with addressing the continued cost of ownership challenges. This will entail, for example, new precursors, chemicals for deposition and other wafer-processing materials, as well as gas delivery, gas handling, pumps and abatement systems. This will also comprise the study and implementation of new solutions for both effluent segregation as described above, including PFAs, as well as for water and other chemicals recycling.

To develop these future technologies, it will be key to develop dedicated equipment and manufacturing technologies for the production and characterisation of advanced integrated photonics, as well as for the production of quantum computing chips:

- In parallel with the new manufacturing/equipment technologies to suit the specific needs of integrated photonics, novel characterisation equipment and methodologies will need to be developed. These may be partly based on available technologies from electronic chip manufacturing and packaging. In addition, completely new and innovative techniques are required. Nanophotonic technologies for enhanced light–matter interaction will require the development of multi-scale fabrication and characterisation techniques suitable for dimensions ranging from a few nanometres to several centimetres. Specific equipment and processes need to be developed to enable industrial-scale fabrication of photonic ICs, such as DUV lithography and epitaxial growth of III-Vs. The hybrid combination of chips from different platforms and technology areas will also be essential to further increase functionality in the modules, and cost- effective volume packaging should therefore be a priority.

- The development of quantum computing technology will require new types of equipment, materials and manufacturing technologies. Advanced implementation options for QIP (superconducting circuits, Majorana states, etc) often require cryogenic environments and processing. Advanced industrial characterisation equipment tailored to operating in highly challenging environments will be key enablers for such developments to reach market applications. This includes new metrology equipment for mapping electrical and magnetic properties with high spatial and temporal resolution.

## 1.1.6 Timeline

All leading European industry and research actors should align their activities with international roadmaps and timelines. Roadmap exercises are being conducted in various projects and communities, including NEREID[21] and the IEEE's IRDS[22], in which European academia, RTOs and industry are participating. For system integration, the International Electronics Manufacturing Initiative (iNEMI)[23] and the new Heterogeneous Integration Roadmap activities are also considered. The European R&D priorities are planned in synchronisation with global timeframes and developments that are under continuous adaptation. The timelines below are high-level derivatives from these global evolutions, and follow the structure of the four Major Challenges described above.

For Major Challenge 1, the roadmap for process technology and device/system integration presents relatively clear timelines, although economic factors will determine the speed of adoption in industrial manufacturing. Dedicated process technologies (e.g. low-power and high-operating temperature) will follow feature scaling with some delay, focusing on other performance indicators. Areas where the roadmaps and timelines are less clear (e.g. new computing paradigms) will be introduced at low technology readiness levels (TRLs).

For Major Challenges 2 and 3, the timeline of the implementation of new technologies largely depends on the needs and roadmaps of the systems, and will result from the interaction within application-driven projects and test-bed initiatives. The timing of new equipment and manufacturing solutions for these challenges should be derived from the schedules of the major European semiconductor manufacturers. This includes roadmaps for key future semiconductor domains, such as automotive, healthcare, safety and security, power, MEMS, image sensors, biochips, organ-on-a-chip, photonics, lighting, etc. Fast implementation and modification of these new device technologies will pave the way for the technologies of tomorrow.

First, the development of sub-2 nm solutions in terms of equipment and materials as part of Major Challenge 4 needs to be two-to-three years ahead of mass adoption, and is of critical importance to maintaining European leadership. Second, new equipment and materials solutions should be developed in line with the needs defined in the roadmaps of Major Challenges 1–3. Lastly, improving manufacturing efficiency and enhancing yield and reliability are ongoing tasks that need to be performed in accordance with the needs of the "more-Moore" and "more-than-Moore" domains. Fundamentals of "manufacturing science" will concern projects at rather low TRLs (typically 3–5), whereas implementation in pilot lines and full-scale manufacturing lines will contemplate higher TRL projects (typically 7–8). For most of the manufacturing science projects, the execution will take place in the medium- to long-term timespan, although shorter-term impact, such as improving the uptime of equipment due to PAD or the improvement of robustness of the manufacturing processes, will get due attention to enhance competitiveness.

| Major challenge | Topic | Short term (2024 – 2028) | Mid term (20289-2033) | Long term (2034 and beyond) |
|---|---|---|---|---|
| **Major challenge 1: Advanced computing, memory and in-memory computing concepts** | **Topic 1.1:** Extensions of the scaled Si technology roadmaps<br>High-performance Ultra-low power 3D integration | N2 R&D<br>2nd generation gate-all-around devices, forksheet integration<br>18 nm FDSOI at technology platform integration level | N1,5 R&D - 3rd generation of Gate-All-Around devices<br>CFET introduction<br>12/10 nm FDSOI at technology platform integration level<br>3D monolithic integration | Sub-1 nm node logic and memory technology (nanowires, nanosheets) at process and device research level<br>Vertically stacked nanosheets<br>3D monolithic integration<br>Beyond 10 nm FDSOI at technology platform integration level |
| | **Topic 1.2:** Exploration and implementation of unconventional devices based on materials beyond Si | SiGe (high Ge) channel<br>Cu alternative solutions | Ge channel<br>Optical interconnects<br>2D materials exploration | III-V channel<br>Low-thermal-budget-processing 2D materials device integration |
| | **Topic 1.3:** Novel device, circuit and systems concepts, such as for near/in-memory, neuromorphic, optical and quantum computing neuromorphic, optical and quantum computing | Near/in-memory computing<br>3D heterogeneous integration (logic/memory) | In-memory computing<br>Neuromorphic computing (spiking)<br>3D monolithic integration<br>Photonic SOI | Quantum computing<br>Optical computing |
| | **Topic 1.4:** Long-term challenges such as steep-slope switches, spin-based transistors and alternatives | | TFET<br>CNTFET<br>2D material FET | NCFET<br>NEMS switch<br>Topologic insulator electronic devices<br>Spin wave devices<br>Mott FET (VO2, HfO2, etc) |
| | **Topic 1.5:** New eNVM technologies | PCRAM<br>STT-MRAM<br>FDSOI embedded MRAM and/or PCRAM | PCRAM<br>SOT-MRAM<br>ReRAM<br>FeRAM | ReRAM (MLC)<br>Hi-density ReRAM<br>VCMA-MRAM<br>ECRAM |
| **Major challenge 2: Novel devices and circuits that enable advanced functionality** | **Topic 2.1:** Application-specific logic integration | ULP 18 nm FDSOI technology integration | 12 nm FDSOI technology integration<br>New architectures for neuromorphic computing<br>3D stacking for monolithic integration | 3D monolithic integration |
| | **Topic 2.2:** Advanced sensor technologies | Continuous improvement of sensitivity (imagers, IMU, etc), range (lidar), and reduction of sensor area and energy consumption<br>Development of miniaturised low power chemical sensors<br>Development of biomedical sensors integrated with micro/ nanofluidics<br>Heterogeneous integration of sensor technologies with (ULP) logic/memory technologies<br>22 nm FDSOI for the IoT | Quantum sensors<br>Ultra-low power chemical sensor systems for pollution monitoring<br>Energy autonomous sensor systems<br>Multi-sensor systems for IoT<br>Integrated biomedical sensor system<br>Heterogeneous integration of sensor technologies with novel device, circuit and systems memory and computing concepts<br>12nm FD-SOI for IoT | Nanoelectronic sensor devices with individual molecule sensitivity and selectivity<br>Nanoelectronic biomedical sensor systems<br>Monolithic integration of sensor technologies with novel devices, circuit and systems memory and computing concepts<br>Beyond 10 nm FDSOI for IoT |
| | **Topic 2.3:** Advanced power electronics technologies | Silicon, BCD, SiC and GaN-based technologies and substrate materials | New CMOS and IGBT processes | B-Ga2O3,<br>AlN |

| Major challenge | Topic | Short term (2024 – 2028) | Mid term (20289-2033) | Long term (2034 and beyond) |
|---|---|---|---|---|
| | | Energy-efficient systems, including energy harvesting | Smart GaN devices (combining logic and power devices)<br>Vertical GaN power devices<br>Towards 300 mm GaN and 200 mm SiC substrates<br>Energy-autonomous systems<br>Energy harvesting and energy storage systems | Diamond |
| | **Topic 2.4:** Quantum sensing technologies | | Integration of cells used in trapped ions, neutral and cold atoms technologies, and entangled photons in a CMOS platform coupled to laser sources and (single) photon detectors<br>Superconductor qubits<br>Maintaining performance when manufactured at chip-scale and optimising SWaP-C (size, weight, power and cost). | Development of entangled qubits for improving the sensitivity growth of "large" diamond single crystals<br>Investigation of color centers-based qubits in wide bandgap semiconductors such as SiC, GaN |
| | **Topic 2.5:** Advanced RF and photonics communication technologies | Enable 5G connectivity<br>RF and mm-wave integrated device options building on, for example, SiGe/BiCMOS (increase of ft), RF and FDSOI, CMOS, PIC,GaN/Si, GaN/SOI and GaN/SiC technologies<br>Towards 300 mm GaN-Si substrates<br>Advanced PCB/substrate packaging options<br>Next-generation SOI for mm-wave<br>photonics SOI<br>200 mm POI | Improve RF front-End components roadmap (switches, LNA, antenna tuners)<br>Strained materials<br>Tiny silicon thickness and uniformity<br>Improve linearity substrate behaviour<br>RF substrate options for advanced CMOS nodes<br>Integration of IIIV semiconductors on silicon and SOI<br>Integration of IIIV semiconductors on photonics SOI<br>RF interposer for heterogeneous integration combining IIIV and CMOS<br>3D stacking of different functions (RF with digital, ...)<br>New materials for advanced functions | |
| | **Topic 2.6:** Flexible and structural substrate electronics | Increased reliability of materials and process techniques, reduction of pattern size | | |
| **Major challenge 3: Advanced heterogeneous integration and packaging solutions** | **Topic 3.1:** Advanced interconnect, encapsulation and packaging technologies | Vertical as well as horizontal integration via TSV, TEV, microbumps<br>Fan-out WLP or embedded wafer-level BGAs and chip- embedding in laminate materials<br>Advanced wafer-stacking technologies<br>Packaging & bonding technologies with advanced thermal management capability | 3D stacking/horizontal connecting of dies/chiplets<br>Advanced nanomaterials (including low-thermal-budget-processing 2D materials, nanowires, nanoparticles, etc)<br>Critical raw materials elimination from packaging bill of materials such as W, Co, Mo, Be, BeO | |

| Major challenge | Topic | Short term (2024 – 2028) | Mid term (20289-2033) | Long term (2034 and beyond) |
|---|---|---|---|---|
| | **Topic 3.2:** Specific power and RF application technologies | RF component miniaturisation for mm-wave applications<br>Package integration of additional functionality such as antennas, passive devices and power sources | RF miniaturisation for THz applications<br>Packaging of wide bandgap materials (GaN, SiC, etc) | New cryogenic compatible packaging platforms for QIP |
| | **Topic 3.3:** 3D integration technologies | Chip I/O-pad level 3D-SiC<br>Chip-package-board co-design | 3D SoC<br>System technology co-optimisation<br>3D stacking for monolithic integration | Ultimate transistor-level 3D ICs |
| | **Topic 3.4:** Enhanced reliability, robustness and sustainability technologies | Enable testing of separate components, before assembly via concepts such as BIST and self-repair | Novel material solutions for high reliability, robustness and high quality | |
| **Major challenge 4: World-leading and sustainable semiconductor manufacturing equipment and technologies** | **Topic 4.1:** Wafer fabrication equipment for nanoscale patterning, layer deposition, metrology, and inspection for advanced logic and memory technologies | Manufacturing equipment for 2 nm node logic and memory | Manufacturing equipment for 1 nm node logic and memory<br>Equipment to enable novel switches, transistors and alternatives based on, for example, 2D materials, topologic insulator and spin-wave devices | Manufacturing equipment for sub-1 nm node logic and memory |
| | **Topic 4.2:** Wafer fabrication equipment for new transistor front end of line (FEOL) and new interconnect back end of line (BEOL) concepts | Manufacturing equipment for 2 nm node transistor and 3D heterogeneous integration interconnect concepts | Manufacturing equipment for 1 nm node transistor and 3D monolithic integrated and optical interconnect concepts | Manufacturing equipment for sub 1 nm node transistor and 3D monolithic and optical interconnect concepts |
| | **Topic 4.3:** Wafer fabrication equipment for new materials and processes | Manufacturing equipment for 2 nm node materials and processes<br>Equipment for manufacturing of components with advanced nanomaterials<br>Production tools for III-V, GaN, SiC or other exotic material substrates | Manufacturing equipment for 1 nm node materials and processes<br>Equipment for materials and processes for new eNVM types such as (high-density) ReRAM<br>Production tools for 300mm wafer substrates based on selected exotic materials | Manufacturing equipment for sub 1 nm node materials and processes |
| | **Topic 4.4:** Assembly and test equipment enabling advanced packaging of single and/or multi-node chips/chiplets | Assembly and test equipment for chip-to-wafer stacking, fan- out WLP, multi-die packaging, “2.5D” interposers and TSVs<br>300 mm photonic SOI<br>200 mm POI | Assembly and test equipment to enable next-generation autonomous sensors, power electronics and RF/optical communication packaged ICs | |
| | **Topic 4.5:**Sustainable semiconductor manufacturing | Reduction of $CO_2$ and GHG emission and of the electrical consumption of semiconductor production lines<br>Use of recycled and reclaimed water | Reduction of $CO_2$ and GHG emission from semiconductor production lines through better abatement systems and reducing gas usage and leakage<br>Use of 100% renewable energy sources | No $CO_2$ and GHG emission by replacing current GHG-related gases ($NF_3$, PFC…) by alternative chemistries<br>Use of recycled metals to prevent the scarcity of some mineral ores<br>Use of 100% recycled and reclaimed water |

## 1.1.7 Synergy with other themes

Europe needs leadership throughout the value chain – from the development of processes, materials and equipment to the production of devices, systems and solutions – and the deployment of services to leverage its strong differentiation potential and drive its competitiveness. The impact of technology choices on applications, and vice versa, is becoming very large and decisive regarding successful market adoption.

The new advanced applications that will drive the future of European economy can rise only through a tight interaction among the key foundational technology layers, with this Chapter 1.1 providing the basic physical components and their manufacturing technology, and:

- Chapter 1.2 (**Components, Modules and System Integration)** their integration technology into smart systems including integration of low power consumption, radiation hardness and More than Moore applications in general.
- Chapter 1.3 (**Embedded Software and Beyond**) the software and control technology
- Chapter 1.4 (**System of Systems**) the methodology to design and combine Smart Systems in System of Systems that can solve all the application issues in a global way.

Cross-sectional technologies like **AI, Connectivity, Architecture and Design and Quality, Reliability, Safety and Cybersecurity**, represent a set of frameworks that define the design and development space of foundational technologies. They define development conditions and methodologies that are needed to realize those smart product solutions that can satisfy the needs of application areas in a safe, secure, sustainable and competitive way.

This Chapter does not exhaust the full spectrum of research and innovation activities that are required to develop the European eco-system for the Digital Economy and the Green Deal. Cooperation will take place with research activities in other programs, both upstream in more advanced and speculative technologies, like the Flagship programs (on Quantum Computing, Graphene, and others) and the Excellent Science pillar, and downstream with programs under Innovative Europe and EUREKA Clusters.

The move towards a sustainable and fully circular European industry in combination with the ongoing digitisation and application of AI technologies is evolving in all aspects of electronics components and systems manufacturing. In general, sustainability, circular economy and digitisation topics are covered in Chapter 3.3 **Digital Industry**; however, there are specific challenges closely related to the interaction of processes, materials, equipment and reliability that are also addressed in this Chapter.

In the photonics domain, the Integrated Photonic Systems Roadmap (IPSR)[24] is defining the way forward, and this roadmap is aligned with the activities being exploited by AIM Photonics in the US. In this roadmap, we increasingly see a trend towards multi-PIC application modules. Similar to the IC industry, the PIC-based developments also do not rely on just silicon photonics for their functionality. Hybrid and heterogeneous integration of functionality from different platforms is essential to enable the currently required and new functionality. This trend also spreads further to integration with electronic ICs, which is becoming a commercial reality. The combination of electronics and photonics at an increasingly intimate scale will be a requirement to keeping Europe at the forefront of this – strategic – foundational technology development. The focus should therefore be to maintain both the manufacturing foundries of chips and the packaging in Europe.

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# 1.2

*Foundational Technology Layers*

# COMPONENTS, MODULES AND SYSTEMS INTEGRATION

## 1.2

# Components, Modules and Systems Integration

### 1.2.1 Scope

Development and production of smart electronic components and systems (ECS) requires physical and functional integration (PFI) of several functionalities into a new physical entity at component, module and system levels. Therefore, PFI is one of the essential capabilities required to maintain and improve the competitiveness of European industry in the application domains of smart systems. Although in practice PFI is often application specific, the materials, technologies, manufacturing and development processes that form these domains are generic and should be standardized and interoperable and reconfigurable where possible. Particularly, heterogeneous integration of devices and components fabricated with separate and different fabrication processes is key to PFI. This Chapter deals with approaches beyond the semiconductor technologies, material families and compact system on a chip (SoC) integration, which are elaborated in the **Process Technology, Equipment, Materials and Manufacturing** (PTEMM) Chapter.

In the development of ever better smart systems and innovative products, heterogeneous integration becomes more and more important at every level of integration, from semiconductor SoC to System-in-Package (SiP) and ultimately to larger modules and systems. The importance of SiP technologies in integration terms is emphasized by the treatment of SiP in both this and the previous chapter from their specific point-of-view. Particularly, in this Chapter alternative technologies (such as additive manufacturing), complementary materials (both at the functional and structural/substrate level) and heterogeneous approaches to assembly, integration and advanced packaging are considered. The term heterogeneous integration is used in its widest meaning: components should be taken to mean any unit, whether individual chiplet/die, MEMS device, passive or active component or assembled package, that are integrated into higher order single components, modules or systems. Developments of heterogeneous integration technologies and platforms include also flexible electronics and photonics solutions. On the other hand, advanced packaging represents the suite of novel technologies, processes and competences that -in a cost-efficient, environmental sound way- allows for the physical, electrical and functional integration of any set of technological diverse components required to build an advanced system. Such system provides for the robust and reliable combined operation in an assembly platform that enables optimal protection or interaction (as appropriate) with its application environment.

Thus, in addition to the usual silicon-based semiconductor technologies, smart components, modules and systems require the following characteristics:

- A combination of device architectures: sensors, actuators, energy generators, storage devices, MEMS/NEMS, MOEMS, LAE, computing processors and communication interfaces (e.g. transceivers, antennae).
- Heterogeneous integration technologies at the component, module and system level, utilizing multi-physics/multi-domain approaches, e.g. nano-electronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, quantum effect, micro-fluidic, acoustic, radiation, RF, and bio- and chemical principles. A multitude of processes: micro and nanotechnologies, 2D and 3D additive manufacturing, lamination, assembly and interconnection technologies, as well as hybrid combinations.

The methods, processes and schemes required for the design, production, assembly and testing of the various components, modules and systems and their integration need to be devised with appropriate quality, reliability, repeatability as well as scalability (appropriate unit cost including life cycle considerations) and sustainability (circular economy, $CO_2$ footprint, efficient use of resources).

Smart components, modules and systems are the key enabling link between basic technologies, e.g. semiconductor or interconnection technology, and key applications as described in the **Application** Chapters. They open the way for widespread use in all application domains by integrating functionalities such as intelligence, sensing, communication and control, even in the smallest devices, through simultaneous development and co-design with **Embedded Software** and **System of Systems** (SoS) technologies and with support from cross-sectional technologies: **Artificial Intelligence** (AI), **Connectivity**, **Architecture and Design**, and **Quality, Reliability, Safety and Cybersecurity**.

Considering the new requirements imposed by modern and future smart systems, mastering the integration technologies at component, module and systems levels, is a significant capability of European industries. Such a strength needs to be sustained and reinforced to ensure Europe's leading position in smart systems engineering, as well as to bring innovations into real-life reliable and sustainable products, services and markets.

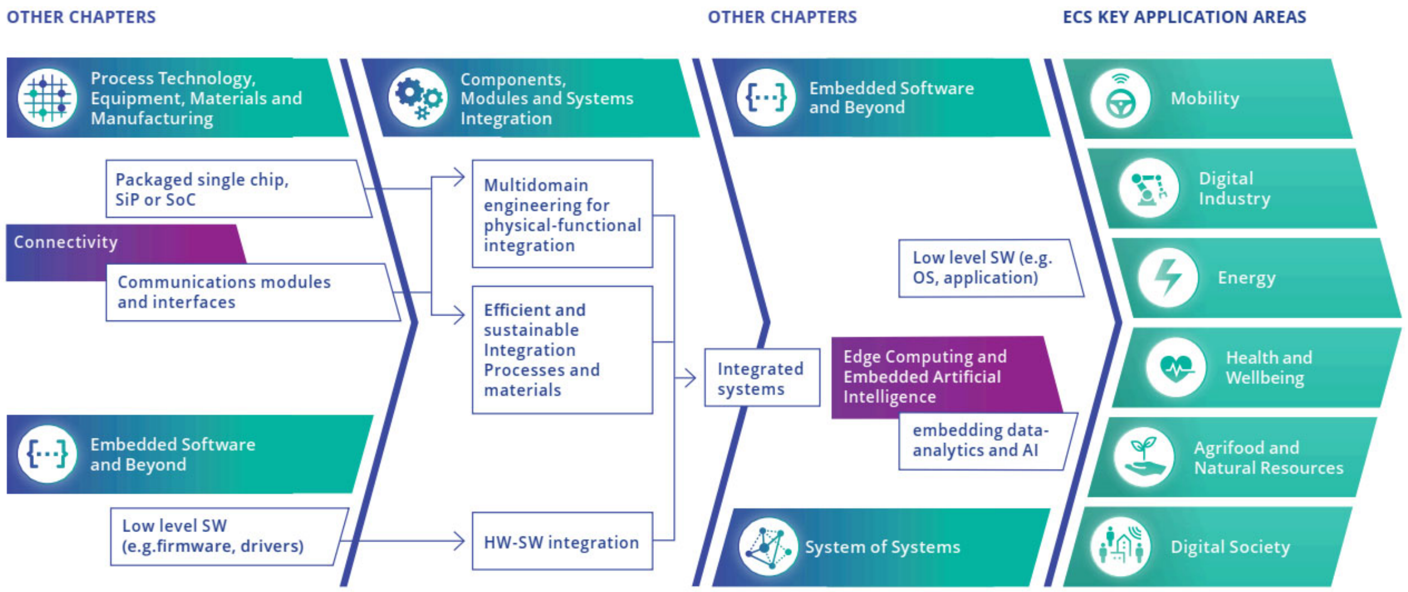

*Figure 1.2.1 The Components, Modules and Systems Integration Chapter focuses on physical-functional integration of devices and components into subsystems and systems, using sustainable and efficient materials and integration processes.*

## 1.2.2 Technology Enabled Benefits

Societal benefits of smart components, modules and systems stem from the applications that they enable, as described in the Application Chapters. Improved integration technologies and miniaturization, together with cost-, energy- and resource-efficient and eco-friendly manufacturing, will make future applications affordable for the broader public, and support sustainability of products and production technologies, enabling responsible use of resources, e.g. by means of assisting in the development of a circular economy, in alignment of the European Green Deal[1] and UN sustainable development goals[2].

Figure 1.2.2 defines an integrated smart system showing its components and modules, while interacting with any sort of environment. Smart systems integrate sensing and/or actuation as well as signal and power/energy processing to enable actions. Smart systems utilize multi-functional perception, and are predictive, configurable, contextual and adaptive.

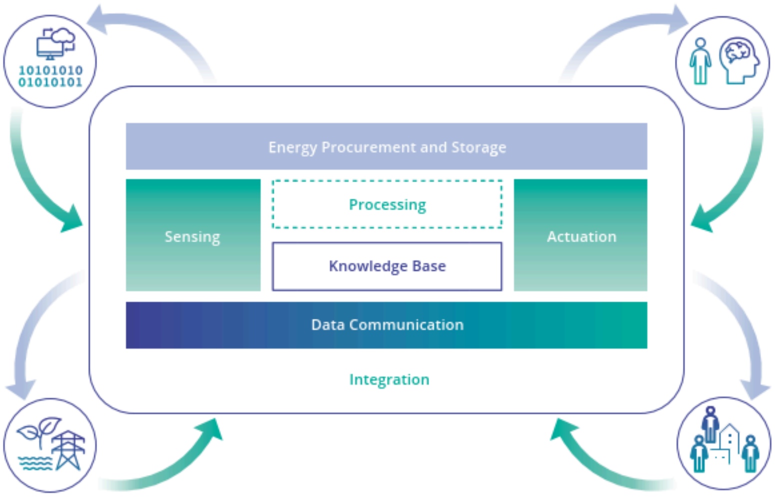

*Figure 1.2.2 Smart systems interact with the user, the (natural, man-made and social) environment and the data sphere. Smart systems provide (and use) support to (and from) their surroundings. The smarter the smart system is, the more cognitive such support can be (Source: EPoSS).*

The Covid-19 pandemic has demonstrated the critical role that smart components, modules and systems can play for the world's security and health. Key topics here range from an acceleration in the analysis of DNA samples, the availability of automated medical support and diagnosis tools, to tracking systems for tracing and controlling the spread of the disease, not to mention the mental and physical assistance that smart devices have provided to quarantined people through cellular networks and the internet.

The Internet of Things (IoT) is one of the main technologies enabled by smart components, modules and systems. It supports such game changers as virtual reality (VR), augmented reality (AR), extended reality (XR), digital helpers, and spread use of AI and edge computing. These elements are pivotal for optimized data collection and profitable machine-to-machine (M2M), human–machine interface (HMI) and human–computer interaction (HCI), bringing smartness to human activities (smart cities, smart transportation, smart grids, smart manufacturing, etc.) and human health and well-being (e-health, m-health, implants, ingestibles, wearables, personalized medicine, inclusion of people with a disability, etc.).

Another major application is digital industry. Smart systems harness data, extract information, distill knowledge and convert it into actions and/or provision of improved decision support. This is achieved by integrating components and modules for data acquisition and context-based actions, signal conditioning and data analysis, and by communicating elements to organize collaborative, adaptive and self-repairing networks. In offering alternative access via the cloud to data processing and knowledge extraction engines, smart components, modules and systems enable the deployment of edge computing, thus reducing the demands on communication bandwidth and system-level power consumption. However, this also creates challenges for the self-powering of edge devices of increasing complexity, and the need for such power demands to be carefully managed and limited, using ambient energies where possible. Software (SW) integrated into such devices (with the appropriate architecture for sustainable processing) needs to be considered very carefully. How, where and when data is gathered, processed and transmitted has major ramifications on the peak and average power consumption not only of the edge devices but also the gateways, servers and the cloud. The most energy efficient manner possible (based on energy sources available) should be found to maximize battery life and reliability. Having billions of connected IoT devices will increase the load on our IoT infrastructure at all levels. So, the overall architecture in inter-play between the entire system components needs to be carefully considered in terms of power, security, latency, processing capability, etc. Resolving this challenge requires not just technology advances, but also close coordination and collaboration between all the “power IoT” stakeholders based on realistic targets and expectations.

Technology advances enabled by components, modules and systems integration are as follows:

- Greater performance and digital configurability of sensors, analogue and RF components, along with high-performance computing functions.
- Technology integration of electronics, cellular/chemical/biochemical interaction, fluidics for multifunctional smart systems.
- Extending pure electrical functionalities to integrated photonics by hybrid and heterogeneous photonic integration, i.e. merging different PIC technologies to compensate for missing functionality in individual cases. This requires seamless integration of electronic and photonic ICs, both at design level and technology level, which makes lower power consumption of electronic and photonic chips inevitable.
- Embedded intelligence in the ECS, typically realized by a combination of hardware and software components, leading to higher functionality, improved interoperability, less demanding or more natural interfacing, both for machine-to-machine interfacing, human-to-machine interfacing (e.g. haptic interfaces) and decentralized signal and information processing, i.e. edge AI.
- Greater performance in power electronics components through an impact on the thermal characteristics and higher power density and electromagnetic interference (EMI) performance of components, modules and systems.
- Reducing energy consumption of electronic components, without decreasing component performance (e.g.., in the detection limit of MEMS/NEMS sensors), on all levels and functions: component, module and system integration, RF transmission.
- Improving energy efficiency and energy autonomy of electronic systems through smart and intelligent battery management, energy harvesting and low leakage storage devices.
- Improved reliability, security, safety, both at software as well as hardware-level, through self-monitoring and self-repair also for harsh environments.
- Wearable and/or disposable smart systems with flexible and stretchable materials, through hybrid integration of traditional integrated circuits with flexible electronics.
- Structural electronics, opening a new form of electronics integration on/in various materials, making the package an active part of the device.
- Closer co-operation between HW and SW developers at the early concept stages (e.g. in designing configurable and context- and constraint- aware data collection and processing architectures) to ensure that, at a system level, the amount and means of processing and communications is optimized and is truly scalable and sustainable.
- Non-fossil and biodegradable materials for greener electronics and reducing environmental impact of ECS and reduction of the use of resources in general, in materials, process energy, recycling of materials.
- Quantum technologies, with components that harness quantum phenomena for computing, communication, imaging and sensing (e.g. superconducting or Si qubits, or ion traps), interfacing components and modules for quantum system integration, from cryogenic temperature (e.g. cryo-CMOS, superconducting circuitry) to room temperature.
- Miniaturization of systems at all levels to increase the performance and to save resources and materials.
- Modular systems allowing inclusion of re-used and recycled components and new high-performance building blocks for sensor-supported intelligence (e.g. sensor fusion and decision-making tasks). Including, including Digital Product Passport concepts to reduce data gaps in intercircularity and recycling.
- Improved system engineering efficiency using highly dynamic systems supporting automated design for easy integration of new hardware or software components / modules.

### 1.2.3 Applications Breakthrough

Technology advances at the component, module and system level will have a key impact on applications. Future smart components, modules and systems will show a strong increase in functional and structural complexity and higher integration levels. They will show more diverse features and material integration in even smaller form factors.

Applications are the driver for such approaches:

- Communication landscape with 5G, 6G and increasing data rates, including Non-Terrestrial Networks (NTN), time-sensitive network (TSN) as well as navigation and localization, including also optical integration, components and systems for fiber networks.
- Autonomous systems– in mobility, transport, logistic, manufacturing or control of buildings and micro-grids, etc. (ensuring faster time response and decreasing the impact of human error).
- Ultralong lifetime remote or difficult to access applications, e.g. structural monitoring of bridges, tunnels, civil structures requiring lower power consumption devices and supporting architectures, particularly for the autonomy of IoT devices, both energy autonomy and decision-making enabled at the edge.
- Healthcare landscape with applications towards prevention, assisted care, Point-of-Care devices and telemedicine, including rehabilitation, disabled assistance as well as treatment.
- Life science and pharma domain moving towards personalized medicine and regenerative medicine based on organ-on-chip technologies and smart multifunctional systems.
- The transition in mobility towards zero-emission power trains, with their significant cost and energy efficiency challenges, including energy systems for high-power charging and/or highly variable and changing conditions.
- Industry 4.0 manufacturing landscape to enable agility and autonomy, as well as energy and resource efficiency, including manufacturing down to lot-size-1.
- Overall transition from stable controlled environments to harsh environments with longer operational lifetime and variable conditions.
- Progression to scalable, fault tolerant and ultimately self-monitoring and repairable/re-configurable networks particularly for long life span applications such as structural health monitoring. Synergies with technologies such as neural networks for such adaptations should be considered.
- Sensing of environmental parameters in smart agriculture, livestock or aquaculture, in manufacturing and working places, at home and in urban areas, e.g. for higher yield, energy efficiency and well-being.
- Imaging applications for security, healthcare, digital industry, (precision) agriculture, food industry, digital society (television, social media) and perception.
- Enabling repair as business, including repair index and set-up of repair processes.

### 1.2.4 Strategic Advantage for the EU

Electronic components, modules and systems are versatile in terms of design, size, material and composition, and thus the network of stakeholders involved in the production process of smart systems is equally complex. Europe’s supply chain for smart systems production consists of more than 6,000 large companies and SMEs[3]. Emphasizing and supporting ECS manufacturing can lead to increasing smart systems activity for European industry. In the ECS sector, this means about nine million jobs across Europe.[4] The European Chips Act is addressing these topics for a stronger European microelectronics value chain.[5]

The Covid-19 pandemic has revealed the vulnerability of global, distributed value chains. New models that will bring greater efficiency and more agile production processes need to be developed, and European manufacturing increased in key areas. This will ensure an effective and swift reaction to sudden market shocks as well as flexible manufacturing, accommodating shorter life cycles of products and fabrication-on-demand.

Europe is stronger in some microelectronic technologies, e.g. in MEMS sensors. MEMS technology is highly different in nature to CMOS, highly benefiting from heterogeneous integration. According to Yole Développement[6], the global MEMS and sensor market (excluding RF filter modules) will almost double from US$48 billion in 2018 to US$93 billion in 2024. Assuming the same annual growth rate, the market should reach US$180 billion by 2030, with Europe supplying at least one-third to one-half of this market, with hopefully the same success in other microsystems markets.

Even though European microchips manufacturing market share is only around 10 % (See Figure in Chapter 1.1.4), the European share of integrated products and ECS systems is much higher, for example in the automotive or telecom sectors. Software including firmware and middleware is an important part of the ECS systems (see Chapters 1.3 and 1.4). The system houses and OEMs also often catch a higher share of value of the final product than component providers. This emphasizes the importance of integration of ECS instead of providing or manufacturing components only.

To summarize, investing in the future of electronic components, modules and systems integration has the following strategic advantages for Europe:

- Strengthening Europe’s economy through the generation of high-tech innovations.

- Increasing the added value in Europe by integrating more functional systems and products, e.g. in automotive, med tech and telecom industries.
- Enabling a successful Twin Transition (Green and Digital) in an economically feasible way through multifunctional smart devices.
- Ensuring European sovereignty and securing strategic Intellectual Property from European companies on advanced technologies in microelectronic ecosystem with regards to heterogeneous integration.

## 1.2.5 Major Challenges

The following three Major Challenges are identified:

- **Major Challenge 1:** Enabling new functionalities in components with More-than-Moore technologies.

  Developing new features for sensors and actuators and smart systems via new materials and methods.

- **Major Challenge 2:** Integration technologies, processes and manufacturing Integration technologies, processes and manufacturing.

  Identifying the system optimum regarding the interplay between components to modules and systems.

- **Major Challenge 3:** Sustainability.

  Sustainable integration processes and recyclability of components, modules and systems to minimize their environmental impact

### 1.2.5.1 Major Challenge 1: Enabling new functionalities in components with More-than-Moore technologies

#### 1.2.5.1.1 State of the art

Physical and functional integration (PFI) considers the development of new elements and methods enabling more functionalities to be integrated physically on components, modules and systems, in the most effective form factor. This requires interdisciplinary technology innovations as smart components, modules and systems may utilize a combination of features based on nano-electronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, micro-fluidic, optical, acoustic, radiation, radio frequency, biological, chemical and quantum principles. Furthermore, many types of devices are to be integrated together, such as sensors, actuators, energy generators, energy storage devices, data processing devices, transceivers and antennae. Different technological approaches such as mainstream silicon technologies, MEMS/NEMS, MOEMS and Large Area Electronics can be combined for the synergistic assembly of electronic and photonic devices. PFI requires not only the integration of physical components together, but also the co-design and integration of hardware and software, especially embedded software to create reliable and sustainable functional systems. This also extends to the development of architectures that enable such systems to be configured dynamically and optimally for a given application.

Physical and functional integration goes beyond the compact monolithic SoC approaches supported by the semiconductor technologies covered in the **Process Technology, Equipment, Materials and Manufacturing** Chapter. The challenge covers new functionalities and materials, using More-than-Moore and system in a package (SiP) technologies, where all functions are designed together to improve performance and compactness, something that also enables the heterogeneous integration of separate devices with different fabrication processes and methods. SiP is indeed a mixed arena between the previous **Process Technology, Equipment, Materials and Manufacturing** Chapter and this one. In the former Chapter, SiP approaches result from the natural technological evolution of back-end semiconductor processes and are mostly related to the compact hybrid/heterogeneous integration of technologically 'homogeneous' components (e.g. chiplets) while this Chapter focuses on different integration methods of components with a higher degree of technological heterogeneity in different platforms, including their Integrated Circuit carriers, such as wafer level fan-out-packages, PCB boards, printing and co-packaging of optics and electronics. This chapter concentrates on the physical integration of hardware, including computational devices into systems, while leaving the software to the **Embedded Software** Chapter.

#### 1.2.5.1.2 Vision and expected outcome

Given the broad range of physical scenarios they face, smart components, modules and systems need to interact with many environments, ranging from lab to industrial and harsh environments to in-vivo.

There is a multitude of operational issues affecting smart components, modules and systems regarding energy, performance and size. With respect to energy, for portable IoT devices, there is a need for low-power operation and provision of energy autonomy (self-powered devices or devices providing short-/medium-/long-term autonomy, depending on the application) on the one hand and dealing with high-power density and thermal stress on the other. Regarding size, the optimal “minimum” size must be achieved. Heterogeneous integration and advanced packaging and interconnection technologies need to be utilized for achieving the best performance in the smallest system-level form factor. In high high-end consumer electronics, high-performance and ultra-dense compact interfaces at all integration levels are needed, from chiplets and chip assembly and packaging to component and module level connectors and connections.

MEMS/NEMS development focuses on sensors and actuators that benefit from the free surfaces and volumes that MEMS/NEMS processing is able to produce in a semiconductor substrate. The former relies on new generations of inertial measurement units (accelerometers and gyroscopes) with increased performance, with or without AI support, magnetometers, pressure sensors, microphones, as well as particle sensors; the latter rely on piezoelectric, electro-statically or electromagnetic driven micro-mirrors, print heads, oscillators (membranes and cantilevers), tunable lenses, loudspeakers and piezoelectric micromachined ultrasound transducers (pMUTs). New piezoelectric materials, such as scandium aluminum nitride (ScAlN) enable new applications and improved performance for MEMS devices, e.g. in acoustic RF filters, in optical systems such as lidars and in ultrasonic sensing. For hydrogen detection applications, existing MEMS technologies for pressure sensing are used and optimized. Additionally, new MEMS concepts for hydrogen detection are assessed to enable the future hydrogen economy.

The technical challenges for new and future integrated photonic components, modules and systems initially lie in a suitable co-design strategy (including associated methods/tools) of the various technologies to be combined as well as in their common processability and hardware integration (compatibility). The high level of integration also requires a special focus on thermal management through thermally more robust components (e.g. laser with temperature-stable wavelength), optimized thermal design, and suitable cooling concepts. This aspect, as well as other requirements, will determine the design and technology of future packages of photonic components. A particular focus is on those cases in which photonics and electronics have to work together at high bandwidths, like very high-capacity transceivers, interfaces to electronic switching circuits in communications and data systems, high pixel-count active sensors, 3D imaging and displays. Another technical challenge is the lack of standard solutions for hybrid integration. Additionally, we face a lack of standards for development (e.g. qualification testing) or even legal framework conditions (e.g. for the regular use of smart glasses and similar applications).

Heterogeneous integration technologies are strongly driven by consumer applications, such as the various types of portable and handheld devices. The manufacturers and associated supply chain for these high-volume applications are primarily based in Asia, and so for PFI Europe needs to reinforce its supply chain of integration and packaging solutions. The convergence between sensing and imaging domains for consumer applications, for example face recognition and AR based on consumer lidar solutions, requires co-integration of (high-speed) electronics and Integrated Photonics into compact systems. Further, portable consumer electronics utilize flexible structures and technologies, which aim at even thinner and more flexible electronic components and systems e.g. for displays, wearables and novel human-machine interfaces (HMI). Structural and 3D electronics enable incorporating electronics in 3D surfaces and mechanical components by means of molding, additive manufacturing or laser direct structuring (LDS). Novel flexible and stretchable substrates (such as thermoplastic polyurethane (TPU) and polydimethylsiloxane (PDMS)), as well as new materials for active components, including conductive and dielectric inks, with organic materials, metal oxides, nanomaterials and 2D materials are required for realizing new applications from touch panels to RF antennas, control electronics, embedded lighting and sensors/actuators.

One of the key application drivers for the PFI of smart components, modules and systems is the IoT and its sensor nodes, which require a wide range of sensor and actuator functionalities, combined with data processing and wireless communication, and with power autonomy provided by energy storage and harvesting devices. In many cases, power autonomy is the limiting factor in such applications. This means the development of low-power solutions for sensors and actuators, as well as radio communication components and processing. Thermal management challenges introduced by increased functionality in a minimum form factor need to be solved. New and improved energy storage, especially low-leakage rechargeable storage devices, needs to be developed as well as universally deployable harvesting solutions to improve the case-specific devices used today. In addition to this, it is important to improve in low-power techniques at the system level with co-design of hardware and software and overall system architecture, e.g. in wireless sensor networks, to ensure reliable, sustainable and energy efficient data collection and processing systems attending to the energy available and the possible processing capabilities split at the edge, gateway and cloud. Reliable and fault-tolerant wireless networks are required for applications where long-term continued sensing is critical (e.g. structural health monitoring of civil infrastructure).

Another domain strongly reliant on PFI are Electronic Control Units (ECUs). Due to their complexity and high degree of integration, these systems benefit from advances in generative design, miniaturization, scalability, increased processing power, cybersecurity, AI and machine learning integration, prognostics and health management as well as sensor fusion.

Components to provide power efficient computational resources, i.e. low-power microprocessors and devices with novel computational architectures such as neuromorphic devices, are needed, as are low-power computational methods, including distributed and low-power AI solutions in hardware, software, and in-sensor data processing. In addition, reliable, energy-efficient, scalable, low-loss interconnection and packaging solutions are a necessity.

Smart components, modules and systems leverage a multitude of materials, such as silicon and other-than-silicon semiconductors, precious and rare earth metals, ceramics, polymers, glass, inks and functional materials for sensing, actuation and energy harvesting, as well as hybrid combinations of substrates and materials (e.g. Si, ceramic, polymer, glass, metallic glass), in packages and in systems, extending the coverage of the usual materials in semiconductor-based technologies. Many of the new features required by future smart systems can only be achieved by introducing novel materials into the devices and systems, from back-end of the line processing of the microchips, or by post-processing on CMOS, to novel IC carrier technologies, including fan-out wafer level packaging and other SiP technologies as well as PCBs or in printing, additive manufacturing or other means. The development of new materials and the compatibility of those (with regard to e.g. process compatibility, environmental compatibility) is critical to the future development of PFI.

Quantum technology provides a new modality for More than Moore technologies not industrially considered earlier due to technology limitations in field-deployability, extreme cooling requirements etc. Recent years have seen rapid technological developments in the technological readiness of many quantum technologies: Quantum sensors, especially those based on gas cells, are being industrialized and miniaturized, promising better stability and accuracy of measurements, e.g. in magnetometry and inertial measurements. Quantum computers are developing into larger and more powerful machines year after year. Quantum communications, or Quantum key distribution (QKD), enable secure encryption based on quantum states of photons. The rise in the applicability of quantum technology is based on successes in materials, fabrication processes and quantum science itself, but also in major part in the successful development of enabling technologies, such as control and low-noise readout electronics, packaging and heterogeneous integration and cryogenic cooling solutions, many of which are based on the successes and processes of electronics and semiconductor industry. Hence, the further development of these enabling technologies should be considered in detail.

The following key focus areas address the multimodality of ECS, which goes beyond semiconductor technology, requiring advanced packaging and heterogeneous integration of diverse materials, components and platforms. Full coverage of the physical-functional integration requires considering both the physical integration technology platforms and the functionalities of the integrated systems.

### 1.2.5.1.3 Key focus areas

- Sensing, imaging and actuation:
  - Sensors and actuators leveraging the integration of MEMS/NEMS, MOEMS and micro-optics elements.
  - Sensors and actuators for biological, medical and diagnostic applications, and for sensing of human vital signs and biomarkers, as well as for selective detection of gas and volatiles, allergens, residues/pollution in food/water, atmospheric particles, hazardous substances and radiation.
  - Sensors and systems enabling integration behind OLED and sensing through the OLED display.
  - Sensors and systems for sensing and imaging in the short wavelength infrared range, based on Ge on Si Integration or Pb free quantum dots, enabling a broad range of new applications in the areas of lighting, biotechnology and life sciences, photovoltaics and information processing.
  - Advanced global shutter and rolling shutter CMOS Image Sensors (CIS) based on novel pixel technology for VIS-NIR imaging applications, with the goal to improve the performance, sensitivity, and efficiency of VIS-NIR CIS pixels, enabling high-quality imaging across a broad spectral range, as well as infrared imaging.
  - Imaging systems: lidars and radars, including multi-modal and hyperspectral, i.e. spectrally resolved, sensors.
  - Sensors and systems utilizing quantum principles, e.g. single photon sensors, including required cryogenic and cooling components and systems.
  - Devices with new features and improved performance for sensing and actuation using novel materials (metal nanowires, carbon nanotubes (CNTs), graphene and other 2D materials, cellulose nanofibers, nitrogen vacancies in diamond, metamaterials, metallic glass etc.), in combination or integrated with/on CMOS.
  - Sensor fusion and virtual sensors including appropriate data and communication infrastructure, e.g. for condition monitoring, prognostics and health management for ECUs.
  - Ultra-low power event-based sensors, e.g. inertial motion & image detection for asset tracking, incident/anomaly detection, etc.
  - Materials that ensure the hermetic sealing of sensors, actuators and systems and at the same time contribute to the miniaturization of components.
- MEMS technology
  - CMOS or GaN-compatible thin film piezoelectric materials, such as ScAlN for piezo-actuated MEMS sensors and actuators.
  - Acoustic piezo-MEMS devices, pMUTs, and Acoustic RF filters for high frequencies above 6 GHz.
  - Audio MEMS devices with more advanced integrated functionality, such as integrated noise cancelling.
- Integrated Photonics
  - New materials for active photonic devices, such as 2D materials, Lithium Niobate, Indium Phosphide; for improved performance, such as higher bandwidth in modulators, and detectors.
  - Light sources (e.g. lasers and laser modules) with higher power and better performance and with tunable wavelength, using external cavity on photonic integrated circuits (PIC).
  - New waveguide materials and components to expand the wavelength range from UV up to mid IR optical elements for beam shaping and manipulation (like ultrathin curved waveguides, meta-lenses, tunable lenses and filters, next generation holograms, ultra-wide-angle holograms).
  - Display technologies (like micro-LEDs, MEMS-mirrors, Phase Arrays) and sensors (e.g. for eye tracking).
  - New devices for Quantum PICs.
- Flexible electronics
  - Sensing devices and power sources compliant with hybrid integration in wearables, considering flexibility, durability (e.g. washability) and biocompatibility.
  - Flexible and stretchable sensors and modules, e.g. OLED displays, OPVs, touch surfaces and other sensors/actuators, conformal antennas.
  - Functional materials for flexible and stretchable devices; organic and inorganic semiconductor materials and inks, perovskites for OPV.
  - Barrier materials, dielectrics, and transparent conductor materials and inks for flexible electronics and additive manufacturing.
- Communications
  - Module-level high-speed wireless communication features, including current and new frequency bands.
  - High-speed photonics communications modules beyond 1 Tb/s.

  - New front-end components, filters and functionalities e.g. active antennas for 5G and 6G communications and non-terrestrial network solutions.
  - Low latency and low power communications in-package/module as well as at system level for the edge and IoT devices.
  - Continuous delivery of new features and fixes through Over-The-Air (OTA) updates to ensure the security of the device over time and reduce the digital waste increasing the life of a device.
  - Strategies and components for Electromagnetic interference (EMI) mitigation and reliable operation in harsh environmental conditions.
- Energy and thermal management:
  - Low-power/low-loss modules for low-power sensing, actuation, processing and communication.
  - Power architectures with digital interfaces driven by dynamic and context aware algorithms that can adapt based on energy available versus needed for sensing, actuation, processing and communication.
  - Energy-autonomous multi-sensor modules and systems including energy harvesting, sensing, actuation, processing and communication.
  - Power management components and modules compatible with harsh environments (high temperatures, vibrations, electromagnetic interference (EMI) conditions for industrial, automotive and space technology).
  - Devices using non-toxic materials for efficient energy sources, storage and harvesting devices (thermoelectric, piezoelectric, tribo-electricity, etc.), and higher performing electrodes and electrolytes for improved capacity and low leakage of energy storage devices or new lightweight energy harvesters for mobility and transportation applications.
  - Solutions for thermal management for integrated photonics and RF systems at different integration levels including advanced and active cooling systems.
  - Thermal management and smart cooling systems for industrial applications and harsh environments.
  - Efficient smart compact cooling solutions and approaches for quantum devices and cryogenic multiplexing with semiconductors or superconducting devices.
- Information processing:
  - Component and system-level features for self-diagnosis and module-level signal processing and control features for self-diagnosis, self-monitoring, and self-learning and self-repair.
  - Sensor level hardware and software solutions for security and privacy and data reliability.
  - Machine learning and artificial intelligence and data analysis at the sensor, module and systems level, i.e. on the edge data analysis embedded at different levels for smarter devices, including AI at sensor level.
  - Integrated and scalable solutions, both Software and Hardware integration with increased processing power for more sophisticated features, especially for edge AI and ECUs.
  - Use of quantum computing and integrating quantum computing for data-analysis.

### 1.2.5.2 Major Challenge 2: Integration technologies, processes and manufacturing

#### 1.2.5.2.1 State of the art

Smart components, modules and systems require a multitude of processes: silicon and other micro- and nano-processing, additive manufacturing, lamination and other interconnection and assembly technologies, as well as hybrid combinations. To increase the integration density and combine the above-mentioned features, many different integration and packaging technologies are required, such as thin film processes, embedding, classic assembly and joining methods, both for single components as well as modules.

Heterogeneous integration, from components up to the system level, requires-engineering on many technology domains, such as power, signal integrity, EMC, thermal, mechanical. All such domains and their hardware and software interplay (power and communications) must be designed together to ensure a high device and system level performance and the necessary integration. The challenge here is to combine all these domains in the design and simulation of integrated systems, often with inadequate information of all the properties of the included materials, components and processes. Where possible historical data and related algorithms should be used to predict and optimize system level performance. This may involve changing sensing intervals and/or how and where data is processed and routed. Furthermore, standardized and interoperable design and simulation methods that enable and support such multi-physics and multimodal design and manufacturing must be addressed, with possibility to parameterize not only the material parameters, but also system parameters, e.g. variability in the quality of the contact (e.g. thermal, mechanical) between the transducer and the ambient energy sources in the case of power harvesting. Modelling and design tools for thermal, mechanical and electrical characteristics in small 3D packages, including molded and additive manufacturing methods are needed, linking to **Architecture and Design; Methods and Tools** Chapter.

Flexible electronics is an enabler to reduce the weight, volume and complexity of integrated systems and products, to create novel form factors and 3D design features. Currently, the majority of flexible electronics products are based on polyimide (PI, Kapton), copper laminate substrates, etching of copper to pattern the circuitry, and conventional SnAgCu (SAC) soldering or anisotropic conductive adhesives (ACA) bonding processes for the assembly of discrete components on the substrate. Development towards smaller feature size in printing technologies increases the requirement of registration, or layer-to-layer alignment accuracy. Development of IC interconnection and bonding technologies especially to flexible and stretchable substrates is critical for improved performance, yield and reliability. In addition, pilot lines and fabrication facilities and capacities need to be developed.

In integrated photonics, if it comes to monolithic integration, the optical waveguides and devices are fabricated as an integrated structure onto the surface of a substrate, typically a silicon wafer. As a result of integration, complex photonic integrated circuits (PICs) can process and transmit light in similar ways to how electronic integrated circuits process and transmit electronic signals. New waveguide and active materials are constantly developed, both for monolithic integration of components, such as SiN waveguides on Silicon or Ge detectors and 2D materials for active components, such as modulators or detectors. The fabrication of PICs consists of a multi-faceted integration problem, including monolithic integration, heterogeneous integration of active components (e.g. laser sources), and high-speed driving electronics for e.g. high-speed communications above 100 GHz bandwidth, thermal management and other functionalities, such as fluidic functions for bio and medical sensing. Further system development regarding integrated photonics includes an often 3D assembly of electronics and photonics with passive optical MEMS as well as optics components like lenses, mirrors and beam splitters.

Integration and packaging technologies for quantum systems are key enablers to make quantum sensors and other systems industrially applicable. The integration and packaging in quantum technology poses several non-typical requirements for preserving the quantum coherence. Such requirements include use of non-typical materials, such as extremely-low loss dielectrics and superconductors. Further, the packaging must support extreme cooling or even cryogenic operation, either by integrating a cooler technology inside, or by being inserted in an external cryo-cooler, which also entails vacuum operation. Thermal conductivity and handling of thermal expansion of different materials at every level, from wafer and chip level integration methods, to packaging and connection to room temperature are critical. Especially quantum computing requires multi-channel high-fidelity control and read-out solutions, with accurate synchronization and timing, from low-frequency to GHz range to the optical range of frequencies, depending on quantum system modality. Cryogenic electronics, cryo-CMOS or similar, are developed for solving these requirements, at the same time increasing the integration level of the quantum system, by introducing the control and readout elements closer to the qubits or other quantum devices.

The critical requirements to enable new advanced applications are to ensure sustainable and cost-efficient manufacturing while providing optimal performance and reliability. Further important developments include integration of different silicon IC components into miniaturized multifunctional modules following different SiP approaches, combining technologies such as flip chip, bonding, lamination and substrate materials such as silicon, glass, ceramics and polymers. Multifunctional integration also requires the development of multi-domain integration – e.g. the integration of photonic and RF functionalities into smaller form factors and together with sensors and CPUs.

For many portable devices e.g. Wireless Sensors Network (WSN) edge nodes, the power source in itself becomes a more complex challenge to integrate materials and devices, moving from traditional batteries and capacitors. This requires a complex combination of energy harvesting transducers, primary and rechargeable storage devices that need to interact with PMICs, MCUs, sensors and transceivers. Collectively they need to make decisions at a node and network level on when to use versus store energy and where to take it from. The physical mounting of transducers and electrically controlling their characteristics (e.g. impedance matching) will also be critical to maximize their performance.

#### 1.2.5.2.2 Vision and expected outcome

The challenge of integration processes, technologies and the manufacturing of smart components, modules and systems is mainly about dealing with the complexity of heterogeneous integration and scalable manufacturing technologies with different economy of scale approaches. These include "intensive" Si-like technologies, or "extensive" printing-like technologies, which under different assumptions and processing paradigms can offer cost affordability and production scalability. Apart from high-volume applications such as medical patches and RF front-end modules for 5G/6G small cells, many industrial applications can also require the availability of components, modules and systems in relatively small quantities over decades, which adds a new challenge to the scalability of manufacturing and implementation of the latest technologies.

The complexity and diversity of heterogeneous components, modules and systems substantially exceeds that of mere microelectronic components due to their multi-physics and multiple domain nature. In addition, the packages will include integrated functionalities, rather than being "passive" boards and frames. Integration and packaging methods should not compromise, but guarantee and even increase the performance of the interlaying components. Especially low-loss integration methods to enable integration of large RF systems or integrated photonics. These technologies would enable e.g. RF front ends or active antennas for millimeter wave frequencies enabling novel beyond-5G telecom solutions, or in integrated photonic communication and sensing systems. Merging different PIC technologies to compensate for missing functionality in individual cases is based on a variety of technologies, such as die flip-chipping, wafer bonding, micro-transfer printing, edge coupling, and others. Amongst current examples, one that is particularly pronounced is the integration of III-V light sources with silicon photonics, which is missing from silicon technology on its own.

In this multifunctional and multimodal integration at the component, module and system level, the development of manufacturing methods that meet the accuracy and repeatability criteria of high-quality and high-reliability products for a broad range of applications and constraints (physical, mechanical, thermal, environmental) is challenging and needs development. This method development shall be accompanied by process modeling leading to a digital twin for manufacturing allowing documentation, simulation and improvement of manufacturing challenges in a digital environment. (see also Chapter 2.4)

Additive manufacturing can provide structural and functional solutions for smart components, modules and systems integration that are not feasible with traditional methods. These methods will enable zero-defect manufacturing starting at lot one. Although additive manufacturing also improves manufacturing flexibility, solutions for the cost-efficient scaling of these fabrication methods must be addressed. 3D component, module and system integration methods will need to be developed to provide greater functionality and miniaturization in a cost-effective, sustainable and scalable way.

With respect to this multi-modality of heterogeneous integration methods, the key focus areas are divided based on the main technologies: advanced packaging and SiP technologies, integrated photonics, flexible electronics, quantum systems and manufacturing methodology as follows.

### 1.2.5.2.3 Key focus areas

- Advanced packaging and SiP technologies
  - Robust heterogeneous 3D integration of sensors, actuators, electronics, processing units, communication, RF front-end components and energy supply into miniaturized systems.
  - Embedding of power sources (energy harvesting transducers, batteries, supercaps, etc.) into a package (PwrSiP) and on a chip (PwrSoC).
  - IC carriers with integrated voltage regulator and capacitance increasing the power delivery efficiency, as well as finer structuring in IC carriers: below 5/5µm line width and spacing and finer micro-vias (below 15µm diam.).
  - Multi-node chiplets for compute applications involving high speed chip-chip interconnections with high resolution electrical and optical routing in substrate or redistribution.
  - Integration with biological and molecular systems, including fluidics and surface coatings and functionalization materials and methods for multi-functionality on the same base structures, e.g. biosensor arrays on Silicon.
  - New functional materials for packaging that enable integration of sensing or other functionality or enhanced functionality into the packaging itself, e.g. packaging as a part of the antenna or sensor functionality, e.g. embedded heatsinking/spreading to increase the thermoelectric energy harvested.
  - New materials and methods for housings and coating features and new substrate materials for specific requirements: high power, high frequencies, disposable, bio-compatible, non-fossil, harsh environments.
  - Rapid prototyping and manufacturing technologies (additive manufacturing, 2D and 3D additive technologies, etc.).
  - High-performance materials for passives enabling close coupled passives for high-density heterogeneous integration such as magnetic cores, high-k dielectrics.
  - Ultra-dense and small interfaces in all integration levels, from chip assembly and packaging to component and module level connectors and connections.
  - Integration of different sensors and sensor hubs for sensor fusion (e.g. combination of acceleration sensor, microphone, microspeaker for enhanced noise cancellation).
  - Manufacturing and characterization processes for hermetic sealing of components or subsystems with low leakage level.
- Integrated Photonics and co-integration with electronics
  - Photonic-electronic system integration based on integrated photonics, including high-speed RF electronics, MEMS/NEMS sensors, etc.
  - Multi-domain electro-photonic integration and electro-optic co-packaging.
  - Wafer-level integration of photonic and electronic components for smart emitters and detectors.
  - Enabling electronic-photonic systems by heterogeneous integration of active components on PICs (III-V semiconductors, ferroelectrics, ultra-low-loss waveguide materials).
  - Heterogeneous integration processes and equipment for integrated photonics, including high-precision component placement and bonding, as well as low-loss fiber coupling to PICs.
  - Quantum PICs: Integration of single photon detectors and sources and quantum photonic system in PICs.
- Flexible electronics
  - Integration towards low vertical form factor (<100 µm) and the miniaturization of external matching networks through integration.
  - Submicron LAE fabrication processes and equipment (printing technologies in general, nanoimprinting, reverse offset printing, etc.) and automated manufacturing equipment for flexible electronics, including testing tools for electrical and non-electrical properties.
  - Interconnections processes and tools for flexible and stretchable devices and structural electronics (in glass, plastics, laminates, etc.).
  - New/alternative non-fossil, organic, biocompatible and compostable substrate materials for e.g. implants, ingestibles, wearables, biosensors.
  - Adhesives, bonding materials and methods for integrating chips on flexible substrates.
  - Use of flexible Si-substrates for 3D form factors and for flexible electronics.

    - Integration and embedding of diverse materials and components such as antennae, PV panels, energy storage devices, magnetics, interconnect, heatsinks, displays, etc in flexible or conformal electronics.
- Quantum systems
    - Materials and methods for integration and packaging of semiconductor electronics, Integrated Photonics and superconducting devices at cryogenic temperatures, including 3D technologies.
    - Integration and interfacing and cabling solutions for combining room temperature systems and cryogenic quantum components, sensors and systems.
    - Integration methods that enable scaling quantum systems efficiently, from wafer level 3D integration to module and system level.
    - Cryogenic electronics, cryo-CMOS and similar for increasing the integration level of quantum systems and enabling scaling up of quantum systems.
    - Development and miniaturization of cryogenic cooling systems, e.g. solid state coolers.
- Manufacturing methodology, characterization and testing
    - Automation and customization in component, module and system integration for large-scale manufacturing, including Industry 4.0 techniques, design for manufacturing based on production data techniques, and lot-size-1 manufacturing, e.g. BIST (built in self test) capability of components.
    - Manufacturing and testing tools (including tests, inspection) for components, modules and systems, enabling zero-defect integration.
    - Process modeling approaches with focus on productivity, yield, trustability, distributed manufacturing.
    - Material properties database for simulation and reliability based on a standardized ontology.
    - Design of new materials from properties requirements by the means of Materials by Design, materials genome and digital design approach.
    - Energy effective joining methods, e.g. low temperature soldering; selective heating processes (i.e. inductive or reactive) to limit overall temperature impact to system while packaging.
    - Self-powered embedded sensors for ongoing performance and condition monitoring and tracking of devices , e.g. for provenance, life cycle assessments, field failure analysis, authentic validation.

### 1.2.5.3 Major Challenge 3: Sustainability

#### 1.2.5.3.1 State of the art

In 2019, world-wide e-waste exceeded 50 million tons, and is forecasted to grow to 70 million tons in 2030[7]. The European Union is one of the most advanced actors in e-waste recirculation processes. Indeed, in this region 42.5% of e-waste is documented to be collected and recirculated as product or component or recycled as material, whereas this is the case for only 9.4% in Americas and 11.7% in Asia. This can be explained by the clearer European and national political support for such initiatives. (Source: NU/UNITAR SCYCLE – Nienke Haccoû)

However, as increased integration will cause the borders between components, modules and systems to become blurred, and more diverse and complex materials are used at each level, the dismantling of systems into their constituent components at the end of their useful life will become increasingly difficult. Many industrial ECS products have lifetimes extending to decades, thus the environmental regulations for recyclability cannot be known in detail by the time of product design. Nevertheless, early consciousness on the issue should preside the start of the product cycle. Based on identified challenges, regulatory measures under the Eco-design Directive are intended to establish design for energy efficiency and durability, repairability, upgradability, maintenance, reuse and recycling. The European Commission presented its new **Circular Economy Action Plan** (CEAP) in 2020 to limit waste generation and encourage recycling, product repair and reuse. Part of this initiative is the digital product passport (DPP), which informs end-customers and businesses about products' sustainability. In general, the concept of the circular economy (CE) builds upon well-implemented strategies to prevent waste generation and includes eco-design rules during product design phase and measures for re-using products and components after a use phase.

The European Platform on Life Cycle Assessment (EPLCA) includes information on the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methods as a common way of measuring environmental performance (**EU Commission Recommendation 2021/2279**). The PEF and OEF are the EU's recommended LCA-based methods to quantify the environmental impacts of products (goods or services) and organizations.

ECS should produce smart systems not only as an enabler for, but also as an element of the circular economy, considering the sustainability of the ECS value chain and the products themselves. Focus should be on the sustainability of the component, module and system production, including processes, materials and maintenance during the primary lifetime. The recyclability of the product must already be considered in the design and manufacturing phase to enable repairability, upgradeability, reconfigurability, extension of lifetime, and re-use in a second life application, and finally the recovery of components and materials for recycling.

Given the increasing burden of improperly dealt with e-waste and considering that a significant part of $CO_2$ emissions arises from the fabrication of the ECS themselves, extending product lifetime is important for reducing ECS-related environmental load. This needs to be addressed by designs that enable repair or replacement of faulty components, avoiding the replacement of the full module or system. To fight obsolescence, hardware and software upgrades should be supported, even in field conditions. Reducing $CO_2$ emissions during the lifetime of the system requires minimizing the power consumption at component, module and system levels while in operation by using low-power hardware and software technologies.

## 1.2.5.3.2 Vision and expected outcome

For increased sustainability of ECS, the circular economy, with its 9R framework (**Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover**) and eco-design, are the main tools to reduce the environmental footprint of ECS. Life-cycle assessment as a framework will be used for identifying hotspots and checking results of the intended reduction. But ECS themselves can also be regarded as an enabler for a more circular economy.

Future ECS products must be environmentally friendly, covering all aspects from materials, manufacturing, operation and maintenance during their lifetime, considering recycling at their end-of-life. Activities must start by ensuring circularity (eco-design, environmentally friendly materials and manufacturing), employing a low $CO_2$ footprint over the whole life cycle, and facilitating the transition to a circular economy, wherever possible. Outcome activities will address:

- Non-fossil, recyclable, biodegradable and compostable materials, without releasing any dangerous materials or having other negative impact on the environment.
- Eco-design including eco-reliability of sustainable and more modular ECS.
- Sustainability and reducing energy consumption and environmental footprint of the manufacturing and integration processes.
- Increasing energy efficiency of ECS, during manufacturing and lifetime, and end-of-life.
- Upstream considerations and design for repair, upgradeability, dismantling, materials separation and recycling, lifetime extension and system health monitoring, self-monitoring and healing.
- Performance and condition monitoring, traceability, (predictive) maintenance, repair, upgrading, reconfiguring, recharging, retrofitting and re-use in second life, including ecosystems and tools to support these actions.
- Product indexes and digital product passports for ECS.
- Enablement of novel sustainable business models.

The development of integration processes based on new design tools will allow the dismantling of components, as their recycling and recovery of materials (urban mining) is essential. Therefore, system design techniques move towards eco-design where we need to rethink the use of multifunctional components and modules. Design for component separation and recyclability is generally required in the selection of materials and the integration technologies. Recycling technologies, as well as new approaches to second life of ECS and re-use in new applications, must be advanced. For example, with the electrification of cars, the recycling and re-use of battery packs, modules, and individual cells, and finally, materials recovery from the cells, becomes more and more important. Finally, we should of course minimize the number of batteries we use and dispose and improve recycling of batteries and battery materials.

The use of new environmentally friendly, recyclable and non-fossil materials (or compostable/biodegradable materials) must be seriously considered to replace existing materials with low recyclability in the near future. The use of these materials can easily be extended to other parts of the system, and the development of biodegradable materials can also contribute to solving the problems of recyclability. Life cycle assessment (LCA) should be used as a design tool to minimize the ECS carbon and environmental footprint, considering the full life cycle and end-of-life.

## 1.2.5.3.3 Key focus areas

- Eco-Design of ECS to promote circularity:
    - Use of replacement materials to comply with Restriction of Hazardous Substances Directive (ROHS) regulations (such as lead, mercury and other metals, flame retardants and certain phthalates, PFAS) and minimization of critical raw materials (CRM) dependence, including rare earths replacement for magnetics, inductors and power integrity.
    - Use of recyclable, biodegradable, compostable, non-fossil materials from sustainable sources in combination with the development of efficient and environmentally benign recycling techniques in accordance with the legislative agenda.
    - Less materials for higher functionalisation.
    - Assessment of the environmental impact of ECS at the design stage, as a tool for sustainable ECS, using life cycle assessment (LCA) or similar framework.
    - Certified up-to-date data for LCA, PEF, PCR and EDP.
    - Development of design, fabrication, integration, recovery, reconfiguration/reuse, repairability and disassembly strategies for products (module dismantling, component recycling, material recovery) and also short-lifetime devices (e.g. single-use medical devices, radio-frequency

    identification, RFID, tags and printed sensors) to meet the existing and emerging regulatory requirements.
  - Improvement of system reliability as a means to guarantee and extend the lifetime of electronic products with the final objective of responding to material efficiency requirements and providing an optimal balance on a life cycle scale.
  - Increasing power efficiency of ECS during lifetime by using low-power techniques with context awareness or energy harvesting.
  - Extensive use of software to increase the sustainability of ECS by extending product lifetime through continuous optimization and adaptation, by making existing ECS more intelligent through the use of AI, in particular at the Edge, and by optimizing the resource usage through hardware and software co-defined strategies. Ensure the trustworthiness and reliability of the ECS, including its software components, with a special attention to approaches involving AI that must be secure, reliable and automatically and autonomously adapted.
  - Promote methodologies allowing for the co-design of ECS hardware and software involving simulations and realistic models, including AI-aided development tools, to continuously estimate key metrics. This must be complemented by instrumentation of the ECS hardware and software to continuously assess the achievements of the key figures of merit over the entire ECS lifetime (including shelf and post-decommissioning).
- Sustainable manufacturing of ECS:
  - Explore the extension of additive manufacturing methods, such as printing, that consume less resources (energy, materials, water) and are compatible with renewable materials, such as bio-based substrates. At the same time, additive manufacturing offers new design capabilities for circular, thin and flexible devices, even for single use (e.g. wearable electrodes) with specified end-of-life management.
  - Optimization of resources and processes in production environments with potential in-situ re-use and regeneration of base materials and chemicals.
  - Reduce energy consumption (and greenhouse emissions) in cleanrooms through the use of renewable energy sources and energy-efficient technologies or tools.
  - Increase water reusage in electronics manufacturing facilities.
  - Improve gas abatement systems.
  - Breakthroughs and development in recycling processes and solutions for energy storage components, such as batteries.
- Sustainable products and business models:
  - Encouraging sustainable supply chains.
  - Introduction of product category rules and product indexes (including info such as energy and resource efficiency, durability, reusability, upgradability and repairability, presence of substances that inhibit circularity, recycled content, remanufacturing and recycling, carbon and environmental footprints, expected waste generation and information requirements) for components and systems to encourage the use of LCA based environmental product declarations.
  - Digital product passports should be promoted, tested and then widely established.
  - Encourage new business models to see value in eco-design and recyclability.
  - Value repairability: An EU-wide repair index inspired by the French repairability index.
  - Condition monitoring for usage as well as for health/performance and anomaly detection.
  - Improve efficiency of e-waste recyclability by robotics, thereby increasing new value streams and business through reuse.

## 1.2.6 Timeline

The following tables illustrate the roadmaps for **Components, Modules and Systems Integration**.

| Major Challenge | Topic | Short Term (2024-2028) | Mid-Term (2029-2033) | Long Term (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Enabling new functionalities in components with More-than-Moore technologies** | **Topic 1.1:**<br>Sensing, imaging and actuation | • Selective gas-sensing<br>• Disease monitoring and diagnostics platforms (in vitro, wearables)<br>• Lidar and radar systems<br>• Functional materials (piezo, ceramics, polymers, metamaterials)<br>• IR sensors integrated with CMOS<br>• H2 low and mid pressure sensors; H2 detection in exhaust | • Selective detection of allergens, residues<br>• Fluidics<br>• Drug delivery<br>• Affordable IR imagers<br>• Hyperspectral imaging<br>• Materials and concepts for Quantum sensors<br>• H2 detection in ambient surrounding | • Convergence of sensing principles (e.g. thermal, optical cameras with lidar/radar)<br>• Multifunctional healthcare support systems (wearables, implants)<br>• integrated Quantum sensors |
| | **Topic 1.2:**<br>MEMS technology | • Novel piezo materials and piezo devices for MEMS/NEMS<br>• Micro-optical (MOEMS) components<br>• compact audio MEMS | • Integration for multifunctional sensors and actuators based on MEMS/NEMS and MOEMS | • Self-monitoring, correcting and -adapting MEMS/NEMS<br>• Highly integrated multifunctional, dynamically adaptive and context recognizing sensors |
| | **Topic 1.3:**<br>Integrated photonics | • Novel devices operating at different wavelengths than used for telecom<br>• Co-packaging and integration of Integrated photonics and high-speed electronics<br>• Photonic health and medical sensors | • Tunable laser sources for PICs<br>• Materials and devices for Quantum PICs<br>• optical elements for beam shaping and manipulation (like ultrathin curved waveguides, meta-lenses, tunable lenses and filters, next generation holograms, ultra-wide-angle holograms)<br>• display technologies (like micro-LEDs, MEMS-mirrors, Phase Arrays) and sensors (e.g. for eye tracking) | • Growth of light-emitting structures on silicon and integration into photonic platforms<br>• Analogue and Neuromorphic photonic computing |
| | **Topic 1.4:**<br>Flexible electronics | • Si devices compatible with integration to flexible devices; thinned IC etc<br>• New flexible non-fossil materials for flexible and structural electronics including active components, transparent conductors, barriers | • Large area flexible and stretchable sensors and actuators<br>• Organic and bio-compatible materials<br>• Wearable smart systems combing simultaneous biochemical and biophysical sensing | • Stretchable smart systems for wearables combing simultaneous biochemical and biophysical sensing<br>• Metamaterial sensors |
| | **Topic 1.5:**<br>Communications | • Real-time, low-latency, low-power, fault-tolerant and self-repairing networks for edge and IoT devices<br>• High-speed photonics communications modules beyond 1Tb/s<br>• Reduction of EMI | • Quantum key distribution<br>• Advanced interconnect photonics at component as well as at system-level<br>• Beyond 5G and 6G communications, including non-terrestrial networks<br>• THz communication<br>• Energy constraint aware and adaptive networks at node and network level<br>• Accurate and stable clocks for 6G and quantum devices | • Quantum internet and cryptography<br>• Beyond 6G<br>• Digital twins at node and network level to help design and optimize energy constraint aware WSN architectures at planning and operational stages |
| | **Topic 1.6:** | • Lightweight energy harvesters and storage | • Low/zero power components and systems | • $CO_2$-neutrality and circular economy for ECS |

| Major Challenge | Topic | Short Term (2024-2028) | Mid-Term (2029-2033) | Long Term (2034 and beyond) |
|---|---|---|---|---|
| | Energy and thermal management | - Multi source energy harvesting PMIC operating down below 10mV and 10uW<br>- Low power components<br>- Energy autonomous systems<br>- Thermal management at different integration levels including advanced and active cooling systems<br>- Multi-modal device and system level energy harvesting/power consumption simulation models | - solution for thermal management in integrated photonics<br>- Advanced encapsulation materials for energy harvesters<br>- Extend chiplet concept (design and manufacturing) to no-IC components<br>- Sensors and actuators for the optimization of battery cells usage during their entire lifetime | - Energy harvesting PMICs embedded in MEMS & NEMS WSN nodes with MCU, sensors, transceivers, etc.<br>- Sensors embedded in energy source components for performance and condition monitoring, lifetime provenance and anomaly detection |
| | **Topic 1.7:**<br>Information processing | - Security and privacy<br>- Explainable AI, edge computing (HW and SW)<br>- Hybrid modelling (physical and data-driven)<br>- Federated data collection from edge to gateway to cloud to minimize strain<br>- Energy constraint aware and adaptive networks and architectures, particularly for the battery powered edge devices | - Integration of information processing close to data acquisition<br>- Hardware solutions for security and privacy<br>- Neuromorphic computing<br>- AI in the edge computing<br>- Quantum simulation and quantum computing for the data-analysis (in the cloud) | - Low-power AI<br>- Neuromorphic on-the-edge computing for sensors and actors<br>- Quantum computing<br>- Quantum simulation |
| **Major Challenge 2:**<br>**Integration technologies, processes and manufacturing** | **Topic 2.1:**<br>Advanced packaging and SiP technologies | - Integration for complexity: Hybrid integration of heterogeneous components into several types of platforms<br>- System health monitoring and self-diagnosis<br>- Integration of biological and molecular functions, integration with fluidics<br>- Embedding of power sources (batteries, energy harvesting) in SiP and IC carriers with digital interfacing | - Integration for harsh environments, and implantable electronics<br>- System health monitoring and self-diagnosis, self-healing<br>- Self-cleaning and self-healing materials | - Maximum functional integration in minimum volume/footprint Advanced photonics<br>- Biological-electronics hybrid systems |
| | **Topic 2.2:**<br>Integrated Photonics and co-integration with electronics | - Photonics integration with RF, sensors; electro-optic co-packaging<br>- High-precision component placement and bonding processes and equipment<br>- Low-loss fiber coupling to PICs | - Heterogeneous integration of active components (e.g. III-V) on PICs on wafer scale<br>- Metamaterials for beam shaping | - Combining electrical and optical interconnects into an electro-optical IC carrier<br>- Monolithically integrated quantum photonics including III-V quantum dots |
| | **Topic 2.3:**<br>Flexible electronics | - Integration processes with flexible, structural and 3D conformable electronics<br>- Materials for chip interconnection; ACA, ICA, flip chip etc.<br>- Large area R2R compatible Interconnection processes and equipment for heterogeneous integration | - Compostable and biodegradable substrate and housing materials<br>- R2R compatible chip assembly and interconnection technologies on stretchable substrates | - Stretchable electronics and system integration<br>- Automated Interconnection processes and equipment for heterogeneous integration |

| Major Challenge | Topic | Short Term (2024-2028) | Mid-Term (2029-2033) | Long Term (2034 and beyond) |
|---|---|---|---|---|
| | **Topic 2.4:**<br>Quantum systems | • Materials and methods for quantum technology integration in cryogenic temperatures<br>• Materials and components for low-loss and high quantum coherence<br>• Cryogenic electronics, cryo-CMOS | • Integration of quantum systems: superconducting, photonic, Silicon technologies<br>• Solid state coolers | • Quantum SiP also in room temperature or with integrated cooling |
| | **Topic 2.5:**<br>Manufacturing methodology, characterization and testing | • I4.0 for manufacturing optimization<br>• Additive manufacturing and rapid prototyping technologies and materials<br>• Improved automation and customization in integration for smaller lots<br>• Database of material properties for simulation and reliability<br>• process model implementation as Digital Twins for Manufacturing Optimization | • I4.0 for manufacturing optimization, Zero-defect integration<br>• Automation and customization in integration for smaller lots<br>• Additive manufacturing and rapid prototyping technologies<br>• Material by design approach | • Automation and customization in integration, lot one<br>• Fully digitalized manufacturing process description – Digital Twin for Manufacturing |
| **Major Challenge 3:**<br>**Sustainability** | **Topic 3.1:**<br>Eco-design of ECS | • Replacement materials to comply with RoHS and minimize CRM dependence<br>• Use of recyclable materials<br>• Less materials for higher functionality<br>• Life cycle analysis as tool for design<br>• Development of design, fabrication, integration, recovery, reconfiguration/reuse, disassembly strategies<br>• Designing for repairability, including modular approach, upgrades and maintenance<br>• Certified up-to-date data for LCA, PEF, PCR and EDP<br>• Eco-design benchmark values for electronic components<br>• Availability and exchangeability of spare parts and tools<br>• Improve system reliability to guarantee and extend the lifetime<br>• Use low-power techniques with context awareness and/or energy harvesting | • Cross-company reuse of “stable” chip designs, including More-than-Moore components<br>• Methodologies allowing for the co-design of ECS hardware and software<br>• Use of biodegradable, compostable, non-fossil materials<br>• Breakthroughs in recycling processes, including energy storage components<br>• Applying results of Green ECS to integrated photonics<br>• Extensive use of SW to increase sustainability of ECS | • Highly integrated re-usable circuit blocs<br>• Circular economy of ECS<br>• Solutions for full recycling and material recovery of ECS, including energy storage components<br>• Environmental footprint and critically based recycling planning (final stage material recycling)<br>• Set up repair process: failure characterization , repair and re-characterization; provide manuals, instructions, schematics and inexpensive spare parts<br>• Warranties and safety-relevance need to be addressed |
| | **Topic 3.2:**<br>Sustainable manufacturing of ECS | • Condition monitoring and predictive maintenance<br>• Increasing the energy and resource efficiency and environmental footprint of components, systems and modules<br>• Use of energy harvesting to minimize/eliminate battery replacement | • Reducing energy consumption and $CO_2$ footprint of integration processes, tools and ECS systems<br>• Processes for re-use and second life<br>• Life cycle traceability of components and systems to capture carbon footprint, authenticity and re-cyclability | • $CO_2$-neutral ECS economy<br>• Zero waste added manufacturing to produce functional modules |

| Major Challenge | Topic | Short Term (2024-2028) | Mid-Term (2029-2033) | Long Term (2034 and beyond) |
|---|---|---|---|---|
| | | • Extension of additive manufacturing methods<br>• Increase water reusage | • Improved recycling and material recovery processes | |
| | **Topic 3.3:**<br>Sustainable products and business models | • Establish a repair index inspired by the French repairability index<br>• Introduce product category rules and product indexes | • Self- condition monitoring energy harvesting solutions to assure long term reliability and for anomaly detection<br>• Repair as business (bonus-malus-systems)<br>• A business model can emerge for third-party repair centers<br>• Closing data gaps in circularity and recycling through Digital Product Passport<br>• Improve efficiency of e-waste recyclability by robotics | • Train skilled repairers; questions around re-certification |

## 1.2.7 Synergy with other themes

Smart components, modules and systems are key elements in a wide range of activities relevant to all **Application** Chapters. Conversely, the new and advanced applications described in those chapters will also give rise to new functionalities and further advances in integration technologies. Most components, modules and systems integration is based on devices developed with techniques described in the **Process Technology, Equipment, Materials and Manufacturing** Chapter. Furthermore, simultaneous development and co-design is necessary with **Embedded Software and Beyond** technologies to ensure integration with hardware and software.

The cross-sectional technologies link to components, modules and system integration in many ways. **Connectivity** solutions are needed for networked systems. **Edge Computing and Embedded Artificial Intelligence** needs to link into integrated systems for AI on the edge and on sensor level already. **Quality, reliability and cybersecurity** methods are paramount for ensuring reliable integrated systems. For successful multi-modal integration of electrical, thermal, and mechanical properties in integrated systems, advanced simulation methods and design tools are required, which is covered in **Architecture and Design: Methods and Tools**.

Thus, the field of components, modules and systems integration draws upon key enabling technologies and integrates knowledge from many disciplines. In addition, integration bridges the gap between components, modules and functional, complex systems. As the development of smart components, modules and systems will benefit from progress in all other technological disciplines, the synergies should not only be in the multidisciplinary development of the technologies, but also in the building of ecosystems (people and infrastructure). This is where all stakeholders can guide and influence each other and collaborate to assist in the development of optimized system- and application-oriented solutions.

## 1.2.8 References

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# 1.3

*Foundational Technology Layers*

# EMBEDDED SOFTWARE AND BEYOND

# 1 Foundational Technology Layers

## 1.3

## Embedded Software and Beyond

### 1.3.1 Introduction

The Artemis/Advancy report[1] states that "*the investments in software technologies should be on at least an equal footing with hardware technologies, considering the expected growth at the higher level of the value chain (Systems of Systems, applications and solutions)*". According to the same report, embedded software and software engineering tools are part of the six technology domains needed for embedded intelligence. Embedded intelligence means incorporating AI algorithms ("classic" or ML ones) in devices or components to give them the ability to reflect on their own state (e.g. operational performance, usage load, environment), execute tasks independently, adjust to novel circumstances, and make data-driven decisions without human input. Such devices will operate in a robust and resilient way, e.g. independent of internet connectivity and are the necessary step towards the next level of digitalisation and sustainability. In this context, embedded intelligence supports the green deal initiative, as one of the tools for enhancing sustainability.

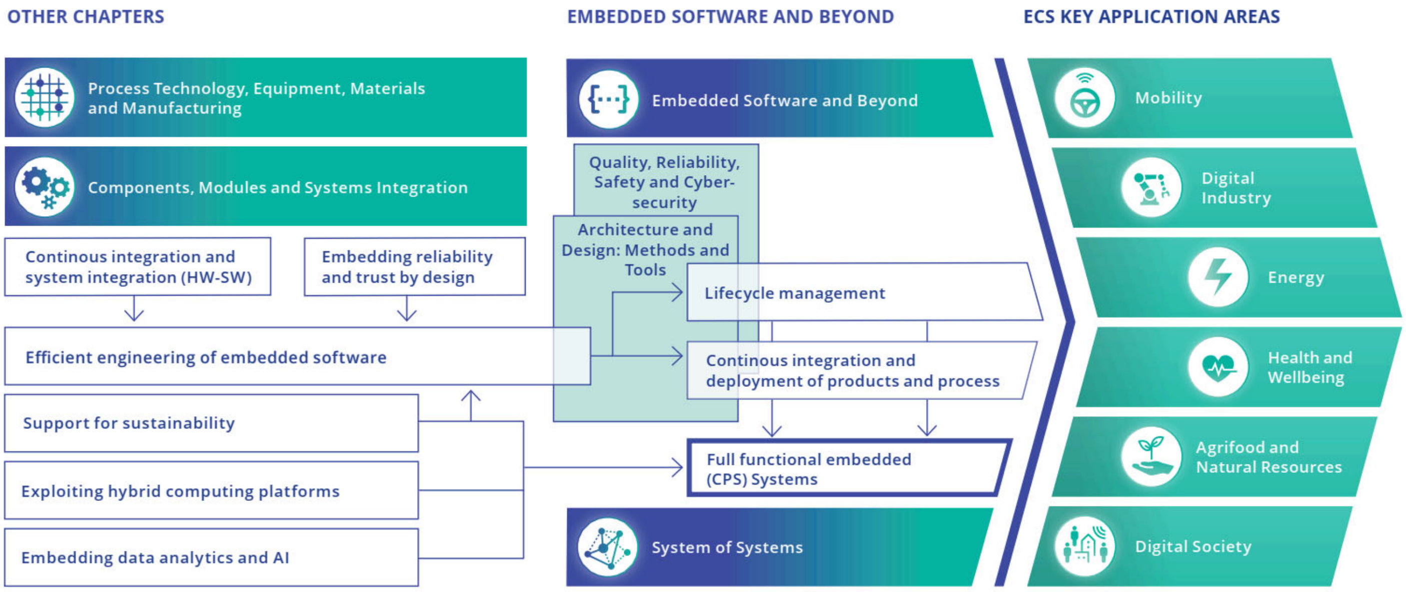


*Figure 1.3.1 - Positioning of the Embedded Software and Beyond Chapter in the ECS-SRIA*

Figure 1.3.1 illustrates the role and positioning of the **Embedded Software and Beyond** Chapter in the ECS- SRIA. The Chapter on **Components Modules and System Integration** focuses on functional hardware components and systems that compose the embedded and cyber-physical systems (CPS), considered in this Chapter. While the **System of Systems (SoS)** Chapter is based on independent, fully functional systems, products and services (which are also discussed in this Chapter), they are also the constituents of SoS-based solutions. The **Architecture and Design: Methods and Tools** Chapter examines engineering processes, methods, and tools, while this Chapter focuses more on the technology stack of **Embedded Software and Beyond**. For the discussion on safe, trustworthy, and explainable AI in the context of embedded intelligence, this Chapter is also linked to **Quality, Reliability, Safety and Cybersecurity (**Chapter 2.4).

This Chapter is called **Embedded Software and Beyond** to stress that embedded software is more than "just software": it is a key component of any system's embedded intelligence, it enables systems to act on external events, and it enables inter-system communication.

Most importantly, Embedded software empowers Embedded and cyber-physical systems (ECPS) to play a key role in solutions for digitalisation in almost every application domain (cf. Chapters 3.1-3.6). From a functional perspective, the role of Embedded Software is becoming increasingly dominant because of the new software-enabled functionalities ECPS (e.g. cars, trains, airplanes and health equipment) need to provide (including aspects as security, privacy and autonomy). In these systems, most of the innovation comes from software, nowadays. ECPS also form the backbone of SoS (e.g. smart cities, air traffic management), providing required interconnection and interoperability. Owing to all these factors, ECPS are an irreplaceable part of the strive towards digitalisation of our society.

At the same time, ECPS need to exhibit required quality properties (e.g. safety, security, reliability, dependability, sustainability, and, ultimately, trustworthiness). Furthermore, due to their close integration with the physical world, ECPS must consider the dynamic and evolving aspects of their environment to provide deterministic, high-performance, and low-power computing, especially when processing intelligent algorithms. Increasingly, software applications will run as services on distributed SoS involving heterogeneous devices (e.g: servers, edge devices) and networks, with a diversity of resource restrictions. In addition, it is required from ECPS that their functionalities and hardware capabilities evolve and adapt during their lifecycles – e.g. through updates of software or hardware in the field and/or by learning. Building these systems and guaranteeing their previously mentioned quality properties, along with supporting their long lifetime and certification, requires innovative technologies in the areas of modelling, software engineering, model-based design, verification and validation (V&V) technologies, and virtual engineering. These advances need to enable engineering of high-quality, certifiable ECPS that can be produced (cost-)effectively (cf. Chapter 2.3, **Architecture and Design: Methods and Tools**).

## 1.3.2 Scope

Common challenges in embedded software and its engineering for ECPS include:

- Interoperability.
- Complexity of requirements and code (safety, security, performance).
- Quality (dependability, sustainability, performance, trustworthiness).
- Lifecycle (maintainability, extendibility).
- Efficiency, effectiveness, and sustainability of software development.
- Adaptability to, and the dynamic environment of ECPS.
- Maintenance, integration, rejuvenation of legacy software solutions.

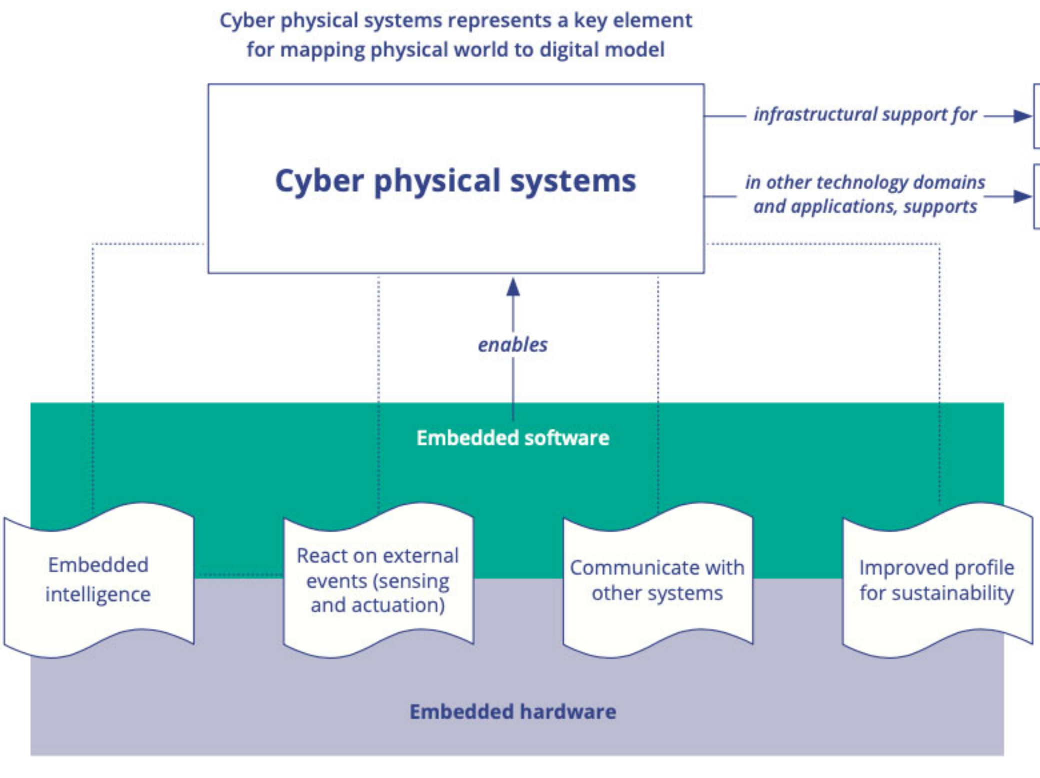
To enable ECPS functionalities and their required level of interoperability, the engineering process will be progressively automated and will need to be integrated in advanced SoS engineering covering the whole product during its lifetime. Besides enabling new functionalities and their interoperability, it will need to cover non-functional requirements (safety, security, run-time performance, reliability, dependability, sustainability, and, ultimately, trustworthiness) visible to end users of ECPS, and to also satisfy quality requirements important to engineers of the systems (e.g. evolution, maintenance). This requires innovative technologies that can be adapted to the specific requirements of ECPS and, subsequently, SoS.

Further complexity will be imposed by the introduction of Artificial Intelligence (AI), machine-to-machine (M2M) interaction, new business models, and monetisation at the edge. This provides opportunities for enhancing new engineering techniques like AI for SW engineering, and SW engineering for AI. Future software solutions in ECPS will solely depend on new software engineering tools and engineering processes (e.g. quality assurance, Verification and Validation (V&V) techniques and methods on all levels of individual IoT and in the SoS domain).

Producing industrial software, and embedded software in particular, is not merely a matter of writing code: to be of sufficient quality, it also requires a strong scientific foundation to assure correct behaviour under all circumstances. Modern software used in products such as cars, airplanes, robots, banks, healthcare systems, and the public services comprises millions of lines of code. To produce this type of software, many challenges have to be overcome. Even though software in ECPS impacts everyone everywhere, the effort required to make it reliable, maintainable and usable for longer periods is routinely underestimated. As a result, every day there are news articles about expensive software bugs and over-budget or failed software development projects. Also, big challenges with correctness and quality properties of software exist, as human well-being, economic prosperity, and the environment depend on it. There is a need to guarantee that software is maintainable and usable for decades to come, and there is a need to construct it efficiently, effectively and sustainably. Difficulties further increase when legacy systems are considered: information and communications technology (ICT) systems contain crucial legacy components at least 30 years old, which makes maintenance difficult, expensive, and sometimes even impossible.

The scope of this Chapter is research that facilitates engineering of embedded software used for ECPS, enabling digitalisation through the feasible and economically accountable building of SoS with necessary quality. It considers:

- Challenges that arise as new applications of ECPS emerge.
- Continuous integration, delivery and deployment of products and processes.
- Engineering and management of ECPS during their entire lifecycle, including sustainability requirements.



Embedded intelligence is the ability of a system or component to reflect on its own state (e.g. operational performance, usage load, environment)

*Figure 1.3.2 - Importance of Embedded Software for Cyber physical systems and its roles.*

### 1.3.2.1 Quantum Technologies

Quantum technology has drawn a growing amount of attention in recent years. This short text briefly explains the three main topics of this fields. An inventory is made of the impact of quantum technologies on embedded software and beyond.

#### The Three Main Topics of Quantum Technology

Quantum computing, quantum internet and quantum sensing are the three main topics of quantum technology. Let's take a look at all three.

**Quantum Computing** Quantum computing is the most captivating of the three. In theory, quantum computers are able to solve some types of computations exponentially faster than classical computers. Shor's algorithm to factor a number in its prime factors is often quoted as an example of this speedup. This opens the road to find cryptographic keys which form the backbone of today's secure communication technologies. Once quantum computers become practical, this may well pose a threat to secure, encrypted communication. The key point here is that this threat requires a significantly larger quantum computer than is available now: for factoring a key of several thousand bits, a logical qubit register of several thousand qubits is required. With the current state-of-the-art, this requires millions of physical (noisy) qubits. Such a large quantum computer is at least 10 to 15 years away, if not more[2].

Nevertheless, quantum computing is casting its shadow ahead. And governments and organisations are already taking countermeasures. Several governments now require all of their services to prepare for the security threat quantum computing will pose. It means that current encryption technologies are to be upgraded to a degree that even challenges quantum computing. This asks for longer encryption keys and more complex encrypting and decrypting algorithms, requiring more resources. Research and development of efficient digital cryptography systems, involving hardware and software, is already ongoing and will play an increasingly important role as quantum computers are coming of age[3].

These observations lead to the conclusion that quantum computing will have an indirect impact on embedded software and beyond, in the next few years. It depends on the speed of evolution and innovation of quantum technology when quantum computing devices will leave the laboratory and make their introduction to the industry. For now, that appears to be a decade away, but vigilance on this subject is required. Europe should strive for independence from other nations in this area to be able to develop this technology on its own, in the light of the recent developments in international relations.

#### Quantum Internet

A quantum internet is an application of quantum networks. Quantum networks enable the communication of qubits. Such networks can be used to connect quantum processors to form more powerful quantum computers. Quantum networks can also be used to create quantum internet applications. One such application is the secure distribution of cryptographic keys: in this setup, cryptographic keys are distributed over a quantum network using entangled qubits, enabling the detection of eavesdropping on the communication. But quantum internet, just like quantum computers, are still in the research and development phase. Practical applications at this moment require complicated setups, often involving cryogenically-cooled devices, preventing wide-spread use today and in the next few years[4].

### Quantum Sensors

Quantum sensors are sensors which detect physical properties by using quantum effects such as quantum entanglement, quantum interference, and quantum state squeezing. Quantum sensors have been in use for quite a long time: medical magnetic resonance scanners, which detect the precession of atomic nuclei in a magnetic field.

Quantum sensors are sensitive to some physical property. It is not so much the measurement of the physical property, but the enhanced accuracy or sensitivity to such a property that makes quantum sensors stand out from classical sensors. As such, the (embedded) software that processes the measurement of quantum sensors does not differ from software that processes measurements from classical sensors[5].

It appears that quantum technology will impact the communication security of embedded systems in the next few years. Implementations for post-quantum cryptography must be researched and developed to stay ahead of quantum technology developments.

## 1.3.3 Technology Enabled Societal Benefits

Computing systems are increasingly pervasive and embedded in almost all objects we use in our daily lives. These systems are often connected to networks, making them part of SoS. ECPS bring intelligence everywhere, allowing data processing and intelligence on the site/edge, improving security and privacy and, through digitalisation, completely change the way we manage business and everyday activities in almost every application domain (cf. chapters 3.1-3.6). ECPS also play a critical role in modern digitalisation solutions, quickly becoming nodes in distributed infrastructures supporting SoS for monitoring, controlling and orchestrating supply chains, manufacturing lines, organisation’s internal processes, marketing and sales, and consumer products.

Considering their role in digitalisation solutions, ECPS represent a key technology to ensure the continuity of any kind of digital industrial and societal activity, especially during crises, and have an indirect but significant impact on the resilience of economic systems. Without ECPS, data would not be collected, processed, shared, secured/protected, or transmitted for further analysis. Embedded software allows for the practical implementation of a large set of such activities, providing the features required by the applications covered in this SRIA, where it becomes a technology enabler. The efficiency and flexibility of embedded software, in conjunction with the hardware capabilities of the ECPS, allow for embedded intelligence on the edge (edge AI), opening unprecedented opportunities for many applications that currently rely on human involvement (e.g. automated driving, security and surveillance, process monitoring). Moreover, digitalisation platforms exploit embedded software flexibility and ECPS features to automate their remote management and control through continuous engineering across their entire lifecycle (e.g. provisioning, bug identification, firmware and software updates, and configuration management). It is the requirement of embedded software to improve sustainability of these platforms.

### 1.3.3.1 Open Source Software & Licenses

Free software (FS) is defined by four freedoms: the freedom to run as you wish, to study and change the source code, to redistribute copies and to distribute copies of your modified versions[6]. Open-source doesn't just mean access to the source code. The Open-Source Initiative (OSI) details the terms the distribution of open-source software must comply with[7]. Today”, more than 100 open-source licenses[8] are compliant with these 10 criteria. OSI recommends 9 of them because they are popular, widely used, or have strong communities[9]: Apache 2.0, BSD-2 & 3, GPL, LGPL, MIT, Mozilla 2.0, CDDL and EPL 2.0.

Open-source components are usually the core building blocks of application software in most innovative domains[10]. To provide developers with an ever-growing selection of off-the-shelf possibilities, which they can use for assembling their products faster and more efficiently, it is essential to understand the benefits and the constrains that come with open-source licenses.

The following license spectrum diagram can summarize the freedom of choice from a user point of view:

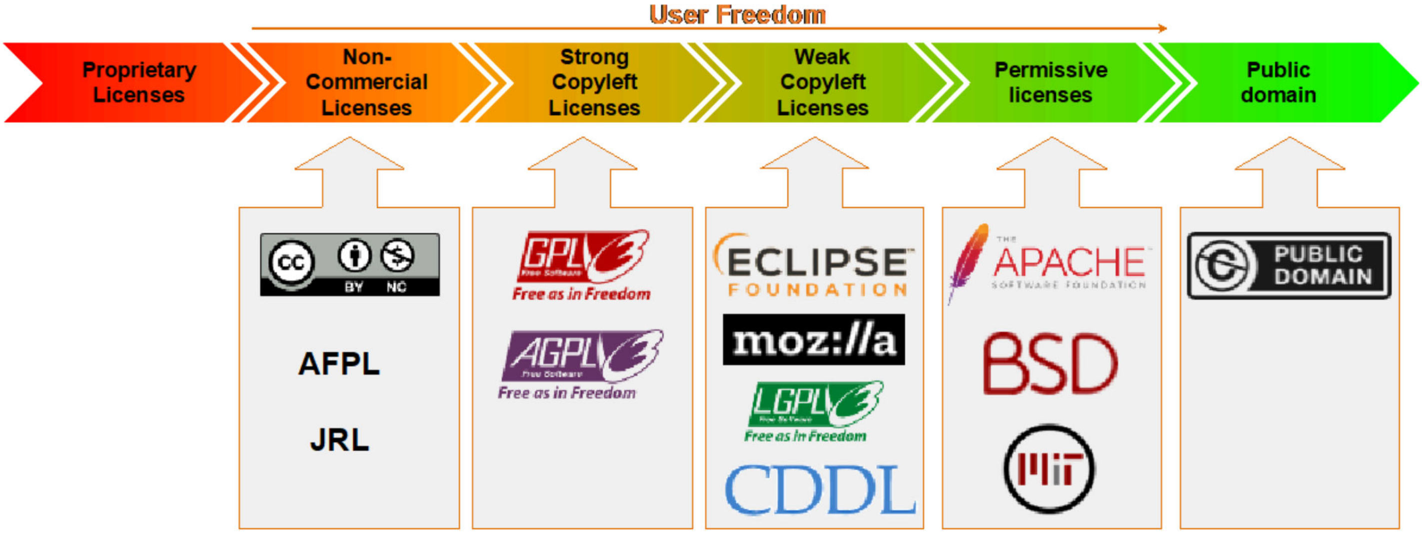


Figure 1.3.3 - Open License Spectrum

A "strong copyleft” license requires that other code that is used for adding, enhancing, and/or modifying the original work also must inherit all the original work's license requirements such as to make the code publicly available. The best-known strong copyleft licenses are GPL, and AGPL. A weak copyleft license only requires that the source code of the original or modified work is made publicly available. Other code that is used together with the work does not necessarily inherit the original work's license requirements. The most known and used licenses with weak copyleft are LGPL and EPL 2.0. A permissive license, instead of copyleft protections, carries only minimal restrictions on how the software can be used, modified, and redistributed, usually including a warranty disclaimer. Apache 2.0, BSD and MIT are the most known and used permissive licenses.

Weak copyleft and permissive licenses are generally considered "business-friendly" licenses, because they do not restrict derivative works. For example, the EPL 2.0 allows sub-licensing and creation of software from EPL or non-EPL code. The Apache 2.0 license does not require that derivative works be distributed under the same terms. The MIT and BSD licenses place very few restrictions on reuse, so they can easily be combined with other types of licenses, from the GPL (not the original 4-clause BSD) to any type of proprietary license[11].

In any case, licensing is an important, complex and broad topic. Therefore, it is recommended to include legal experts when a product with third-party opensource dependencies is developed or an open-source license is considered for a product. Notice also, that only some open-source licenses will also grant you access to patents that might be covering some functionality.

## 1.3.4 Applications Breakthrough

Embedded software significantly improves the functionalities, features, and capabilities of ECPS, increasing their autonomy and efficiency, and exploiting their resources and computational power, as well as bringing to the field functionalities that used to be reserved only for data centres, or more powerful and resource-rich computing systems. Moreover, implementing specific functionalities in software allows for their re-use in different embedded applications due to software portability across different hardware platforms. Examples of increasing computational power of ECPS are video conferencing solutions: less than 20 years ago specialised hardware was still required to realise this function, with big screens in a dedicated set-up that could not be used for any other but a dedicated application. Today, video conferencing is available on every laptop and mobile phone, where the main functionality is implemented by software running on standard hardware. The evolution is pushing to the “edge” specific video conferencing functionalities, adopting dedicated and miniaturised hardware supported by embedded software (video, microphone, and speakers), thus allowing the ECS value chain to acquire a new business opportunity.

Following a similar approach, it has been possible to extend the functionalities of mobile phones and smart watches, which today can a.o. count steps, keep track of walked routes, monitor health, inform users about nearby restaurants, all based on a few extra hardware sensors and a myriad of embedded software applications. The trend is to replace specialised hardware applications with software running on generic computing hardware and supported by application-specific hardware, such as AI accelerators, neural chips. This trend is also contributing to the differentiation of the value creation downstream and upstream, as observed in the Advancy report [12] (see Figure 1.3.4).

These innovations require the following breakthroughs in the field of embedded software:

- Increased engineering efficiency and an effective product innovation process (cf. Chapter 2.3 Architecture and Design: Methods and Tools).
- Enabled adaptable systems by adaptable embedded software and machine reasoning.
- Improved system integration and verification and validation.
- Embedded software, and embedded data analytics and AI, to enable system health monitoring, diagnostics, preventive maintenance, and sustainability.
- Data privacy and data integrity.
- Model-based embedded software engineering and design as the basis for managing complexity in SoS (for the latter, cf. Chapter 2.3 Architecture and Design: Methods and Tools).
- Improved multidisciplinary embedded software engineering and software: architecting/design for (systems) qualities, including reliability, trust, safety, security, overall system performance, installability, diagnosability, sustainability, and re-usability (for the latter, cf. Chapter 2.3 Architecture and Design: Methods and Tools and Chapter 2.4 Quality, reliability, safety and cybersecurity).
- Upgradability, dealing with variability, extending lifecycle and sustainable operation.

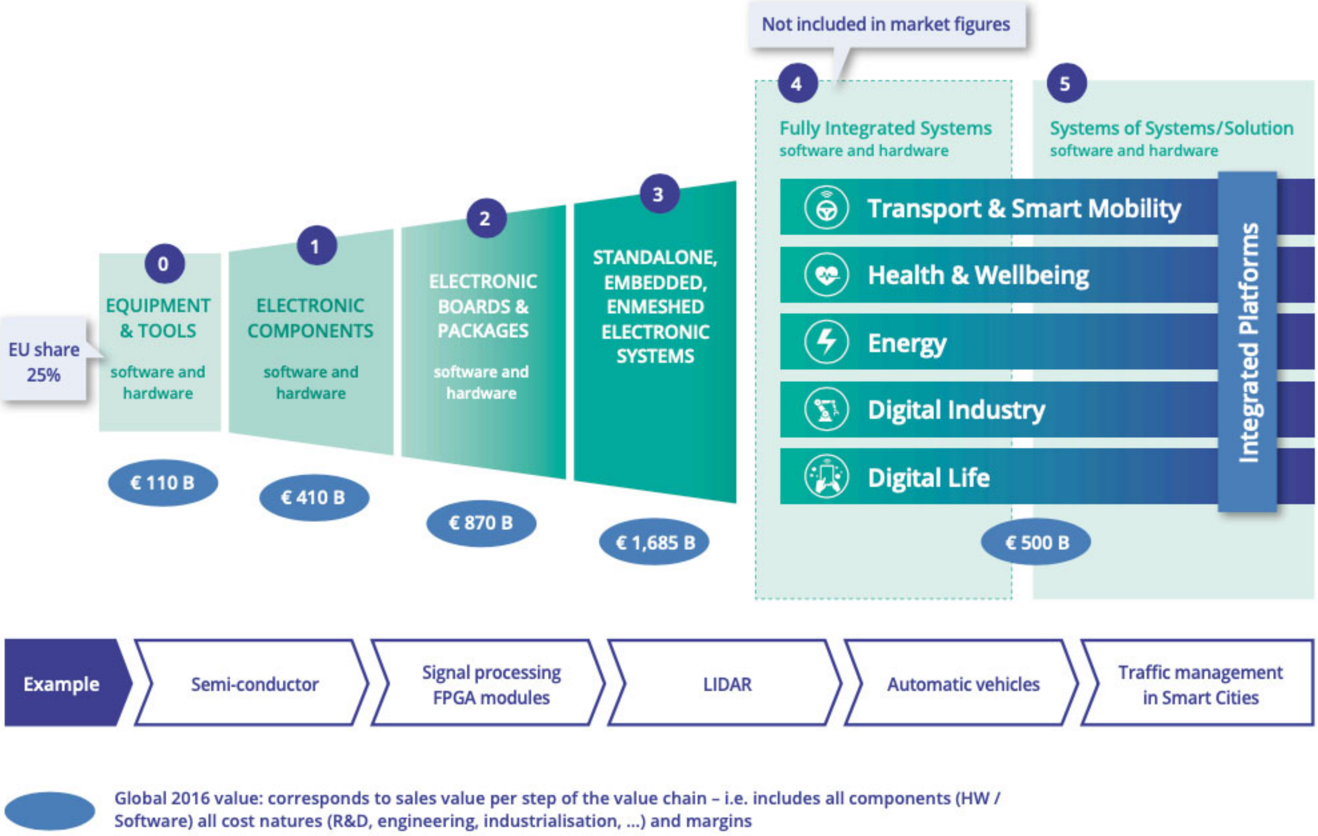


*Figure 1.3.4 - Advancy (2019) [13]report: value creation*

## 1.3.5 Strategic Advantage for the EU

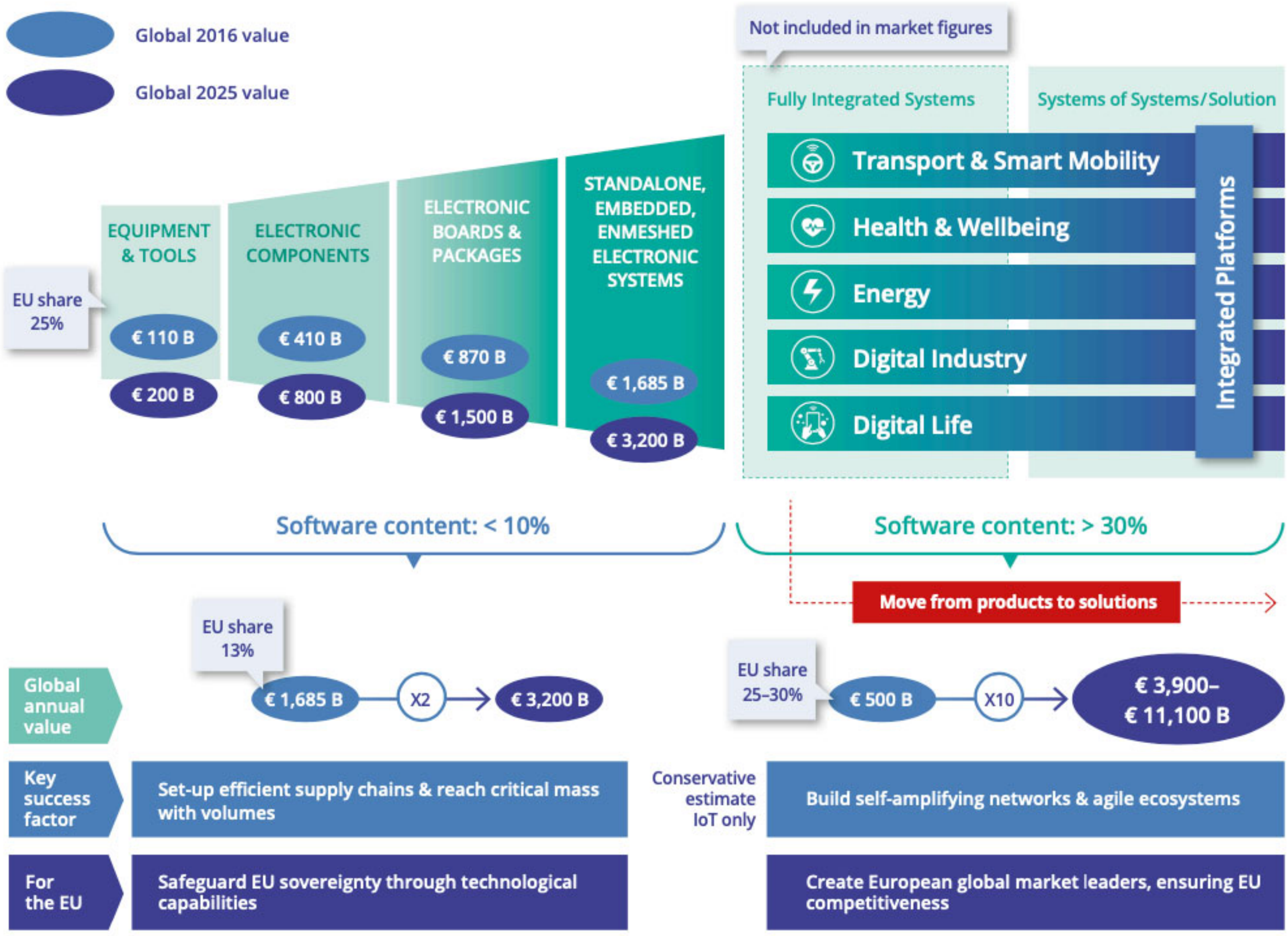
The ambition of growing competences by researching pervasive embedded software in almost all devices and equipment is to strengthen the digitalisation advance in the EU and the European position in embedded intelligence and ECPS, ensuring the achievement of world-class leadership in this area through the creation of an ecosystem that supports innovation, stimulates the implementation of the latest achievements of cyber-physical and embedded systems on a European scale, and avoids the fragmentation of investments in research and development and innovation (R&D&I).

European industry that is focused on ECS applications spends about 20% of its R&D efforts in the domain of embedded digital technologies, resulting in a cumulative total R&D&I investment of €150 billion for the period 2013–20. The trend in product and solutions perspective estimates a growth from €500 billion to €3.100–11.100 billion, which will be greatly determined by embedded software (30%).

About 60% of all product features will depend on embedded digital technologies, with an estimated impact on European employment of about 800,000 jobs in the application industries directly resulting from its development.

The current employment levels in the embedded intelligence market in Europe is estimated to be 9.1 million, of which 1.1 million are jobs in the embedded software area, with €15 billion being expected to be allocated to collaborative European R&D&I projects in technologies for embedded software and beyond.

Model-based and AI-supported technologies will contribute considerably to the mitigation of shortage in software engineering resources, and improve software consistency and quality.



Note: rounded figures. (1): 2025 estimate value potential for the Internet of Things, not the full potential for ECS end-applications.
Source: Decision, IDC, Advancy research & analysis

*Figure 1.3.5 - Global and European value chain 2016–25 (Source: Embedded Intelligence: Trends and Challenges, A Study by Advancy[14], Commissioned by ARTEMIS Industry Association, March 2019).*

## 1.3.6 Major Challenges

Research and innovation in the domain of embedded software and beyond will have to face seven challenges, each generated by the necessity for engineering automation across the entire lifecycle of sustainability, embedded intelligence and trust in embedded software.

- **Major Challenge 1:** Efficient engineering of embedded software.
- **Major Challenge 2:** Continuous integration and deployment.
- **Major Challenge 3:** Lifecycle management.
- **Major Challenge 4:** Embedding data analytics and artificial intelligence.
- **Major Challenge 5:** Support for sustainability by embedded software.
- **Major Challenge 6:** Software reliability and trust.
- **Major Challenge 7:** Hardware virtualization for efficient SW engineering.

### 1.3.6.1 **Major Challenge 1: Efficient engineering of embedded software.**

#### 1.3.6.1.1 State of the art

Embedded software engineering is frequently more a craft than an engineering discipline, which results in inefficient ways of developing embedded software. This is visible, for instance, in the time required for the integration, verification, validation and release of embedded software, which is estimated to exceed 50% of the total R&D&I expenses.

A new set of challenges to engineering embedded software is introduced with the emergence of heterogeneous computing architectures into the mainstream. It will be common for embedded systems to combine several types of accelerators to meet power consumption, performance requirements, safety, and real-time requirements. Development, optimisation, and deployment of software for these computing architectures proves to be challenging. If no solutions are introduced which automatically tailor software to specific accelerators[15,16], developers will be overwhelmed with the required effort.

Software engineering is exceeding the human scale, meaning it can no longer be overseen by a human without supporting tools, in terms of velocity of evolution, and the volume of software to be designed, developed and maintained, as well as its variety and uncertainty of context. Engineers require methods and tools to work smarter, not harder, and need engineering process automation and tools and methods for continuous lifecycle support. To achieve these objectives, we need to address the following practical research challenges: shorter development feedback loops; improved tool-supported software development; empirical and automated software engineering; and safe, secure and dependable software platform ecosystems.

## 1.3.6.1.2 Vision and expected outcome

The demand of embedded software is higher than we can humanly address and deliver, exceeding human scale in terms of evolution speed, volume and variety, as well as in managing complexity. The field of embedded software engineering needs to mature and evolve to address these challenges and satisfy market requirements. In this regard, the following four key aspects must be considered.

### A. From embedded software engineering to cyber physical systems engineering

Developing any high-tech system is, by its very nature, a multi-disciplinary project. There is a whole ecosystem of models (e.g. physical, mechanical, structural, (embedded) software and behavioural) describing various aspects of a system. While many innovations have been achieved in each of the disciplines separately, the entirety still works in silos, each with their own models and tools, and only interfacing at the borders between them. This traditional separation between the hardware and software worlds, and individual disciplines, is hampering the development of new products and services.

Instead of focusing only on the efficiency of embedded software engineering, we already see that the field is evolving into direction of cyber physical systems (cf. Chapter 2.3 **Architecture and Design: Methods and Tools**), and software is one element of engineering. Rather than silos and handovers at the discipline's borders, we expect tools to support the integration of different engineering artefacts and enable, by default, effective development with quality requirements in mind – such as safety, security, reliability, dependability, sustainability, trustworthiness, and interoperability. New methods and tools will need to be developed to further facilitate software interaction with other elements in a system engineering context (cf. c\Chapter 2.3 **Architecture and Design: Methods and Tools**).

Artificial intelligence is a technology that holds a great potential in dealing with large amounts of data, and potentially could be used for understanding complex systems. In this context, artificial intelligence has the potential to automate some daily engineering tasks, moving boundaries of type and size of tasks that are humanly possible in software engineering.

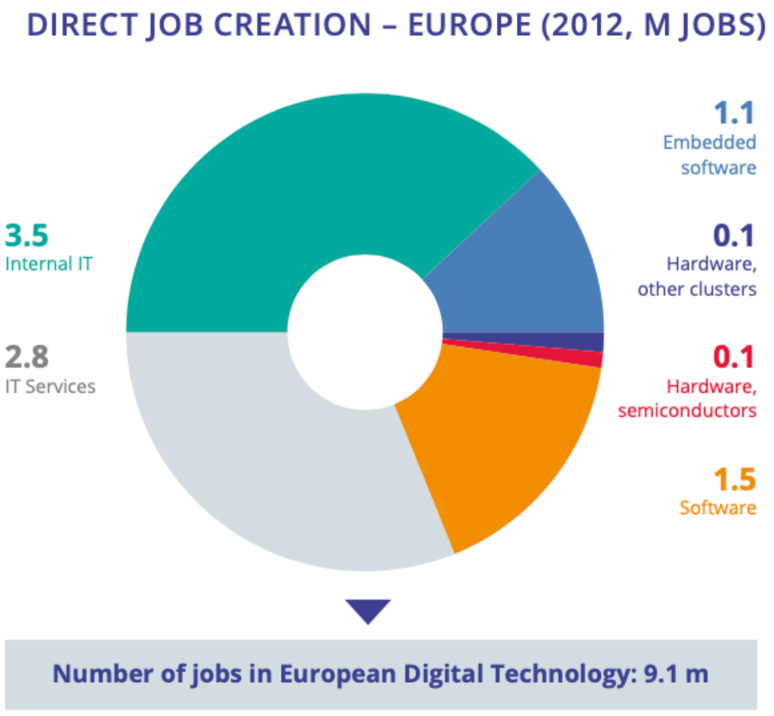


*Figure 1.3.6 - Direct job creation – Europe (2012, m jobs) Source: EU, IDC, Destatis, Roland Berger*

### B. Software architectures for optimal edge computing

At the moment, Edge computing lacks proper definition and, including many different types of managed and unmanaged devices, this leads to uncertainty and difficulties on how to efficiently and effectively use software architectures, including aspects as resource, device, and network management (between edge devices as well between edge and fog/cloud), security, useful abstractions, privacy, security, reliability, and scalability. Additionally, automatic reconfiguration, adaptation and re-use face a number of challenges. These challenges are caused by diversity of edge devices and wide range of requirements in terms of Quality of Service (e.g. low latency, high throughput). In addition, sustainability and reliability are difficult to ensure when trying to prioritize between Quality of Service on the edge and end-to-end system Quality of Service.

Furthermore, the lack of definition also hampers the growing need for energy efficient computing and the development of energy consumption solutions and models across all layers from materials, via software architecture to embedded/application software. Energy efficiency is vital for optimal edge computing.

Lastly, as AI is also moving towards the edge (i.e., Edge AI) defining lightweight models and model architectures that can deal with low amounts of data available on the edge and still provide good model accuracy are desperately needed. Finally, this limits transfer of common solution patterns, best practices, and reference architectures, as Edge computing scope and configuration requires further clarification and classification.

Since edge devices need to be self-contained, edge software architectures need to support, from the one side, virtual machine-like architectures, and from the other side they need to support the entire software lifecycle. The fact that there are many different types of edge devices also requires an interoperability standard to ensure that they can work together. Innovations in this field should focus on, amongst others, software-hardware co-design, virtualisation and container technologies and new standard edge software architecture (middleware).

It is essential to discuss types of quality properties that become more significant as Edge computing is introduced, and based on these, build use cases that profit from quality properties specific to edge computing. There is a need for new approaches that enable early virtual prototyping of edge solutions, as well as approaches that enable verification and validation of quality properties during the entire life cycle of edge software systems. One of the possibilities for profiting from Edge is to focus on digital twins to monitor divergences from expected behaviour and implement logic that will benefit from Edge's low latency when making critical decisions, especially in safety critical software systems.

#### C. Integration of embedded software

To ensure software development is more effective and efficient, it is necessary to place greater focus on integrating embedded software into a fully functional system. First, innovation in continuous system integration must include more effective ways of integrating legacy components into new systems (see also D). Second, for the integration of data and software, the embedded software running in the field has to generate data (such as on run-time performance monitoring, system health, quality of output, compliance to regulations, user interactions) that can be re-used to improve its quality and performance. By improving this, the data and software integration can not only improve the efficiency of embedded software itself, but also the internal coordination and orchestration between components of the system by ensuring a rapid feedback cycle. Third, it is paramount to enable closer integration of software with the available computing accelerators. This must be done in a way that frees developers from additional effort, while at the same time uses the full potential of heterogeneous computing hardware.

#### D. Using abstraction and virtualisation

The recent focus on model-driven (or "low-code") software development has sparked a new approach to managing complexity and engineering software. Generating embedded software from higher-level models can improve maintainability and decrease programming errors, while also improving development speed. However, creating and managing models of real systems with an appropriate level of detail that allows for simulation and code generation is a challenge. Managing models and their variability is a necessity if we want to prevent shifting the code legacy problem to a model legacy problem where there are too many models with too much variety.

The core elements of the domain are captured in a language of the domain. The introduction of domain-specific languages (DSLs) and aspect-oriented languages has allowed for the inclusion of aspects and constructs of a target application domain into the languages used to develop embedded software. This abstraction allows for shortening the gap between software engineers and domain experts. We expect innovations in DSLs and tool support to establish a major boost in the efficiency of embedded software development.

The increased level of abstraction allows for more innovation in virtualisation of systems and is a step towards correctness by construction instead of correctness by validation/testing. Model-based engineering and digital twins of systems are already being used for a variety of goals – such as training, virtual prototyping and log-based fault analysis. Furthermore, they are necessary for supporting the transition towards sustainable ECPS. Innovations in virtualisation will allow DSLs to be (semi-)automatically used to generate digital twins with greater precision and more analysis capabilities, which can help us to explore different hardware and software options before a machine is even built, shortening development feedback loops due to such improved tool-supported software development.

#### D. Resolving legacy

Legacy software and systems still constitute most of the software running in the world today. It is only natural that the amount of legacy software increases in the future. While it is paramount to develop new and improved techniques for the development and maintenance of embedded software, we cannot ignore the systems currently in operation. New software developed with novel paradigms and new tools will not run in isolation, but rather have to be used increasingly in ecosystems of connected hardware and software, including legacy systems.

There are two main areas for innovation here. First, we need to develop efficient ways of improving interoperability between new and old. With years of development, and a need to continue operations, we will have to depend on legacy software for the foreseeable future. It is therefore imperative to develop new approaches to facilitating reliable and safe interactions, including wrapping old code in re-usable containers. Second, we must innovate the process to (incrementally) migrate, rejuvenate, redevelop and redeploy legacy software, both in isolation and as part of a larger system. We expect innovations in these areas to increase efficiency and effectiveness in working with legacy software in embedded software engineering.

### 1.3.6.1.3 Key focus areas

The key focus areas in the domain of efficient embedded software engineering include the following.

There is a strong relation between Major Challenges 1, 2, 3, and 6 below, and Chapter 2.3 "Architectures and Design: Methods and Tools", specifically Major Challenges 1 and 2.

- Model-based software engineering:
  - Model-based software engineering enabling systems to become part of SoS.
  - Model inference to enable re-use, refactoring and evolution of existing subsystems in SoS.
  - Model-based testing that takes the re-use of uncontrolled systems into account.
  - Embedded software architectures to facilitate building SoS.
- Digital twinning:
  - Virtualisation as a means for dealing with legacy systems.
  - Virtualisation and virtual integration testing (using Digital Twins and specialized design methods, like, e.g. contract based design, for guaranteeing safe and secure updates (cf. Architecture and Design: Methods and Tools Chapter 2.3).
  - Approaches to reduce re-release/re-certification time, e.g. model-based design, contract-based design, and modular architectures.
  - Distinct core system versus applications and services.
  - Design for X (e.g design for test, evolvability and updateability, diagnostability, and adaptability).
- Constraint environments:
  - Knowledge-based leadership in design and engineering.
  - Resource planning and scheduling (including multi-criticality, heterogeneous platforms, multicore, software portability).
  - Simulation and Design for software evolution over time, while catering for distinct phases.
  - Exploiting hybrid compute platforms, including efficient software portability.
- Software technology:
  - Virtualisation as a tool for efficient engineering.
  - Interface management enabling systems to become part of SoS.
  - Technology for safe and dependable software ecosystems.
  - Artificial intelligence-based tools to support software engineering, software production and testing efforts.
  - Co-simulation platforms.
- SW engineering tools:
  - Integrating embedded AI in software architecture and design.
  - Programming languages for developing large-scale applications for embedded systems.
  - Models & digital twins, also at run-time for maintainablility and sustainability.
  - Programming models, compilers, code generators, and frameworks for optimal use of heterogeneous computing platforms.
  - Co-simulation platforms.
  - Tools, middleware and (open) hardware with permissible open-source licenses.

## 1.3.6.2 **Major Challenge 2: Continuous integration and deployment**

### 1.3.6.2.1 State of the art

It is fair to assume that most future software applications will be developed to function as part of a certain platform, and not as stand-alone components. In some embedded system domains, this idea has been a reality for a decade (e.g. in the AUTomotive Open System Architecture (AUTOSAR) partnership, which was formed in 2003). Increasingly the platforms have to support SoS and IoT integration and orchestration, involving a large amount of diverse small devices. Guaranteeing quality properties of software (e.g. safety and security) is a challenging task, and one that only becomes more complex as the size and distribution of software applications grow, especially if software is not properly designed for its intended operational context (cf. Chapter 2.3 Architecture and Design: Methods and Tools). Although we are aiming towards continuous integration on the level of IoT and SoS, we are still struggling with the integration of code changes from multiple contributors into a single software system.

One aspect of the problem relates to the design of SoS[17], which are assumed to be composed of independent subsystems but over time have become dependent. Orchestration between the different subsystems, that may involve IoT as well, is an additional issue here. Another aspect relates to the certification of such systems that requires a set of standards. This applies especially for IoT and SoS and it is complicated by the introduction of AI into software systems. Although AI is a software-enabled technology, there are still many issues on the system level when it comes to its integration into software systems. It is particularly challenging to ensure their functional safety and security, and thus to certify such systems. Some of the existing initiatives include, e.g. for vehicles, ISO 21448 (Road Vehicles – Safety Of The Intended Functionality (SOTIF)), ISO/TR 4804 (followed by ISO/AWI TS 5083, currently in development), ANSI/UL 4600 Standard for Safety for the Evaluation of Autonomous Products, and SAE J3016, which recommends a taxonomy and definitions for terms related to automated driving. Note, that AI may be applied as an engineering tool to simplify certification.

Finally, integration and delivery practices are part of the engineering processes. Although methodologies already exist to achieve this (such as DevSecOps and ChatOps), these mostly relate to software production. With ECPS, continuous integration becomes increasingly more complex due to the wide range of hardware architectures and platforms, each with its own unique characteristics. Continuous integration must account for this diversity, requiring cross-compilation and testing on various target devices. Continuous delivery must deal with the fact that the products into which the new software modules have to be delivered are already sold and 'working in the field', often in many different variants (i.e. the whole car fleet of an OEM). Even in domains where the number of variant systems is small, retaining a copy of each system sold at the producing company in order to have a reference target is prohibitive. Thus, virtual integration using model-based design methods (including closed-box models for legacy components) and digital twins used as integration targets as well as for verification & validation by physically accurate simulation are a mandatory asset for any system company to manage the complexity of ECPS and their quality properties. System engineering employing model-based design and digital twins must become a regular new engineering activity.

## 1.3.6.2.2 Vision and expected outcome

Europe is facing a great challenge with the lack of platforms that are able to adopt embedded applications developed by individual providers into an ecosystem (cf. Reference Architectures and Platforms in Chapter 2.3). The main challenges here are to ensure the adequate functionality of integrated systems (which is partially solved by the micro-services approach), while ensuring key quality properties such as performance, safety, and security (see also Major Challenge 6), which is becoming increasingly complex and neglected as we adopt approaches that facilitate only integration on the functional level. Instrumental for these challenges is the use of integration and orchestration platforms that standardise many of the concerns of the different parts in the SoS, some of which are connected via IoT. In addition, Automated engineering processes such as CI/CD will be crucial to adapt. The primary DevOps methodology needs to be adjusted for the ECPS. For example, CI pipelines will enable toolchain selection configuration for cross-compiling, or they will include real-time testing and validation, which can be more challenging to automate and verify. Integrating automated tests for hardware interactions can be complex and require specialized hardware-in-the-loop (HIL) testing setups.

ECPS will become a part of an SoS and eventually SoECPS. SoS challenges like interoperability, composability, evolvability, control, management and engineering demand ECPS to be prepared for a life as a part of a SoS (cf. Chapter 1.4 System of systems). Thus, precautions at individual ECPS's are necessary to enable cost efficient and trustworthy integration into SoS.

Therefore, it is essential to tackle these challenges by good engineering practices: (i) providing sets of recommended code and (system to system) interaction patterns; (ii) avoiding anti-patterns; and (iii) ensuring there is a methodology to support the integration from which the engineers of such systems can benefit. This implies aiming to resolve and pre-empt as many as possible of the integration and orchestration challenges at the platform design level. It also involves distribution of concerns to the sub systems in the SoS or IoT. Followed by automated engineering processes applying the patterns and dealing with the concerns in standardised ways. Besides this, it is necessary to facilitate communication between different stakeholders to emphasise the need for quality properties of ECPS, and to enable (automated) mechanisms that raise concerns sufficiently early to be prevented, while minimising potential losses.

On the development level, it is key to enhance the existing software systems development methodologies to support automatic engineering, also to automate the validation and verification processes for new features as they are being introduced into the system. This might need the use of AI in the validation and verification process. At this level, it is also necessary to use software system architectures in the automation of verification and other engineering practices, to manage the complexity that arises from such integration efforts (also see Major Challenge 3 below).

**Artificial Intelligence and Machine Learning**

Progress in AI keeps being fast-paced. While typical ECPS-needs such as Computer Vision are dominated by AI since quite some time, recent progress in Large Language Models (LLMs) opened the door to serious AI-assisted engineering tools. Hence, AI is on the way to becoming an important tool for the engineering of Embedded Software, while being an essential part of Embedded Software at the same time.

**AI in Embedded Software.** Simply speaking, AI lets us implement functions we don't need to understand as they are learned automatically. This has advantages and drawbacks. We take advantage of this property in tiny sensors, where AI (e.g. TinyML) automatically approximates a mapping of property changes of some material to a measurement value, in prediction, control or virtual sensing, where AI has learned to interpret time series, images, or other forms of data, and many other tasks, including detection and tracking of objects. AI functions can also serve as (automated) abstractions. With this versatility, wide-spread adoption, and a potential non-understanding of what was learned, come challenges like fitting the AI functionality to the available resources (cf. RISC-V with research on AI accelerators), testability / explainability / trustworthiness / integration in safety critical applications, real-time performance, updateability / continuous learning / maintainability, and more. In general, AI in Embedded Software faces all the same challenges standard Embedded Software has, some in a more demanding form of course. For example, using sub-symbolic AI in a safety-critical context is without a clear-cut solution regarding the trustworthiness issues. To compensate for these, extensive monitoring, and the implementation of certain architectures (e.g. Simplex) might be necessary. This shows that relying on AI in a system will have a big impact on the system design. Relying on AI will also have a massive impact on verification planning and software engineering as, e.g. proper training and validation data sets need to be provided.

**AI for Embedded Software engineering.** Software engineering is the discipline of building software in a proper way. AI can help with that, and AI functionality has been explored in tools for software engineering for some time. However, up to now AI-algorithms were mostly used in tools for verification (automated test case generation, checking) and less so in others. Recent developments in LLMs demonstrate the huge potential for using AI in areas like model or code generation from natural language, refactoring or "rejuvenation" of legacy software, porting software while preserving investment, or automatically adapting software to different settings/platforms. Like before, the major challenge is that there is no guarantee on the correctness or fit-for-purpose on the output of these LLMs, which is a major research opportunity at the same time. In future, AI is likely to replace many of the software-coding activities done by engineers today. Also, domain specific models will speed-up software design & generation by a considerable amount, and AI will support engineers in system understanding and in mastering complexity.

Summing up, AI hasn't yet shown its full potential for the use in and around Embedded Software – there are still many challenges left as demanding research topics. However, based on the current state-of-art and results, it is clear that AI will be a core part of future Embedded Software and ECPS.

The RISC-V instruction set architecture (ISA) is the fifth version of the Berkeley ISA that has seen exponential commercial and academic adoption in the last 10 years thanks to its open-source nature, as well as its modularity, extendibility, and simple architecture. Many commercial users adopt RISC-V in their System-On-Chips, from both open-source repositories (where the Register-Transfer-Level description of the RISC-V CPU is published), or from closed-source IP vendors. The increase in silicon devices together with the need for digital sovereignty caused many national and international organizations to take action, and RISC-V is a main actor of this revolution. For example, the European Commission[18] is building an open-source ecosystem to expand its innovation on RISC-V to compete with existing commercial alternatives, covering hardware design and system-on-chips, all the way to electronic design automation tools and the full software stack. In this scenario, OpenHW Group[19] and the Eclipse Foundation[20] play a key role in developing open-source, high-quality, silicon-proven RISC-V IPs under a permissive license. Both the not-for-profit foundations are driven by their members, who invested in RISC-V and open-source-based System-On-Chip. The modularity and extendability of the RISC-V ISA allow users to design their own architecture to meet the ultra-low-power and energy-efficient edge-computing devices constraints, as well as high-performance server machines requirements. For example, the "RVV RISC-V Vector" ISA extension allows to process multiple data concurrently, or custom extensions for security to encrypt data more efficiently. For this reason, it is crucial to have a holistic software stack to cope with the wide range of applications, taking into account the deployment of efficient applications leveraging the different ISA extensions and computer architectures.

#### 1.3.6.2.3 Key focus areas

The key focus areas identified for this challenge include the following:

- Continuous integration of embedded software:
  - Model based design and digital twins to support system integration (HW/SW) and HW/SW co-development (increasingly new technologies have to be integrated).
  - Applying automation of engineering, taking architecture, platforms and models into account.
  - Virtualisation and simulation as tools for managing efficient integration and validation of configurations, especially for shared resources and other dependability issues.
  - Application of integration and orchestration practices to ensure standard solutions to common integration problems.
  - Integration and orchestration platforms and separation of concerns in SoS and IoT.
  - Enabling reliable and safe continuous SW delivery to already working devices.
- Verification and validation of embedded software:
  - (Model) test automation to ensure efficient and continuous integration of CPSs.
  - Enabling secure and safe updates (cf. Major Challenge 3) and extending useful life (DevOps).
  - Continuous integration, verification and validation (with and without AI) enabling continuous certification with automated verification & validation (especially the focus on dependability), using model-based design technologies and digital twins; also when SoS and IoT are involved.
  - Certification of safety-critical software in CPSs.

### 1.3.6.3 Major Challenge 3: Lifecycle management

#### 1.3.6.3.1 State of the art

Complex systems such as airplanes, cars and medical equipment are expected to have a long lifetime, often up to 30 years. The cost of keeping these embedded systems up to date, making them relevant for the everyday challenges of their environment is often time-consuming and costly. This is becoming more complex due to the fact that most of these systems are cyber-physical systems, meaning that they link the physical world with the digital world, and are often interconnected with each other or to the internet. With more and more functionalities being realized by embedded software, over-the-air updates – i.e. deploying new, improved versions of software-modules unto systems in the field – become an increasingly relevant topic. Apart from updates needed for error and fault corrections, performance increases and even the implementation of additional functionalities – both optional or variant functionalities that can be sold as part of end-user adaptation as well as completely new functionalities that are needed to respond to newly emerging environmental constraints (e.g. new regulations, new features of cooperating systems). Such update capabilities perfectly fit and even are required for the 'continuous development and integration' paradigm.

Embedded software also has to be maintained and adapted over time, to fit new product variants or even new product generations and enable updateability of legacy systems. If this is not effectively achieved, the software becomes overly complex, with prohibitively expensive maintenance and evolution, until systems powered by such software are no longer sustainable. We must break this vicious cycle and find new ways to create software that is long-lasting and which can be cost-efficiently evolved and migrated to use new technologies. Practical challenges that require significant research in software sustainability include: (i) organisations losing control over software; (ii) difficulty in coping with modern software's continuous and unpredictable changes; (iii) dependency of software sustainability on factors that are not purely technical; (iv) enabling "write code once and run it anywhere" paradigm.

## 1.3.6.3.2 Vision and expected outcome

As software complexity increases, it becomes more difficult for organisations to understand which parts of their software are worth maintaining and which need to be redeveloped from scratch. Therefore, we need methods to reduce the complexity of the software that is worth maintaining, and extracting domain knowledge from existing systems as part of the redevelopment effort. This also relates to our inability to monitor and predict when software quality is degrading, and to accurately estimate the costs of repairing it. Consequently, sustainability of the software is often an afterthought. This needs to be flipped around – i.e. we need to design "future-proof" software that can be changed efficiently and effectively, or at least platforms for running software need to either enable this or force such way of thinking.

As (embedded) software systems evolve towards distributed computing, SoS and microservice-based architectural paradigms, it becomes even more important to tackle the challenges of integration at the higher abstraction levels and in a systematic way. Especially when SoS or IoT is involved, it is important to be able to separate the concerns over the subsystems.

The ability of updating systems in the field in a way that safety of the updated systems as well as security of the deployment process is maintained will be instrumental for market success of future ECPS. Edge-to-cloud continuum represents an opportunity to create software engineering approaches and engineer platforms that together enable deployment and execution of the same code anywhere on this computing continuum.

The ability of keeping track of system parameters like interface contracts and composability requires a framework to manage these parameters over the lifetime. This will enable the owner of the system to identify at any time how the system is composed and with what functionality.

Instead of focusing just on the efficiency of embedded software engineering, we already see that the field is evolving into the direction of cyber physical systems (cf. Chapter 2.3 **Architecture and Design: Methods and Tools**), and software is one element of engineering.

Many software maintenance problems are not actually technical but people problems. There are several socio-technical aspects that can help, or hinder, software change. We need to be able to organise the development teams (e.g. groups, open source communities) in such a way that it embraces change and facilitates maintenance and evolution, not only immediately after the deployment of the software but for any moment in the software lifecycle, for the decades that follow, to ensure continuity. We need platforms that are able to run code created for different deployment infrastructures, without manual configuration.

The expected outcome is that we are able to keep embedded systems relevant and sustainable across their complete lifecycle, and to maintain, update and upgrade embedded systems in a safe and secure, yet cost-effective way.

## 1.3.6.3.3 Key focus areas

The key focus areas identified for this challenge include the following.

- Rejuvenation of systems:
    - Software legacy and software rejuvenation to remove technical debt (e.g. software understanding and conformance checking, automatic redesign and transformation).
    - Continuous platform-agnostic integration, deployment and migration.
    - End-of-life and evolving off-the-shelve/open source (hardware/software).
- Managing complexity over time:
    - Interplay between legacy software and new development approaches.

    - Vulnerability of connected systems.
    - Continuous certification of updates in the field (reduce throughput time).
    - Intelligent Diagnostics of systems in the field (e.g. guided root cause analysis).
- Managing configurations over time:
    - Enable tracking system configurations over time.
    - Create a framework to manage properties like composability and system orchestration.
- Evolvability of embedded software:
    - Technology, including automation of engineering and the application of integration and orchestration platforms, for keeping systems maintainable, adaptable and sustainable considering embedded constraints with respect to resources, timing and cost.
    - Embedded software architectures to enable SoS.

### 1.3.6.4 **Major Challenge 4: Embedding Data Analytics and Artificial Intelligence**

#### 1.3.6.4.1 State of the art

For various reasons – including privacy, energy efficiency, latency and embedded intelligence – processing is moving towards edge computing, and the software stacks of embedded systems need to support more and more analysis of data captured by the local sensors and to perform AI-related tasks. As detailed in the Chapter “Edge Computing and Embedded Artificial Intelligence”, non-functional constraints of embedded systems, such as timing, energy consumption, low memory and computing footprint, being tamperproof, etc., need to be taken into account compared to software with similar functionalities when migrating these from cloud to edge. Furthermore, the Quality, Reliability, Safety and Security Chapter states that key quality properties when embedding of AI components in digitalized ubiquitous systems are determinism, understanding of nominal and degraded behaviours of the system, their certification and qualification, and clear liability and responsibility chains in the case of accidents. When engineering software that contains AI-based solutions, it is important to understand the challenges that such solutions introduce. AI contributes to challenges of embedded software, but itself it does not define them exclusively, as quality properties of embedded software depend on integration of AI-based components with other software components.

For efficiency reasons, very intensive computing tasks (such as those based on deep neural networks, DNNs) are being carried out by various accelerators embedded in systems on a chip (SoCs). Although the “learning” phase of a DNN is still mainly done on big servers using graphics processing units (GPUs), local adaptation is moving to edge devices. Alternative approaches, such as federated learning, allow for several edge devices to collaborate in a more global learning task. Therefore, the need for computing and storage is ever-increasing, and is reliant on efficient software support.

The “inference” phase (i.e. the use after learning) is also requiring more and more resources because neural networks are growing in complexity exponentially. Once carried out in embedded GPUs, this phase is now increasingly performed on dedicated accelerators. Most middle and high-end smartphones have SoCs embedding one of several AI accelerators – for example, the Nvidia Jetson Xavier NX is composed of six Arm central processing units (CPUs), two inference accelerators, 48 tensor cores and 384 Cuda cores. Obtaining the best of the heterogeneous hardware is a challenge for the software, and the developers should not have to be concerned about where the various parts of their application are running.

Once developed (on servers), a neural network has to be tuned for its embedded target by pruning the network topology using less precision for operations (from floating point down to 1-bit coding) while preserving accuracy. This was not a concern for the “big” AI development environment providers (e.g. Tensorflow, PyTorch, Caffe2, Cognitive Toolkit) until recently. This has led to the development of environments designed to optimise neural networks for embedded architectures[21] to move towards the Edge.

Most of the time the learning is done on the cloud. For some applications/domains, making a live update of the DNN characteristics is a sought-after feature, including all the risks of security, interception. Imagine the consequences of tampering with the DNN used for a self-driving car! A side-effect of DNN is that intellectual property is not in a code or algorithm, but rather lies in the network topology and its weights, and therefore needs to be protected.

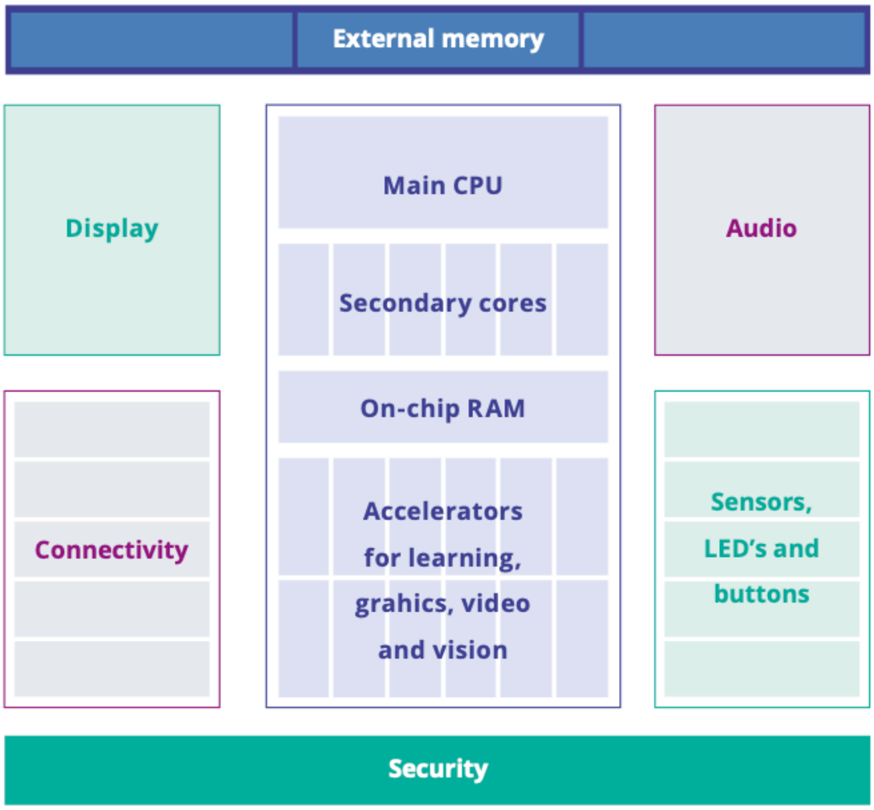


*Figure 1.3.7 - Data analytics and Artificial Intelligence require dedicated embedded hardware architectures*

## 1.3.6.4.2 Vision and expected outcome

European semiconductor providers lead a consolidated market of microcontroller and low-end microprocessor for embedded systems, but are increasing the performance of their hardware, mainly driven by the automotive market and the increasing demand for more performing AI for advanced driver-assistance systems (ADAS) and self- driving vehicles. They are also moving towards greater heterogeneity by adding specialised accelerators. On top of this, Quality, Reliability, Safety and Security Chapter lists personalization of mass products and resilience to cyber-attacks, as the key advantage and the challenge characterizing future products. Embedded software needs to consider these and find methods and tools to manage their effects on quality properties of software that integrates them. Also, embedded software engineering will need to ensure interoperability between AI-based solutions and non-AI parts.

In this context, there is a need to provide a programming environment and libraries for the software developers. A good example here is the interchange format ONNX, an encryption format for protection against tampering or reverse engineering that could become the foundation of a European standard. Beside this, we also need efficient libraries for signal/image processing for feeding data and learning into the neural network, abstracting from the different hardware architectures. These solutions are required to be integrated and embedded in ECPS, along with significant effort into research and innovation in embedded software.

## 1.3.6.4.3 Key focus areas

The key focus areas identified for this challenge include the following.

- Federated and distributed learning:
  - Create federated learning at the edge in heterogeneous distributed systems (analysis, modelling and information gathering based on local available information).
  - Federated intelligence at the edge (provide context information and dependability based on federated knowledge).
- Embedded Intelligence:
  - Create a software AI framework to enable reflecting and acting on the systems own state.
  - Dynamic adaption of systems when environment parameters and sensors like IoT devices are changing.

- Data streaming in constraint environments:
    - Feed streaming data into low-latency analysis and knowledge generation (using context data to generate relevant context information).
- Embedding AI accelerators:
    - Accelerators and hardware/software co-design to speed up analysis and learning (e.g. patter analysis, detection of moves (2D and 3D) and trends, lighting conditions, shadows).
    - Actual usage-based learning applied to accelerators and hardware/software co-design (automatic adaptation of parameters, adaptation of dispatch strategies, or use for new accelerators for future system upgrades).

### 1.3.6.5 **Major Challenge 5: Support for sustainability by embedded software**

#### 1.3.6.5.1 State of the art

The complete power demand in the whole ICT market currently accounts from 5% to 9% of the global power consumption[22]. The ICT electricity demand is rapidly increasing and it could go up to nearly 20% in 2030. Compared to estimated power consumption of future large data centres, embedded devices may seem to be a minor problem. However, when the devices are powered by batteries, they still have a significant environmental impact. Energy efficient embedded devices produce less hazardous waste and last longer without the need for replacement.

The growing demand for ultra-low power electronic systems has motivated research into device technology and hardware design techniques. Experimental studies have proven that the hardware innovations for power reduction can be fully exploited only with proper design of the upper layer software. The same applies to software power and energy modelling and analysis: the first step towards the energy reduction is complex due to the inter- and intra-dependencies of processors, operating systems, application software, programming languages and compilers. Software design and implementation should be viewed from a system energy conservation angle rather than as an isolated process.

For sustainability, it is critical to understand quality properties of software. These include in the first place power consumption, and then other related properties (performance, safety, security, and engineering-related effort) that we can observe in the context of outdated or inadequate software solutions and indicators of defected hardware. Power reduction strategies are mainly focusing on processing, storage, communication, and sometimes on other (less intelligent) equipment.

For the future embedded software developers, it is crucial to keep in touch with software development methodologies focused on sustainability, such as green computing movement or sustainable programming techniques. In the domain of embedded software, examples include the estimation of the remaining useful life of the device, the network traffic and latency time optimization, the process scheduling optimization or energy efficient workload distribution.

#### 1.3.6.5.2 Vision and expected outcome

The concept of sustainability is based on three main principles: the ecological, the economical and the social. The ideal environmentally sustainable (or green) software in general requires as little hardware as possible, it is efficient in power consumption, and its usage leads to minimal waste production. Embedded software designed to be adaptable for future requirements without the need to be replaced by a completely new product is an example of environmentally, economically, and socially sustainable software.

To reach the sustainability goal, the embedded software design shall focus also on energy-efficient design methodologies and tools, energy efficient and sustainable techniques for embedded software and systems production and to the development of energy aware applications and frameworks for the IoT, wearable computing or smart solutions or other application domains.

It is evident that energy/power management has to be analysed with reference to the context, underlying hardware and overall system functionalities. The coordinated and concentrated efforts of a system architect, hardware architect and software architect should help introduce energy-efficient systems (cf. Chapter 2.3, Architecture and Design: Methods and Tools). The tight interplay between energy-oriented hardware, energy-aware and resource-aware software calls for innovative structural, functional and mathematical models for analysis, design and run-time. Model-based software engineering practices, supported by appropriate tools, will definitely accelerate the development of modern complex systems operating under severe energy constraints. It is crucial to notice the relationship between power management and other quality properties of software systems (e.g. under certain circumstances it is adequate to reduce the functionality of software systems by disabling certain features, which results in significant power savings). From a complementary perspective, when software is aware of the available hardware and energy resources, it enables power consumption optimisation and energy saving, being able to configure the hardware resources, to activate/deactivate specific hardware components, increase/decrease the CPU frequency according to the processing requirements, partition, schedule and distribute tasks.

Therefore, in order to enable and support sustainability through software, software solutions need to be reconfigurable in the means of their quality. There have to exist strategies for HW/SW co-design and accelerators to enable such configurations. For this to be possible, software systems need to be accompanied with models of their quality properties and their behaviour, including the relationship between power consumption and other high level quality properties. This will enable balancing mechanisms between local and remote computations to reduce communication and processing energy.

Models (digital twins) should be aware of energy use, energy sources and the sustainability of the different sources. An example of this in SoS are solar cells that give different amounts of energy dependent on time of day and weather conditions.

#### 1.3.6.5.3 Key focus areas

The following key focus areas have been identified for this challenge:

- Resource-aware software engineering.
- Tools and techniques enabling the energy-efficient and sustainable embedded software design.
- Development of energy-aware and sustainable frameworks and libraries for the main embedded software application areas (e.g. IoT, Smart Industry, Wearables).
- Management of computation power on embedded hardware:
    - Management of energy awareness of embedded hardware, embedded software with respect to, amongst others, embedded high-performance computing (HPC).
- Composable efficient abstractions that drive sustainable solutions while optimising performance:
    - Enabling technologies for the second life of (legacy) cyber-physical systems.
    - Establish relationships between power consumption and other quality properties of software systems, including engineering effort (especially in cases of computing-demanding simulations).
    - Digital twins can contribute in management quality properties of software systems with the goal of reducing power consumption, as the major contributing factor to the green deal, enabling sustainability.

### 1.3.6 **Major Challenge 6: Software reliability and trust**

#### 1.3.6.6.1 State of the art

Two emerging challenges for reliability and trust in ECPS relate to computing architectures and the dynamic environment in which ECPS exist. The first challenge is closely related to the end of Dennard scaling[23]. In the current computing era, concurrent execution of software tasks is the main driving force behind the performance of processors, leading to the rise of multicore and manycore computing architectures. As the number of transistors on a chip continues to increase (Moore's law is still alive), industry has turned to a heavier coupling of software with adequate computing hardware, leading to heterogeneous architectures. The reasons for this coupling are the effects of dark silicon[24] and better performance-to-power ratio of heterogeneous hardware with computing units specialised for specific tasks. The main challenges for using concurrent computing systems in embedded systems remain: (i) hard-to-predict, worst-case execution time; and (ii) testing of concurrent software against concurrency bugs[25].

The second challenge relates to the dynamic environment in which ECPS execute. On the level of systems and SoS, architectural trends point towards platform-based designs – i.e. applications that are built on top of existing (integration and/or middleware) platforms. Providing a standardised "programming interface" but supporting a number of constituent subsystems that is not necessarily known at design time, and embedding reliability and trust into such designs, is a challenge that can be solved only for very specialised cases. The fact that such platforms – at least on a SoS level – are often distributed further increases this challenge.

On the level of systems composed from embedded devices, the most important topics are the safety, security, and privacy of sensitive data. Security challenges involve: (i) security of communication protocols between embedded nodes, and the security aspects on the lower abstraction layers; (ii) security vulnerabilities introduced by a compiler[26] or reliance on third-party software modules; and (iii) hardware-related security issues[27]. It is necessary to observe security, privacy and reliability as quality properties of systems, and to resolve these issues on a higher abstraction level by design[28], supported by appropriate engineering processes including verification (see Chapters 2.3 and 2.4).

#### 1.3.6.6.2 Vision and expected outcome

European industry today relies on developed frameworks that facilitate production of highly complex embedded systems (for example, AUTOSAR in the automotive industry).

The ambition here is to reach a point where such software system platforms are mature and available to a wider audience. These platforms need to enable faster harvesting of hardware computing architectures that already exist and provide abstractions enabling innovators and start-ups to build new products quickly on top of them. For established businesses, these platforms need to enable shorter development cycles while ensuring their reliability and providing means for verification & validation of complex systems. The purpose of building on top of these platforms is ensuring, by default, a certain degree of trust for resulting products. This especially relates to new concurrent computing platforms, which hold promise of great performance with optimised power consumption.

Besides frameworks and platforms that enable easy and quick development of future products, the key enabler of embedded software systems is their interoperability and openness. In this regard, the goal is to develop and make software libraries, software frameworks and reference architectures which need to ensure, by design, the potential for monitoring, verifying, testing and auto-recovering of embedded systems. That enables interoperability and integration of products developed on distributed computing architectures available to a wider audience. One of the emerging trends to help achieving this is the use of digital twins. Digital twins are particularly suitable for the verification of safety-critical software systems that operate in dynamic environments. However, development of digital twins remains an expensive and complex process, which has to be improved and integrated as part of the standard engineering processes (see Major Challenge 2 in Chapter 2.3).

We envision an open marketplace for software frameworks, middleware, and digital twins that represents a backbone for the future development of products. While such artefacts need to exploit the existing software stacks and hardware, they also need to support correct and high-quality software by design. Special attention is required for Digital Twin simulations of IoT devices to ensure reliability and trust in operating in real life.

### 1.3.6.6.3 Key focus areas

Focus areas of this challenge are related to quality aspects of software. For targets such as new computing architectures and platforms, it is crucial to provide methodologies for development and testing, as well as for the team development of such software. These methodologies need to take into account the properties, potentials and limitations of such target systems, and support developers in designing, analysing and testing their implementations. As it is fair to expect that not all parts of software will be available for testing at the same time, it is necessary to replace some of the concurrently executing models using simulation technologies. Finally, these achievements need to be provided as commonly available software modules that facilitate the development and testing of concurrent software.

The next focus area is testing of systems against unexpected uses, which mainly occurs in systems with a dynamic execution environment. It is important here to focus on testing of self-adapting systems where one of the predominant tools is the simulation approach, and more recently the use of digital twins.

However, all these techniques are not very helpful if the systems are not secure and reliable by design. Therefore, it is necessary to investigate platforms towards reliability, security and privacy, with the following challenges.

- Reliable software on new hardware including edge, fog and cloud processing: (co) verification of distributed, also heterogenous systems.
- Verification and validation of ML models.
- Robustness against unexpected uses:
  - Trustworthy, secure, safe, privacy-aware.
  - Validating self-adapting systems for example through simulation.
- Security and privacy as a service:
  - To become part of the software architecture.
  - Means and techniques for continuous system monitoring and self-monitoring.

## 1.3.6.7 Major Challenge 7: Hardware virtualization for efficient SW engineering

### 1.3.6.7.1 State of the art

Hardware virtualisation provides efficient abstraction from the physical hardware, thus allowing to decouple software engineering lifecycles from the underlying hardware. This is usually implemented either by full-scale hypervisors like VMware and KVM, or via containerisation as combination with the hosting operating system, e.g. Docker and Kubernetes. It enhances efficiency through resource isolation and allocation, and eases deployment by offering lightweight, portable, and scalable software packaging. Additionally, hardware-assisted virtualisation extensions such as Intel VT-x and AMD-V have improved performance and security by offloading virtualisation tasks to the hardware.

Hardware virtualisation is expected to offer numerous benefits, including increased flexibility, portability, and security for safety-critical and non-safety-critical applications.

### 1.3.6.7.2 Vision and expected outcome

- **Standardized Abstraction Models** for hardware components to enable cross-platform compatibility, fostering ease of development and integration.
- **Timing Models**: Developing state-of-the-art timing models to predict and verify real-time behaviour accurately.
- Unified **APIs** for different hardware components to promote interoperability.
- **Performant run-time environments** supporting shared memory access control, leveraging hypervisor technologies like XEN and KVM, as well as Bytecode/WebAssembly technologies.

- Virtualisation of communication (**Virtual Networks**) supporting Quality of Service (QoS) mechanisms to guarantee real-time communication in mixed-criticality environments.
- Hardware Abstraction for **Sensors and Actuators**, to achieve their interchangeability.

### 1.3.6.7.3 Key focus areas

To realize the potential of hardware virtualisation, research and development will focus on three aspects.

- Standard development methods and frameworks for the development of hardware abstractions, integrated with existing tools.
- Verification and validation frameworks, supported by automation, which allow for the validation of applications within virtualisation, as well as the validation of specific target systems, to confirm performance and timeliness.
- Run-time environments for safety-critical applications.

## 1.3.7 Timeline

The following table illustrates the roadmaps for Embedded Software and Beyond. The assumption is that on the topics listed, that technology should be ready (TRL 8–9) in the respective time-frames.

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024-2028) | MEDIUM TERM (2029-2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Efficient engineering of embedded software** | **Topic 1.1**: Modelling-based software engineering | Model-based software engineering enabling systems to become part of SoS | Model inference to enable re-use of existing subsystems in SoS | Model-based testing taking re-use of uncontrolled SoS into account |
| | **Topic 1.2** Digital twinning | Virtualisation of legacy systems | support virtual integration testing across variants | Support/allow (re)certification of systems via digital twins |
| | **Topic 1.3:** Constraint environments | Resource planning and scheduling<br>Design for software evolution over time | Embedded software architectures to enable SoS | Exploiting hybrid computer platforms, including efficient software portability |
| | **Topic 1.4:** Software technology | Virtualisation as tool for efficient engineering<br>Technology for safe and dependable software ecosystems | Interface management enabling systems to become part of SoS | Develop new software architectures for edge computing<br>Artificial intelligence to assist and support efforts in software engineering |
| | **Topic 1.5:** Software engineering tools | Co-simulation platforms | Middleware controlling dynamically embedded (mobile) hardware solutions<br>Compilers and link to new hardware | Programming languages for developing large-scale applications for embedded SoS |
| **Major Challenge 2:**<br>**Continuous integration and deployment** | **Topic 2.1:** Continuous integration | DevOps modelling<br>Virtualisation | Simulation on a virtual platform | Digital twin<br>Model-based engineering based on digital twins |
| | **Topic 2.2:** Verification and validation | Virtualisation of test platform | Model-based testing | Integration & orchestration platforms for IoT and SoS |
| **Major Challenge 3:**<br>**Life-cycle management of embedded software** | **Topic 3.1**: Rejuvenation of existing systems | Software legacy and software rejuvenation<br>Design for rejuvenating systems in a later phase | End-of-life and evolving off-the-shelve/open- source solutions | The cloud-for-edge continuum - “Write once, run anywhere” on this computing continuum<br>Composability, properties contracts and orchestration systems<br>Interoperability: must be ensured in integration platforms |
| | **Topic 3.2:** Managing complexity over time | Diagnostics of systems in the field | Continuous certification | Interplay between legacy |
| | **Topic 3.3:** Managing Configurations over time | Full life-cycle configuration tacking | Methods and tools managing composability and system orchestration | Individualized systems configuration management |
| | **Topic 3.4:** Evolvability of embedded software | Adaptable embedded software | Dynamical embedded software | Autonomous embedded software<br>Autonomous processes (IoT & edge embedded HW/SW co-design) |
| **Major Challenge 4:**<br>**Embedding data analytics and AI** | **Topic 4.1:** Federated learning | Create federated learning at the edge in heterogeneous distributed systems | Federated intelligence at the edge | Safe, trustworthy & explainable AI<br>AI is playing several key roles in innovation, e.g. as a tool for SW development/engineering<br>Embedded intelligence |
| | **Topic 4.2** Embedded Intelligence | Self-reflection: software AI framework supports acting on own system state | OS support for new HW (GPU, ASIC, neuromorphic computing ,…) and platforms (EdgeAI,..) | Support dynamic adaption of systems |
| | **Topic 4.3:** Data streaming in constraint environments | Feed streaming data into low-latency analysis and knowledge generation | Support processing by new HW (GPU, ASIC,…) | |
| | **Topic 4.4:** Embedding AI accelerators | Accelerators and hardware/software co-design to | Actual usage- based learning applied for accelerators and | Use of AI in autonomous systems |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024-2028) | MEDIUM TERM (2029-2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| | | speed up analysis and learning | hardware/software co-design | |
| **Major Challenge 5:**<br>**Support for sustainability by embedded software** | **Topic 5.1:** resource-aware software engineering | Integration of green-aware aspects in software integration | Adaptive processing based on energy-awareness | |
| | **Topic 5.2:** Tools for energy efficient SW design | Rejuvenation technologies | Design for extending lifetime | Digital twins that support green deal and enable sustainability (e.g. contain power models) |
| | **Topic 5.3:** Energy aware frameworks & libraries | Support monitoring/ reporting energy production / energy profiles | Support scale-able processing depending on available energy | Energy-optimal distributed computation |
| | **Topic 5.4:** Management of computation power on embedded HW | SW/HW support for energy awareness of embedded systems | Support for embedded HPC | |
| | **Topic 5.5:** Composable efficient abstraction | Enabling technologies for the second life of (legacy) cyber-physical systems | Establish relationships between power consumption and other quality properties | |
| **Major Challenge 6:**<br>**Software reliability and trust** | **Topic 6.1**: Reliability of software and new hardware | Code coverage of reliability tooling and porting<br>Simulation and mock-up based approaches for handling concurrency | Embed reliability on software architecture level | Use of quantum computing<br>IoT digital twin simulation<br>Validation and verification through simulation and mock-up based approaches for handling concurrency |
| | **Topic 6.2:** Robustness (trustworthy, secure, safe, privacy- aware) | Trustworthy, secure, safe, privacy-aware<br>Testing self-adapting systems using simulation | Define a maturity model for robustness of embedded software and beyond | |
| | **Topic 6.3:** Security and privacy as a service | Design for security and privacy as a service | Architecture for security and privacy as a service | |
| **Major Challenge 7:**<br>**Hardware virtualization for efficient SW engineering** | **Topic 7.1**: development methods and frameworks for hardware abstractions | Modular building blocks available for creating abstraction layers for common multicore-CPU/SoC platforms | Design automation for abstraction layers built from formal HW description | Methodology and tools automating abstraction layer design, providing certain guarantees (safety, security, determinism etc.) |
| | **Topic 7.2**: validation of application frameworks | Support virtualized V&V of applications on abstraction layers for wide range of target systems and variants thereof | Automated Validation of properties like safety, security and runtime determinism | |
| | **Topic 7.3:** Run-time environments for safety-critical applications | Highly performant & analyse-able run-time environments supporting shared memory access control | Hardware abstraction frameworks fit to be certified for safety-critical domains (automotive, aeronautics,…) | Hardware abstraction frameworks fit for certification in **highly** safety-critical applications (e.g. ASIL-D in automotive) |

## 1.3.8 Synergy with other themes

Opportunities for joint research projects, including groups outside and within the ECS community, can be expected in several sections of the Application chapters, the chapters in the technology value stack and with cross sectional chapters. There are strong interactions with the **System of Systems** chapter. In the System of Systems Chapter, a reasoning model for system architecture and design is one of the main challenges. Part of system architecture and design is the division in which the system functions will be solved in hardware, and which will be solved in Embedded Software and Beyond.

Embedded Software can be divided into two parts: software enabling the hardware to perform, and software implementing certain functionalities. Furthermore, there are connections with the cross-technology chapters, **Edge Computing and Embedded Artificial Intelligence, Architecture and Design: Methods and Tools, and Quality, reliability, safety and cybersecurity**.

With respect to AI, using AI as a technology and software components powered by AI in embedded solutions will be part of this chapter, while innovating AI will be part of the Edge Computing and Embedded Artificial Intelligence chapter, and discussing its quality properties will be part of the **Quality, reliability, safety and cybersecurity**.

With respect to the **Architecture and Design: Methods and Tools chapter, all methods and tools** belong there, while **Embedded Software and Beyond** focuses on development and integration methodologies. The challenges of preparing useful embedded solutions will be part of the **System of Systems** chapter and the **Embedded Software and Beyond** Chapter. The embedded software solutions for new computing devices, such as quantum computing, will be part of the **Long-Term Vision** Chapter.

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# 1.4

*Foundational Technology Layers*

# SYSTEM OF SYSTEMS

## 1.4

## System of Systems

### 1.4.1 Scope

The System of Systems (SoS) technology layer represent the upper layer of ECS technology stack for digitalisation solutions. This technology layer emerges from the composition of embedded and cyber-physical systems (CPS), connectivity and distributed software platforms.

In the ECS domain, a constituent system of a System of Systems (SoS) is defined as a set of embedded hardware hosting software designed to perform a particular task or solve a specific problem. A constituent system can be distributed, but from a logical/conceptual perspective it is "contained" in one unit and it is autonomous and/or independent from the other constituent systems, (i.e. it shows managerial and operational independence from any other constituent system). The complexity of these constituent systems is rapidly increasing with the development of the underlying HW/SW technologies, as well as the rising demand by the users of these systems for functional and extra-functional requirements.

According to the definition developed by Mayer, 1998[1], SoS must satisfy five characteristics: (i) the operational independence of constituent systems; (ii) the managerial independence of constituent systems; (iii) geographical distribution; (iv) emergent behaviour; and (v) evolutionary development processes. A system that does not satisfy these characteristics is not considered a SoS.

For existing systems this independence results in composing or integrating systems that were not designed together, to perform a combined task besides their 'normal' task. SoS engineering aims at methods and architectures to resolve this, typically addressing resource sharing, and access to data and services. Model-based techniques for the design of an SoS can be used in a similar way as for regular systems; however, the integrating systems rely on different models and paradigms. Further methodology is needed to address that systematically.

Newly developed systems must be designed such that they are prepared for forms of SoS integration. Here, model-based techniques are useful, for example, in the application of AI techniques e.g. for learning dynamically how systems must work together while increasing the semantic level of interoperability. Research should address the development of methodology and standard patterns, interfaces and artifacts for SoS that complement current methodology for system design. Focus should be on the aspects that are specific for SoS such as the mentioned independence, and the integration into an SoS: discovery and use of services, the sharing of data and resources, the support for extra-functional properties and the very late binding, to be negotiated at interfaces. Such negotiation requires predictive models that support taking sharing decisions and build on interoperability and trustworthiness.

In modern hyper-connected digital solutions, systems rarely operate independently. On the contrary, the primary added value of these digital solutions is the cooperation between heterogeneous systems to solve more complex problems by exploiting the set of multi-technology, multi-brand and even multi-domain functionalities generated by the cooperation. While talking or reading, SoS is typically pronounced entirely "System of Systems". A SoS emerges from the composition/integration of multiple systems to perform a task or reach an objective that none of the constituent systems can perform or reach on their own. In the SoS, each constituent system is considered a "black box": it remains operational and managerial autonomous and/or independent, relying on its own hardware, software, and networking resources, and remaining focused on its own goals. At the SoS level, the SoS evolves with components, functions and purposes added, removed, and modified, leading to an increasing dynamicity and variability along their life cycle (a life cycle that is intertwined with the life cycles of constituent systems and potentially never finishes!). The SoS structure evolves with the addition or removal of the constituent systems, which always cooperate, coordinate, and adapt to achieve the SoS goals, providing additional features to the SoS as a whole and capabilities and functionalities unavailable in the constituent systems. Having an up-to-date inventory and real time monitoring of the SoS is challenging.

A charging station for electric vehicles represents an example of a constituent system: it is logically and physically a single CPS, is capable of autonomously providing all the functionalities required by the recharging process and is independent of other charging stations – and even the electric grid if it is equipped with solar panels. When we connect a fleet of charging stations, adopting for example an IoT-based solution, the new distributed infrastructure of charging stations becomes a SoS. Single charging stations are operationally independent, but at the SoS level can cooperate with each other and with vehicles offering new functionalities and services. As a SoS, the recharging infrastructure can support different categories of charging standards, different charging processes, different energy sources, operators, brands, etc. – features and functionalities that were not previously available. For the end user, the SoS allows the possibility to automatically plan a trip that ensures the geographical coverage of recharge points compatible with the vehicle, a functionality that single charging stations and vehicles cannot independently provide. Application areas of SoS are very diverse, covering most industrial and societal domains.

Like a nervous system – i.e., partially centralized, distributed and peripheral – a software integration infrastructure is a key element of a SoS. Such infrastructure supports the dynamic integration of SoS functionality from edge to cloud. The integration infrastructure provides administrative and monitoring support enabling the desired functionalities and properties. Examples of such support are look-up, late binding, loose coupling, monitoring, interoperability, resilience, fail-over, security, safety, engineering, operation, real time. Such infrastructure supports an SoS to execute its desired/planed objective.

SoS infrastructure platforms play an important role for the ECS value chain and the related ecosystem, representing the structural element that physically and virtually contributes to allow all the individual systems to be part of the SoS. SoS infrastructure platforms allow for management of SoS interaction, maintenance and evolution, enabling the creation of added-value services and applications, contributing to the development of relations between the value chain stakeholders, as well as generating and implementing new business opportunities.

To create added value, a SoS need to be trustworthy, and here e.g. end-to-end security issues have to be properly taken into account. A secure SoS should be able to defend against both deliberate attacks and accidental threats, and also its misuse. Moreover, it is not enough to ensure that each of the constituent systems is secure in the pre-deployment phase, but also that the evolved/composed/integrated SoS, whose exact composition may be not known in advance, is secure. Dynamic adaption to e.g. security or safety requirements and risks analysis should be considered over time in relation to emergent functionalities, properties and behaviors arising from the complex interactions among the constituents of the SoS. New methodology and tools for risk and vulnerability assessment and threat modeling are needed. Artificial intelligence, machine learning and ontology/semantic-based approaches can complement each other for improved knowledge and decision-making processes in an SoS structure. AI/ML can make predictions based on experience or training, while ontologies/semantics provide information based on reasoning which also can optimise and accelerate machine learning processes.

Technical solutions in the SoS infrastructure platform domain should be open and ensure a certain level of domain independency, simplifying their adoption and allowing their re-use in different vertical applications. At the same time, it is also unrealistic to imagine that a single SoS infrastructure platform could drive an entire market because, considering the interdisciplinarity and complexity required to develop them, very seldom will a single vendor be able to provide a complete end-to-end and domain-independent solution. However, platform "competition" will at least have to identify a set of European solutions that covers key vertical domains. For key European vertical domains an SoS has to address a multitude of cross sectorial requirements like e.g. security, safety, evolution, maintenance, trustworthiness. For example, security and safety certification issues both at component, system and SoS level should be properly addressed aiming at really mitigating risks/threats in competitive scenarios, while also considering the EU Cybersecurity Certification framework.

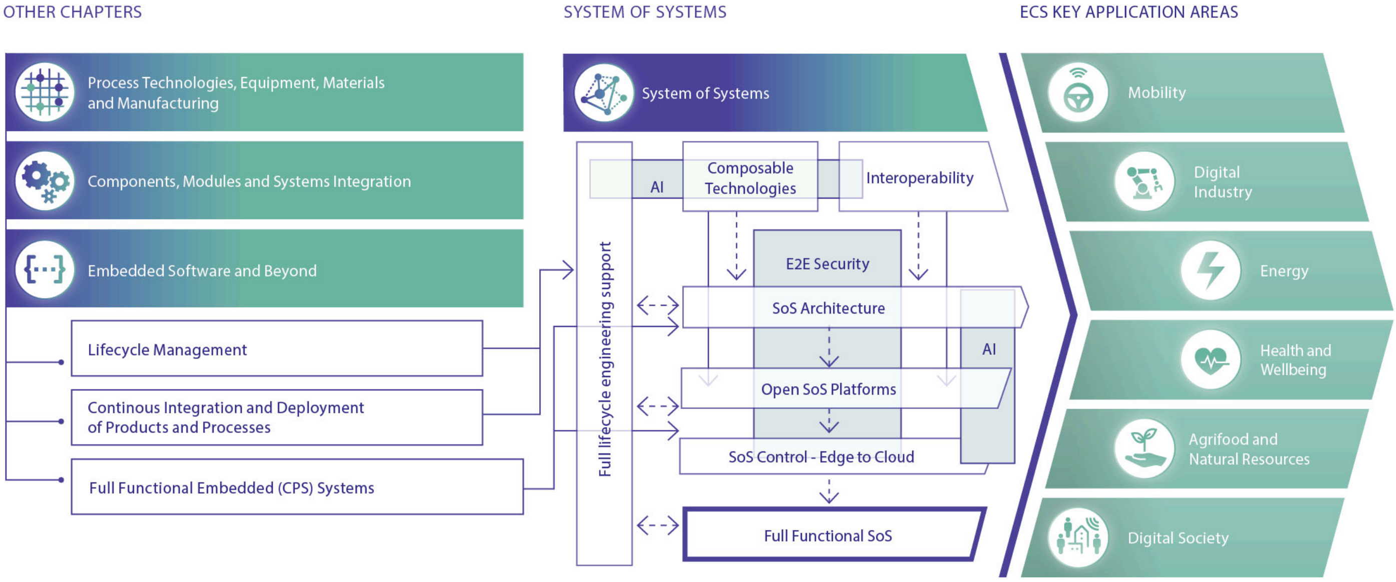

*Figure 1.4.1 - Structure: System of Systems*

## 1.4.2 Technology Enabled Benefits

There is a very strong market pull[2] for SoS that are embedded and cyber physical systems in supply chains, smart grids, smart cities, etc. There is also a similar situation for very complex systems such as autonomous vehicles, distributed EV-charging infrastructures, lithography machines, operation theatres, etc.

This market pull indicates the existence of large societal and associated market benefits. A few examples taken from the core ECS application areas include:

- goods and people logistics in high-density cities and rural areas,
- highly distributed and flexible production close to customers,
- customer adaptation in real time for service production,
- evolution of SoS solutions over long time periods and with adaptation to changing needs.

Such capabilities are applicable to all the targeted application areas of this SRIA. An example here is autonomous vehicles, which will become components in the complex logistics systems of cities, countries, and regions. SoS-related technologies will be key to providing efficient utilisation of autonomous vehicle assets while also offering timely delivery of goods and personnel. Another example is the integration infrastructures adopted in production to allow it and meet customer demands locally. Here, the interoperability of SoS technologies across domains is an essential capability. Yet a third example is how services can be adapted to local environments and customer needs without the need for prohibitively costs (re-engineering).

This market pull is motivated by societal requirements such as the European Green Deal, environmental footprint, rapid societal changes, quality of life, safety and security, etc. In the past, embedded systems technology has been a key to enabling automation to address this. The progression to SoS will become an even more powerful technology for addressing high-level societal priorities.

The further integration of "smart everything" into "ubiquitous smart environments" will introduce large and very complex SoS with complex physical interactions. Mastering this technology will enable the European industry to provide solutions to meet ECS application areas and associated societal benefits. In this context the technology competence and innovation in the field of embedded and cyber-physical based SoS will be a critical asset to succeed in the market.

## 1.4.3 Applications Breakthrough

Improvements in SoS technology will have an impact on all ECS application areas. For health and wellbeing, the challenges addressed within the field of systems of embedded and cyber-physical systems will enable faster translation of ideas into economically viable solutions, which can be further scaled up in daily health practice. Examples of health and wellbeing application breakthroughs supported here are:

- Interoperability of health data.
- Strengthening where and how healthcare is delivered, supporting home-based care.
- Supporting the clinical workforce and healthcare consumers to embrace technology-enabled care.
- High level of digital trust.
- Data security technology for interoperability between security hardware and software components.
- Improved integration and analysis of multimodal data.
- Integration platforms for embedded ultrasound, low-power edge computing, and AI and digital health.

For the mobility application area, the provision of EU capabilities within SoS will support breakthroughs regarding:

- Achieving the Green Deal for mobility with the 2 Zero goals of –37.5% $CO_2$ by 2030.
- Increased road safety through the CCAM[3] programme. Competitiveness of the European industrial mobility digitalisation value chain.
- Ensuring inclusive mobility for persons and goods by providing mobility access to everyone, with a focus on special needs.

In the energy application domain, the provision of improved SoS capabilities and engineering efficiency will support breakthroughs regarding:

- Significant reduction and recovery of losses (application and SotA-related).
- Increased functionality, reliability, and lifetime (incl. sensors & actuators, ECS HW/SW, semiconductor power devices, artificial intelligence, machine learning, monitoring systems, etc.).
- Management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility. Grid stabilisation through e-vehicle charging.
- Energy supply infrastructure for e-mobility, digital live, and industry 4.0.
- "Plug and play integration" of ECS into self-organised grids and multi-modal systems, real- time digital twin capability in component and complete system design (to simulate system behaviour).
- Safety and security issues of self-organised grids and multi-modal systems through smart edge devices and high-level IT security (resilient communications and trustworthy AI).
- Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.
- Energy technologies in the circular economy approach: predictive and condition-based maintenance with repair and recycle capabilities.
- Aligning with standardisation of our energy systems.

In the industry and agrifood application domains, the provision of advanced SoS architectures, platforms and engineering automation will support the EU regarding:

- Intelligent control room systems to enable correlations between machine malfunctions and load parameters to be detected immediately, thereby enabling maintenance work to be carried out early and on schedule, with a reduction in costly downtimes.
- Food industry imposes specific requirements (e.g. in food processing) that may take advantage of smart (bio-)sensing for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
- AI/machine learning (ML) and big data models must be devised and used to offer further intelligent decision-making and, whenever possible, should be employed directly at-the-edge for greater energy efficiency.
- Industrial IoT (IIoT) systems can provide the flexibility to tailor-make new products to help cope with ever-demanding diets.
- Remotely piloted autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, to improve efficiency.

- Smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced) – e.g. weather/climate information for predictive models providing risk assessments and decision support for Integrated Pest Management (IPM).
- IoT devices specialising in pests and disease measurements, such as insect traps and other systems based on image recognition or AI models.
- Large-scale and high-precision measurements of plant growth, architecture and composition.
- Winning the global platform game on various application sectors (that are currently strong) and in building effectively and, at a high level, outperforming applications and systems for industrial and business needs.
- Preparing for the 5G and beyond era in communications technology, especially its manufacturing and engineering dimension.
- Solving IoT and SoS cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive.
- Interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management that allows for the (semi)autonomous deployment and operation of a large number of devices.
- Decision support for AI, modeling and analytics in the cloud and also in edge/fog settings.

In the digital society application domain, the provision of improved, robust, secure and interoperable connectivity will support the overall strategy regarding:

- Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
- AI into the design, manufacturing, production and deployment processes, productivity can be improved.
- Collaborative product-service engineering, life cycle engineering: extending R&D to consider how products and systems will be integrated into the industrial service program of the company. This should possibly be enhanced by obtaining further knowledge to provide services for other similar products (competitors!) as well their own installed base.
- Remote engineering and operations, tele-presence: operating or assisting in operations of industrial systems from remote sites.
- Local and global services: organising services locally close to customers and centrally at vendors' sites.
- Edge/cloud solutions: implementing distributed service applications on effective edge-cloud systems.
- Full lifecycle tutoring: monitoring activities, level of stress and performance-oriented behavior during the product's life, from anticipating its end of life to properly handling its waste and recycling, including improved re-design for the next generation of products.

### 1.4.4 Strategic Advantage for the EU

As societal demands for efficiency and sustainability will increase over the coming decade, the ability to design tools and architectures to fulfill these demands becomes of high strategic value in the SoS and high-tech systems market. Europe has a globally leading position in the automotive and industrial automation sector – for both sectors, this lead is based on legacy technology and market appreciation.

The shift in the mobility sector towards electrification and autonomous mobility necessitates a large adoption of Systems of Systems in e.g. vehicles and roadside infrastructure. The European market has a high-end profile that can pave the way for this technology shift. Fast-paced technology and competence development, combined with the practical innovation scenarios outlined in the Part on applications, will help develop strategic advantages for European industry.

Similar situations can be identified in healthcare technology and in the electronics and components sectors, where world-leading companies provide very complex products and services. These can be internally regarded as a SoS or monolithic cyber-physical systems. It is obvious that these products and services will interact with surrounding production technology and services. Market competitiveness is built on capabilities such as flexibility and interoperability – again, a strong industrial technology, competence and innovation capability in this direction will provide a strategic advantage for Europe.

SoS and their formalisation were originally conceived and studied in the defense domain, but they are (and will be) vital infrastructure for many other vertical domains, including transportation, energy, healthcare and wellbeing, natural resource management, agriculture, disaster response, consumer products, finance, media, etc. In all these verticals, the shared enabling technology is represented by open SoS platforms that can play a central role in digitalisation solutions to orchestrate entire supply chains, manage assets, production, operations, processes, marketing and sales, and also in ensuring business continuity and resilience during global crises. It is clear that for Europe, important application areas will have different requirements, indicating that the SoS platforms should preferably be able to address and operate differences regarding e.g. security, safety, reliability and robustness.

The market for open SoS platforms is still very new, and several aspects still need to be completely constructed. Nevertheless, IoT platforms, which currently represent the larger subset of the SoS platforms market, is a very rapidly growing market: a recent study indicated that IoT platform revenues already amounted to US $55 billion in 2019 and were estimated to reach US $66 billion by 2020, with an annual growth of 20%[4]. With the impact of IoT and its evolution towards SoS, the current and future expectations of the market justify investment in SoS research and innovation[5].

The Advancy report on embedded intelligence very clearly points to the SoS market pull for the complete ECS value chain, with market growth being projected at €3.4–10.6 trillion[6]. Rapid EU advancement in the SoS area is therefore critical to the whole ECS value chain.

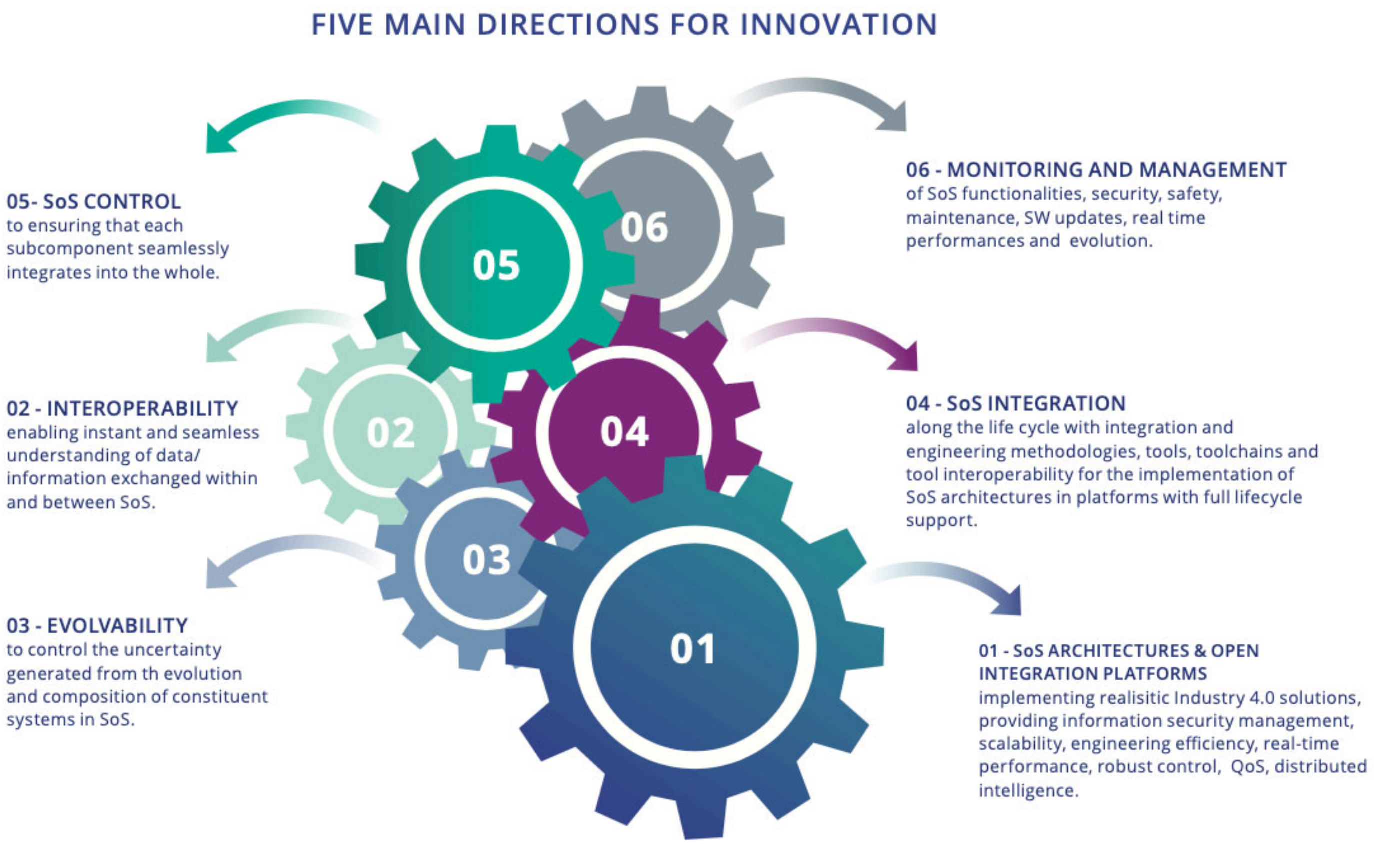

*Figure 1.4.2 - Six Main Directions of Innovation (source: Eurotech).*

## 1.4.5 Major Challenges

Six major challenges have been identified for the System of Systems domain:

- **Major Challenge 1**: SoS architecture and open integration platforms.
- **Major Challenge 2**: SoS interoperability.
- **Major Challenge 3**: Evolvability of SoS composed of embedded and cyber-physical systems.
- **Major Challenge 4**: SoS integration along the life cycle.
- **Major Challenge 5**: Control in SoS composed of embedded and cyber-physical systems.
- **Major Challenge 6**: SoS monitoring and management.

### 1.4.5.1 **Major Challenge 1: SoS architecture and open integration platforms.**

SoS architecture and open implementation platforms encompassing the multidimensional, multi-stakeholder, multi-technology and evolutionary nature of large SoS with key aspects along the full life cycle regarding e.g. safety, security, scalability, engineering efficiency, real time performance, advanced control, QoS, distributed intelligence.

#### 1.4.5.1.1 State of the art

SoS requires architecture that encompasses the multidimensional, multi-stakeholder, multi-technology and evolutionary nature. Architecting a SoS is fundamentally different from architecting a single embedded system. The complexity of SoS architecting can be exemplified by the architecture of a complete smart city, with all its subsystem, stakeholders, technologies and evolutionary nature.

The current industrial state of the art consists in a couple of major commercial and proprietary information/communications/control/technology platforms offering industrial solutions for complex solutions from companies like e.g. Schneider Electric[7], Siemens[8], Bosch[9], Emerson[10], ABB[11], Advantech[12], AutoSAR. These proprietary digital platforms, at various levels, support design, implementation and operation of SoS architectures tailored for dedicated solutions in sectors including e.g. manufacturing, water and wastewater, minerals and mining, oil and gas, energy sectors, smart cities and automotive.

The current industrial state-of-the-art SoS's are based on extensions to existing major enterprise resource planning (ERP), manufacturing execution system (MES), supervisory control and data acquisition (SCADA), distributed control systems (DCS), robot controllers (RC), computer numerical controllers (CNC), and programmable logic controllers (PLC) products. Such extensions are mostly based on a central service bus concept. Such service buses are responsible for integrating legacy ERP, MES, SCADA, DCS, RC, CNC and PLC technologies from multiple vendors, at best. For emerging SoS application areas like autonomous driving, smart energy grid, smart agriculture and smart cities, the SoS technology is still in an emerging phase. Still Europe is the leading player for industrial automation and digitalisation, with a very strong position in the upcoming areas of autonomous driving, smart energy, smart agriculture and smart cities.

To take the next step, Europe and other regions have invested in a number of open SoS integration frameworks and platforms. A summary of these is shown in Figure 1.4.4[13].

Most platform initiatives are based on Service Oriented Architectures (SoA) and microservices, which points towards a primary technology for such platforms. Although none of these open SoS platforms are currently in wide commercial usage, early examples can be found in small IoT solutions in various application areas. Major industrial usage remains rare, but MES-level adoption can be found in automotive production, for example.

Open architectures and reference implementations such as e.g. the IMC-AESOP approach[14], Eclipse Arrowhead[15], Eclipse Basyx[16], FiWare[17], PERFoRM30[18] are providing a link to standardisation activities in national and international innovation platforms. In the automotive domain, AutoSAR is developing in the microservice direction. Such standardisation activities are e.g. DIN Specification 91345[19] “Reference Architecture Model for Industry 4.0” (RAMI 4.0), the “Industrial Internet Architecture” (IIA), the “High Level Architecture of the Alliance for Internet of Things Innovation”, the “NIST Big data Reference Architecture”, to name just a few. A complementary overview of such high-level architecture frameworks is shown in Figure 1.4.3[20].

| ID | NAME | SCOPE |
|---|---|---|
| **AF-EAF** | Air Force Enterprise Architecture Framework | Air Force IT systems |
| **AFIoT** | IEEE P2413 – Architecture Framework for the Internet of Things | IoT |
| **AF4Orgs** | Architecture Framework for Organisations | A whole organisation or part of an organisation situated in its environment. |
| **CAFCR** | Customer Objectives, Application, Functional, Conceptual and Realisation model | Embedded systems |
| **CBDI-SAE CBDI** | Service Architecture and Engineering (CBDI-SAE,™) for SOA | Service-oriented architectures |
| **DoDAF US** | Department of Defense Architecture Framework | US DoD |
| **ESAAF** | European Space Agency Architecture Framework | Space-based SoS |
| **IIRA** | Industrial Internet Reference Architecture | Industrial Internet systems |
| **4+1** | Kruchten's 4+1 view model | Software architecture |
| **MEGAF** | MEGAF | Software, system and enterprise architecture |
| **MODAF** | (UK) Ministry of Defence Architecture Framework | Defence |
| **NAF** | NATO C3 Systems Architecture Framework | C3 systems interoperability |
| **NIST-EAM** | NIST Enterprise Architecture Model | Enterprise systems |
| **OSSAF** | Open Safety and Security Architecture Framework | Public safety and security (PS&S) |
| **RM-ODP ISO** | Reference Model for Open Distributed Processing | Open distributed processing systems |
| **RWSSA** | Rozanski and Woods | Information systems |
| **TOGAF** | The Open Group Architecture Framework | Enterprise systems |
| **ZF** | Zachman Framework | Enterprise systems |

*Figure 1.4.3 - SoS architecture panorama*

Europe has a strong investment in large projects that have delivered open platforms for the implementation of solutions based on SoS platforms[21]. Considering the platforms referred to in Figure 1.4.4, Eclipse Arrowhead, AUTOSAR, FiWare and BaSyx have all been developed with substantial European leadership and partnership.

| FEATURES | ARROWHEAD | AUTOSAR | BASYX |
|---|---|---|---|
| **Key principles** | SOA, local automation clouds | Run-time, electronic control unit (ECU) | Variability of production processes |
| **Realtime** | Yes | Yes | No |
| **Run-time** | Dynamic orchestration and authorisation, monitoring, and dynamic automation | Run-time environment (RTE) layer | Run-time environment |
| **Distribution** | Distributed | Centralise | Centralise |
| **Open source** | Yes | No | Yes |
| **Resource accessibility** | High | Low | Very low |
| **Supporters** | Arrowhead | AUTOSAR | Basys 4.0 |
| **Message patterns** | Req/Repl, Pub/sub | Req/Repl, Pub/sub | Req/Repl, |
| **Transport protocols** | TCP, UDP, DTLS/TLS | TCP, UDP, TLS | TCP |
| **Communication protocols** | HTTP, CoAP, MQTT, OPC-UA | HTTP | HTTP, OPC-UA |
| **Third-party and legacy systems adaptability** | Yes | Yes | Yes |
| **Security manager** | Authentication, authorisation and accounting Core system | Crypto service manager, secure onboard communication | -- |
| **Standardisation** | Use of existing standards | AUTOSAR standards | Use of existing standards |

| FIWARE | IOTIVITY | LWM2M | OCFW |
|---|---|---|---|
| Context awareness | Device-to-device communication | M2M, constrained networks | Resource-oriented REST, Certification |
| No | Yes<br>(IoTivity constrained) | No | No |
| Monitoring, dynamic service selection and verification | No | No | No |
| Centralise | Centralise | Centralise | Centralise |
| Yes | Yes | Yes | No |
| High | Medium | Medium | Low |
| FIWARE Foundation | Open Connectivity Foundation | OMA SpecWorks | Open Connectivity Foundation |
| Req/Repl, Pub/sub | Req/Repl, Pub/sub | Req/Repl | Req/Repl |
| TCP, UDP, DTLS/TLS | TCP, UDP, DTLS/TLS | TCP, UDP, DTLS/TLS, SMS | TCP, UDP, DTLS/TLS, BLE |
| HTTP, RTPS | HTTP, CoAP | CoAP | HTTP, CoAP |
| Yes | No | No | No |
| Identity manager enabler | Secure resource manager | OSCORE | Secure resource manager |
| FIWARE NGSI | OCF standards | Use of existing standards | OCF standards |

*Figure 1.4.4 - Open SoS integration frameworks and platforms*[22]

For the cross-domain requirements on e.g. security, safety, evolution application and business critical details need to be considered. As an example thereof security takes on new dimensions in the case of SoS. In this Chapter, security is taken to be the ability to prevent leaking information and to prevent the taking over of control of the SoS by agents not being part of the SoS, but also the guarantee that no hostile party can prevent the sharing of essential information between the systems comprising the SoS. Several security aspects require attention. First, the level of security of each individual system requires attention: the lower bound to security of a SoS is determined by the system with the lowest security level, and by the link with the lowest security level between systems ("weakest link in the chain"). Thus requirements like Quality, Reliability, Safety and Cybersecurity at the system and SoS levels are covered in Chapter 2.4 of this ECS-SRIA.

However, combining a very large number of systems in a SoS can result in a lower overall security level than the lowest security level of any system in the SoS: an attacker can now combine and relate information from two or more systems which in combination can reveal new information.

Systems must not only defend and monitor possible attacks, but also measures must be taken allowing the communication of intrusions in one system to the other systems in the SoS. Only in this way resilience and cybersecurity can be attained.

The spectrum of systems making up a SoS includes both systems in the cloud, where security can be closely monitored as in e.g. data warehouses, and systems at the edge. Edge systems pose a higher level of cyber insecurity because of the limited resources often available at the edge (e.g. power, communication bandwidth).

Another aspect is SoS safety. Here architectures and platforms need to address safety from various application domains and their standards and regulations. More details related to the ECS application domain requirements on Quality, Reliability, Safety and Cybersecurity at the system and SoS level are covered in Chapter 2.4 of this ECS-SRIA.

### 1.4.5.1.2 Vision and expected outcome

This Major Challenge is expected to lead to a set of EU strategic open SoS integration platforms capable of supporting a wide range of solutions in diverse fields of applications covering the ECS supply chain and supporting efficient lifecycle management.

This requires new and improved platform technologies comprising:

- Robust design- and run-time infrastructure enabling integration and orchestration of functionalities from edge to cloud.
- Infrastructure platform support for multi-level security, security management, safety, safety management, scalability, engineering efficiency, real-time performance, closed loop and digital control, QoS, distributed intelligence and other key application area requirements.
- Interoperability to legacy SoS technology.
- Interoperability to existing and emerging IoT and SoS technologies and platforms.
- A high degree of autonomous operation, resilience, failover and mitigation management.
- Enabling SoS flexibility.
- Engineering support through model based engineering and associated domain specific languages (c.f. Chapter 2.3 Architecture and Design: Method and Tools).

The expected outcome is a set of EU strategic open source platforms. These infrastructure platforms should have long-term governance with industry-friendly licensing schemes such as e.g. Eclipse ECL2. Such platforms should also have strong EU-based value chain support.

To cope with increasing complexity, the SoS engineering community is constantly researching improvements to its engineering processes. To ensure the complexity remains manageable, modeling approaches are used. The challenge in these approaches is to find the right level of abstraction that also allows for reasoning about the system while still containing sufficient information to connect to lower levels of abstraction, often by generating code for some underlying implementation platform.

It is not only that the complexity of the SoS is growing, but there are also extra-functional requirements that are often interlinked playing an increasingly important role. For example, with the demand for greater speed and the concomitant energy consumption, systems are often required to process information quickly but within a tight energy budget. These two requirements are clearly conflicting and choosing the right trade-off can be a balancing task. With the realisation that the planet’s resources are limited, as exemplified in the European Green Deal, also comes the demand for resource conservation, resulting in more and intertwined requirements, putting greater demand on the dynamic and evolution capabilities of both the SoS architectures and the architecture tools that support the complexity of SoS.

Some important but necessary aspects of SoS architecture are:

- Security and trust,
- Safety,
- Robustness,
- Composability,
- Evolution,
- Interoperability,
- Engineering tools and procedures,
- Advanced control,
- Energy consumption,
- Resilience.

### 1.4.5.1.3 Key focus areas

The key focus is how SoS architectures and their open implementation platforms can enable and leverage important and necessary aspects while also enabling efficient adaptation to specific application solutions.

To support EU strategic autonomy, a small number of SoS architectures and integration platforms should be driven by EU-based ecosystems. Important features that such platforms should provide include:

- a robust SoS integration platform capable of supporting a wide range of solutions in diverse fields of applications,
- integration platform and associated engineering tools and toolchains that support the complete engineering process in both design- and run-time, including SoS critical aspects such as e.g. security, safety and risk mitigation,
- suitable and adaptable engineering processes, with associated training material for solution engineering.

### 1.4.5.2 **Major Challenge 2: SoS interoperability**

SoS interoperability enables instant and seamless understanding of information exchanged within and between networked and distributed systems.

#### 1.4.5.2.1 State of the art

Interoperability in the SoS domain is a rising problem for cost-effective engineering and operation of systems of embedded and cyber-physical systems (see Figure 1.4.5).

There is currently no industrial solution to this problem. Academia and industry are experimenting with approaches based on, for example, ontologies[23], machine learning[24] and open semantic frameworks[25]. Even if no clear winning approach can be identified based on current research results, growing interest can be noted for e.g. ontology, data and model driven approaches. Automating considerable parts of interoperability engineering (design-time and run-time) will improve SoS operational quality.

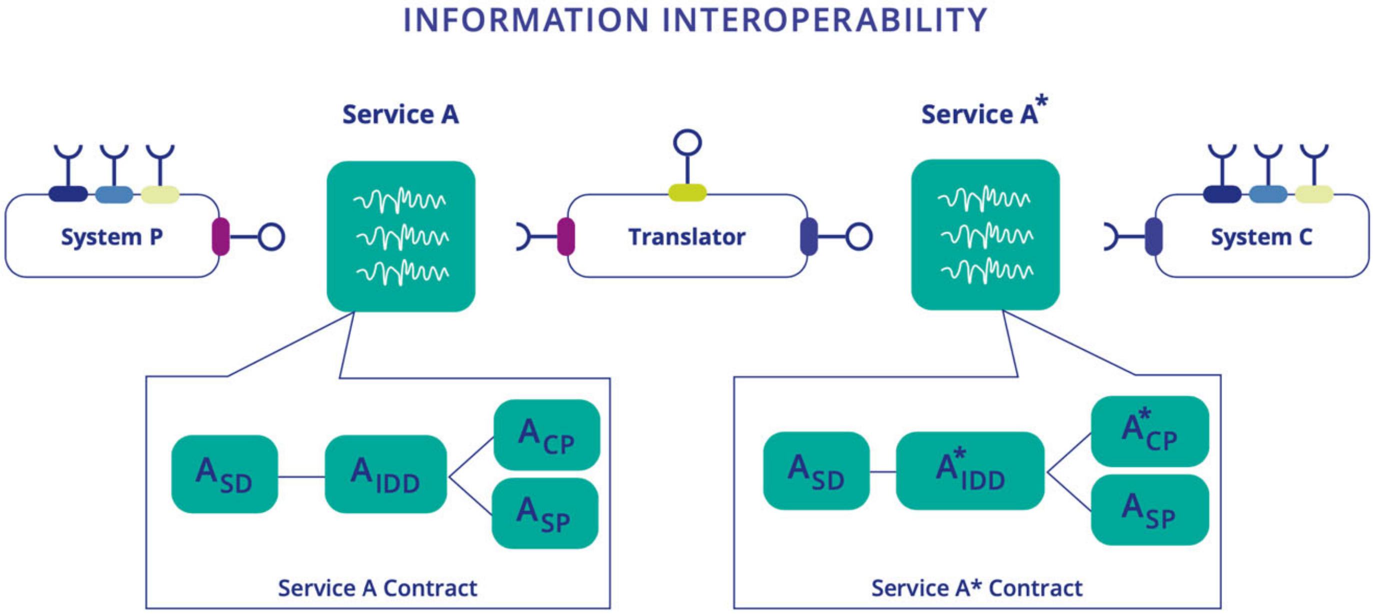

*Figure 1.4.5 - Information interoperability between two service providers can be addressed by means of translators. The design of such translators for the payload information is currently necessary to provide for every situation where interoperability is requested.*

#### 1.4.5.2.2 Vision and expected outcome

To enhance EU leadership and sovereignty in the field of SoS based on embedded and cyber-physical systems, autonomous information translation for understanding is a necessity. Some integration platforms already focus on protocol and information interoperability (Derhamy, 2018 ) [26]. To enable the cost- and time-efficient engineering of solution integration and extension, their updates and upgrades over the lifecycle is crucial. Therefore, SoS integration platforms have to provide mechanisms for dynamic and instant information translation across the ontologies and semantics used the individual constituent systems of the SoS.

#### 1.4.5.2.3 Key focus areas

To facilitate substantial cost reductions for SoS solutions, autonomous and dynamic mechanisms for information translation are required. Such mechanisms should cover:

- Translation between standardised data models (e.g. ISO 10303[27], ISO 15926[28], BIM[29]).
- Translation between different implementations of standardised data models.
- Automated data model translation.
- Autonomous data model translation.
- Efficient and flexible engineering procedures.
- Engineering tools that support the complete engineering process in both design- and run-time.
- Support for key automation requirements.
- Automated translation engineering e.g. AI-driven, model based code generation.

### 1.4.5.3 Major Challenge 3: Evolvability of SoS composed of embedded and cyber-physical systems.

SoS intrinsic nature is dynamic and SoS evolve with components, functions and purposes added, removed, and modified along their continuously evolving lifecycle (a life cycle that potentially never finishes). A SoS has properties, behaviours and functionalities that mainly do not reside in any constituent system but in the SoS as a whole and allow the SoS to achieve its own goals. These properties, functionalities and behaviours at the SoS level emerge in a direct relationship to the SoS evolution and, being potentially unknown, must be monitored and managed, i.e., detected, identified, understood and controlled. Because the results of the composition/evolution could be uncertain, SoS architectures and platforms, open and proprietary in conjunction with the proper engineering support (methods and tools), should provide solutions to manage the evolution and resulting uncertainty emergent properties, functionalities and behaviours.

#### 1.4.5.3.1 State of the art

Evolvability and composability is a multi-dimensional key aspect of SoS evolution, one that affects their architectures, properties, functionalities and behaviours from different perspectives (evolvability, trust, interoperability, scalability, availability, resilience to failures, etc.). Primarily, composability must ensure the persistence of the five major attributes that characterise a SoS (see Maier, 1998[30]). Vertical (hierarchical) composability provides the most common way to build a SoS that is typically structured in a hierarchical stack composed of adjacent layers. Vertical composability has to deal with the different abstraction levels of the stack layers, adopting aggregation and de-aggregation solutions as references to compose the constituent systems of the SoS. Architectural composability, on the other hand, is fundamental for SoS design, specifically when critical requirements such as trust or safety must be satisfied (see Neumann 2004[31], for an extensive report on trustworthy composable architectures).

In the hierarchical structure of a SoS, the constituent systems that are at the same level typically compose horizontally (in parallel or serially), potentially generating competing chains of constituent systems. Serial composability represents a critical issue for all properties that are not automatically transitive, such as trust. Indeed, the inclusion of AI in embedded and cyber-physical systems increases the required level of trust, as well as the uncertainty of the results of the composition process (see, for example, Wagner, 2015[32]).

When the constituent systems expose high-level services, service composability allows for the creation and provision of new added-value services at the SoS level, combining the resources, functionalities, information, etc., of the constituent systems. Eventually, the engineering process deals with composability, enabling it by design (already present from the constituent systems level) and/or managing it during the operations of the SoS, to address the dynamic nature of SoS in time (run-time composability associated with evolutionary development and potential emergent properties, behaviours, and functionalities).

#### 1.1.5.3.2 Vision and expected outcome

The dynamic nature of SoS is based on the composition and integration of embedded and cyber-physical systems. The role of composability is to ensure that functional and extra-functional properties (scalability, quality of service (QoS), performance, reliability, flexibility, etc.), and the functionalities and behaviours of the constituent systems are preserved in the SoS or combined in a predictable and controlled way, even when the constituent systems recombine dynamically at run time. The lack of solutions to dynamically manage composability represents one of the limitations preventing the diffusion of SoS.

Composability should be conceived as a quality of SoS that makes them future proof: (i) the relationships between components that allow them to recombine and assemble in different and potentially unlimited architectural combinations, and ensure and exploit the re-use of components; (ii) the extension of components lifetime within the evolution of the SoS during its lifecycle; (iii) the possibility that SoS will easily evolve, adapting to new contexts, new requirements and new objectives; and (iv) the simple substitution of faulty, inadequate and/or new components with a minimal impact for the SoS, guaranteeing the survival and sustainable evolution of the SoS. Composability also have to consider cross sectorial requirement like e.g. security, safety, trust, evolution.

Ensuring composability at the SoS level represents a very challenging goal, potentially generating serious and critical consequences, and even preventing the integration of the SoS. Indeed, considering a property that characterises a constituent system with a certain attribute, it is not guaranteed that the same property will characterise it when the constituent system becomes part of a SoS. In addition, if the property is still present, it is not guaranteed that it will have the same attribute. The same applies to the constituent system’s functionalities, behaviours, etc.

As a consequence, one major effect of the composition, integration, evolution of the constituent systems is the evolution of the SoS, with emergent properties, functionalities and behaviours which generate uncertainty. For instance, when SoS evolution affects security, safety, trust, interoperability, scalability, availability, resilience to failures, etc., the impact of the uncertainty could potentially be extremely serious.

The inclusion of AI in SoS increases the importance of composability, because it may significantly increase the complexity, variability and fuzziness of composability results. AI enables a completely new category of applications for SoS. Therefore, the availability of specific solutions for the validation, verification and certification of SoS composed of AI-based systems is a critical requirement.

Predicting and controlling the effects of composability is also fundamental for the interaction of humans along the SoS lifecycle and the protection of human life should be ensured in SoS evolution. Uncontrolled and unmonitored composition could lead to deviations from expected behaviours or generate unknown emergent behaviours potentially dangerous for humans. The increasing level of automation introduced by SoS accentuates this criticality, and will require that humans still intervene in cases of emergency (for example, in automated driving).

The solutions proposed to manage composability will also have to support the multi-domain nature of SoS, the presence of different stakeholders in its lifecycle, and the different regulations and standards that apply to these domains. From an engineering perspective, emergent behaviours require that the development of SoS, applying composability, is evolutionary and adaptive over the SoS continuously evolving lifecycle, which potentially may never finish. In fact, SoS architectures and platforms, jointly with the proper engineering support, will have to provide solutions to control the uncertainty of evolvability and ensure adequate countermeasures.

#### 1.4.5.3.3 Key focus areas

Since the technology base, and the organisational and human needs are changing along the SoS lifecycle, SoS architecting will become an evolutionary process based on composability. This means: (i) components, structures, functions and purposes can be added; (ii) components, structures, functions and purposes can be removed; or (iii) components, structures, functions and purposes can be modified as owners of the SoS experience and use the system. In this sense, the dynamically changing environmental and operational conditions of SoS require new architectures that address the SoS goal(s), but thanks to composability will also evolve to new system architectures as the goal(s) change.

Evolution in SoS is still an open research topic requiring significant effort and the key areas of research and innovation include:

- Methods and tools for engineering evolvability of systems of embedded and cyber-physical systems, e.g. AI driven, model based (c.f. Chapter 2.3. Architecture and Design: Methods and Tools).
- Evolutionary architectures in systems of embedded and cyber-physical systems.
- Evolvable solutions for trust, availability, scalability, and interoperability.
- Evolvable solutions capable for managing resulting uncertainty emergent properties, functionalities and behaviours, including resilience to failures.
- Evolvability in systems of cyber-physical systems through virtualisation, e.g. digital twins.
- Methods and tools to manage emergencies in embedded and composable systems of cyber-physical systems.
- Service-based vertical and horizontal evolvability to enable high-level, and potentially cross-domain, interoperability of embedded and cyber-physical systems.

### 1.4.5.4 **Major Challenge 4: SoS integration along the life cycle**

Integration and engineering methodologies, tools, tool chains and tool interoperability are fundamental to enable the implementation of SoS solutions using SoS architectures and platform technologies, supporting the whole lifecycle.

#### 1.4.5.4.1 State of the art

Europe is a world leader in the engineering of systems of systems. Major European companies such as Siemens, ABB, Schneider, Valmet, Bosch and Endress+Hauser, together with a number of large system integration companies (e.g. Afry, VPS and Midroc), offer complete engineered solutions, making Europe the leading global automation SoS provider.

Most solutions for embedded and cyber-physical systems engineering are based on highly experienced teams of engineers supported by a heterogeneous set of SoS engineering tools. For example, engineering practice and associated standards provide design-time solutions based on, for example, IEC 61512 (ISA 88)[33], IEC 62264 (ISA95)[34], IEC81346[35], ISO 10303, ISO 15924, IEC 62890[36]. The proposed Industry 4.0 architectures, formally provided by the DIN specification 91345 RAMI 4.0, have not yet made it into industrialised engineering procedures, or associated tools and toolchains. Therefore, the industrial state of the art for SoS engineering still has its major base in legacy technology.

The current state of the art engineering of SoS remains more an art than a well-structured integration and engineering process. For example, the analysis of emergent behaviour of very large SoS is still at a foundational research level in academia.

### 1.4.5.4.2 Vision and expected outcome

The European leadership in application fields such as distributed automotive and industrial automation and digitalisation indicates some excellent skill sets in the art of SoS engineering. In the short to medium term, Europe has to transfer these skills into systematic and robust engineering procedures supported by integrated and efficient tools and toolchains. Please also refer to Chapter 2.3 and Chapter 1.3

This is expected to lead to engineering processes, tools and toolchains covering the whole life cycle that to significant extent can be automated while supporting integration between multiple stakeholders, multiple brand and multiple technologies. To support such integration and engineering efficiency, solution quality and sustainability concrete advancements like in Figure 1.4.6[37] will become necessary. The advancement may include integration and engineering process capabilities like:

- Flexible integration and engineering procedures.
- Model-based engineering procedures and tool,
- Supported by interoperable and flexible toolchains.
- Integration of multi-stakeholder engineering processes.
- Automation of substantial parts of the integration and engineering process.

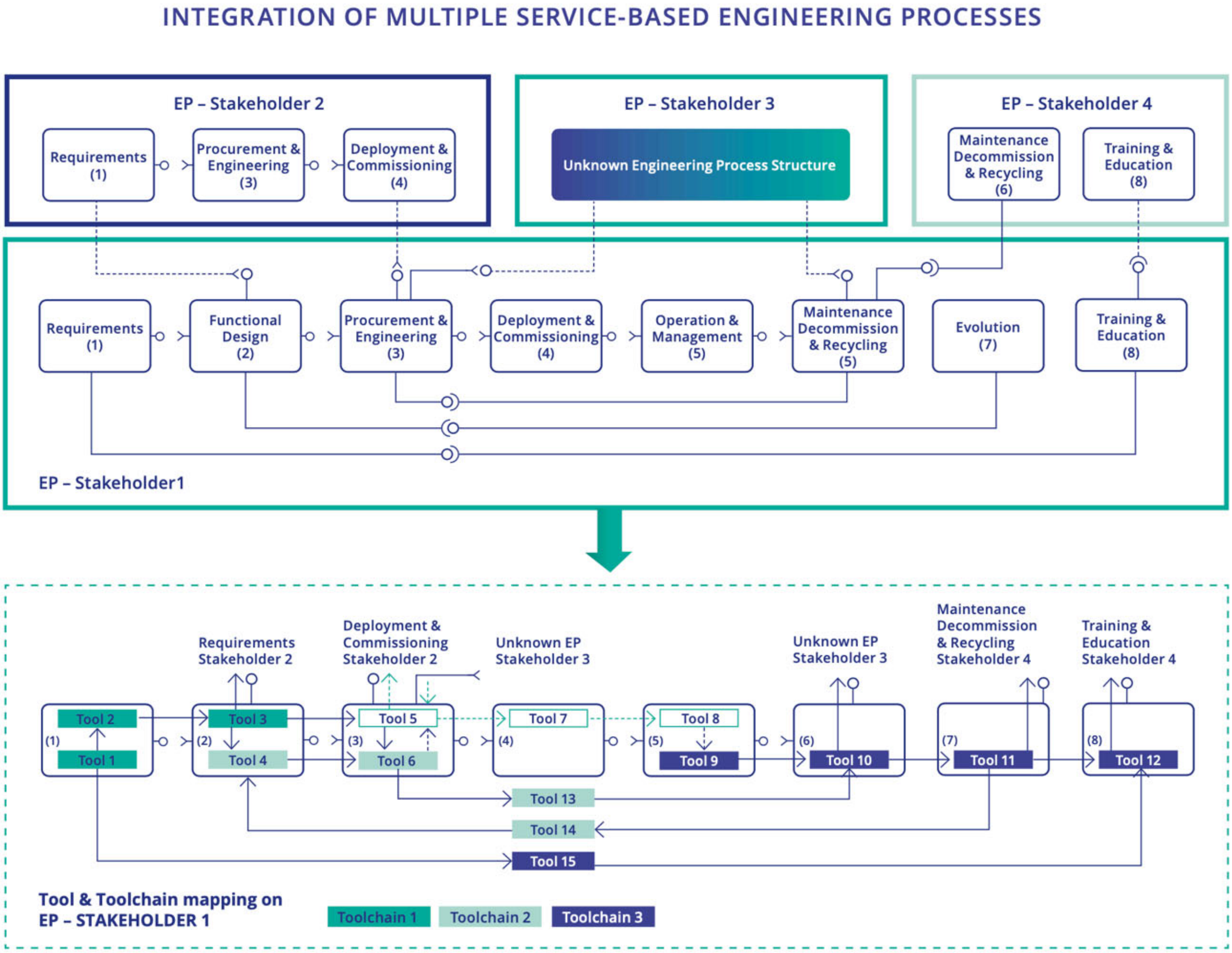

*Figure 1.4.6 - Example of conceptual service-oriented view on the integration of multiple service-based engineering processes (EP) from different stakeholders, including the engineering process mapping with integrated toolchains and tools*

### 1.4.5.4.3 Key focus areas

In support of EU leadership and sovereignty in the field of SoS engineering the ambition is to invest in a small number of integration platforms and their associated tools, toolchains and engineering processes. Strong European-based ecosystems should be created and provided with long-term governance also connected to open source. These engineering processes, methodologies, tools and toolchains shall provide, for example:

- Efficient and flexible engineering processes.
- Model-based engineering.
- AI-supported engineering tools and processes
- Engineering tools supporting the complete engineering process along the system's lifecycle.
- Support for key automation requirements.
- Automated engineering.
- SoS traceability and analytics interoperable with engineering tools and tool chains.
- SoS evolution impact analysis.
- Automated testing validation and verification (TV&V) along the life cycle.

In particular, SoS TV&V introduces a significant challenge, mainly due to complexity, to the effects of composition (not always known in advance) and to SoS dynamic evolution over time. For SoS, a full TV&V procedure prior to deployment is practically unrealistic. Typically, the TV&V of each constituent system is asynchronous and independent of SoS, challenging the SoS TV&V with feature and capability evolution. For this motivation, a structured framework methodology and tools is necessary to demonstrate an appropriate level of confidence that the feature under test is present in the SoS, and that no undesirable behaviours are also present. This implies a need for end-to-end system capabilities metrics and, according to the flow of data, control and functionalities across the SoS, additional test points, recurring tests and AI-empowered data collection. This analysis should be considered to address changes in the constituent systems and to receive feedback on anomaly behaviours.

## 1.4.5.5 Major Challenge 5: Control in SoS composed of embedded and cyber-physical systems

When control in SoS is considered, one must again consider that they represent an integration of physical systems through networks and computers. Often, the subcomponents of these systems belong to different domains, possibly with physical interactions between them. A core feature of SoS is that sensing, computation/control and data exchange through networks inextricably links physical objects to each other. Not surprisingly, at the heart there are algorithms/methodologies that provide the necessary signals for their control, ensuring that each subcomponent seamlessly integrates into the whole. Embedded computers control and monitor the physical processes using data networks. Thus, feedback loops are established where physical processes affect computations and vice versa.

Some examples of SoS where control and monitoring play crucial roles are smart grids, connected (semi)autonomous automotive systems, medical monitoring, industrial plant control systems, robotics, automatic pilot avionics and rail network control.

### 1.4.5.5.1 State of the art

In alignment with the traditional architectures in “Control and Automation”, automation, control and monitoring schemes in most SoS today are characterized by a hierarchical and centralised architecture, made up of layers of sensors and actuators, controllers, and associated computers that are distributed throughout the often complex, interconnected SoS. In terms of control, the atomic unit of a SoS can be found on the field level, where direct control of so-called agents takes place. This can be e.g. the control of a single generator in a power plant, which itself is part of a smart grid. The actions of field control are directed by higher levels such as plant supervisory control, scheduling control or plant-wide optimisation.

### 1.4.5.5.2 Vision and expected outcome

As complexity of SoS increases steadily, so does the number of systems involved in its control performance. As a result, when using state of the art control methodologies the communication effort would grow exponentially. Thus, balancing communication effort and control performance is a key factor. In this context and in view of limiting data traffic in a SoS, synchronisation of systems becomes a major control goal as it is directly linked to the stability of the control system.

In addition, control of complex cyber physical SoS must address other important aspects such as scalability (i.e. to deal with a variable number and interconnection of systems and control loops) and network phenomena (such as computation/communication latency, data loss). Looking at the aspect of data management, open SoS control platforms should ensure information security management, SoS scalability, SoS engineering efficiency and also SoS real-time performance.

### 1.4.5.5.3 Key focus areas

For this Major Challenge we envision the following key focus areas:

- Tools for control system analysis of SoS.
- Considering humans, environment and the economy in the loop.
- Engineering tools and methods for SoS control design.
- Reduction of communication effort, variable structure, variable number of systems in control loops.
- Control system testing, validation and verification (TV&V) in design and run-time.

## 1.4.5.6 Major Challenge 6: SoS monitoring and management

Management of SOA based SoS will require structured and scalable approaches to status monitoring and strategies and methodologies to address SoS management from a number of perspectives e.g. functional, security, safety, maintenance, SW updates, real time, evolution.

### 1.4.5.6.1 State of the art

Current industrial state of the art for monitoring and management of SoS reflects back to monitoring and management of production automation, energy grid automation and similar. Looking closer we find a plethora of commercial application solutions tailored to specific applications. Many of these are very application and site specific and “home brewed”.

There is a wide set of different realms to be monitored and managed, ranging from modern production processes, smart grids, smart cities, automotive traffic networks, only to name some of them. Furthermore, for each of these realms their operation requires different competences and groups within an organisation, and it follows different guidelines. Some examples are:

- Status of operation
- Safety
- Real time performance
- Real time monitoring of sensors and actuators, incl. fault detection and isolation
- Validation of signals (using redundancies created by the data network of the SoS)
- Control
- Maintenance
- Assets
- Security

These aspects do have more or less known and understood relationships/dependencies which also will change in run-time. This provides a monitoring and management landscape which is very heterogeneous and dynamic.

A wide set of tools is available, each supporting one or a few of these dimensions. In most cases these tools mandate underlying information sources and data models, which sometimes correlates with current major industrial standards like ISA95, BIM, ISO 15926 and ISO 10303.

In summary a very complex and heterogeneous landscape of, to a large extent non-interoperable, tools and methodologies with no or little capacity to be integrated across SoS dimensions.

### 1.4.5.6.2 Vision and expected outcome

The emerging closer digital integration of industrial and societal functionalities and domains requires SoS integration and associated monitoring and management in very complex and heterogeneous environments. The current state of the art is far from efficiently enabling this. Such enabling will require closer cooperation and integration between several levels of the ECS domain stack. An example thereof is the integration and functional interoperability between open and proprietary SoS architecture and implementation platforms, embedded software its tools and platforms and solution engineering its processes, tools and implementation platforms. Here solution requirements on lifecycle and evolution as well need to be considered.

### 1.4.5.6.3 Key focus areas

To advance towards the vision technology and knowledge steps are required regarding:

- Monitoring and management strategies and architectural concepts in OT-IT environments.
- Methodologies and technologies for monitoring and management of multiple and interrelated SoS dimensions.
- Processes and technology for life cycle monitoring and management over SoS dimensions.
- Engineering support, tools and methods, for monitoring and management strategy and policy implementation.

### 1.4.6 Timeline

The following tables illustrate the roadmaps for System of Systems.

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1: SoS architecture and open integration platforms** | **Topic 1.1**: Robust SoS integration platform capable of supporting a wide range of solutions in diverse fields of applications | Architectures and associated implementation platforms with sufficient granularity and engineering support for efficient implementation of real-world Industry 4.0 solutions | Architectures and implementation platform with support for a wide set of autonomous operation e.g. M2M business execution | Architectures with support for self-X e.g. self-healing, self-extension etc. |
| | **Topic 1.2**: integration platform and associated engineering tools and toolchains that support the complete engineering process in both design- and run-time, including SoS critical aspects such as security, safety and risk mitigation | Preliminary lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc. | Full lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc. | Autonomous management of functional and non-functional dimensions |
| | **Topic 1.3**: suitable and adaptable engineering processes with training material for solution engineering | Hardware and software tools, methodology and training material suited for training of professionals and students at university level | Model based engineering support proving partial engineering automation of solutions | Automated SW engineering for most solution engineering stages. |
| **Major Challenge 2: SoS interoperability** | **Topic 2.1**: Translation between standardised data models e.g. ISO 103030, ISO 15926, BIM, … | Translation technologies enabling translation of standardised data models and demonstrated at TRL 5-7 | Fully autonomous translation | |
| | **Topic 2.2**: Translation between different implementations of standardised data models | Translation technologies enabling translation of different implementations of standardised data models and demonstrated at TRL 5-7 | Full cross-domain interoperability | |
| | **Topic 2.3**: automated data model translation | Technologies and tools for automating the engineering of data model translations | Fully automated information translation | |
| | **Topic 2.4**: autonomous data model translation | Technology and tools for enabling autonomous data model translation in run-rime | Fully autonomous translation | |
| **Major Challenge 3: Evolvability of SoS composed of embedded and cyber-physical systems** | **Topic 3.1**: methods and tools for engineering evolvability of systems of embedded and cyber-physical systems | Persistence of operational independence, managerial independence, geographic distribution, emergent behavior and evolutionary development | Full predictable and controllable composition of functional and extra-functional properties | Full predictable and controllable composition of functional and extra-functional properties, also covering dynamically recombining SoS |
| | **Topic 3.2**: evolutionary architectures in systems of embedded and cyber-physical systems | Modular and evolvable architectures. | Evolvability and composability by design | Automated evolvability and composability analysis in design time and run-time |
| | **Topic 3.3**: evolvable solutions for trust, availability, scalability, and interoperability. | Modular frameworks addressing trust, availability, scalability and interoperability- | Modular frameworks and open integration platforms addressing e.g. trust, availability, scalability, interoperability | Open modular frameworks and integration platforms addressing e.g. trust, availability, scalability, interoperability, evolvability, composability |
| | **Topic 3.4**: evolvable solutions capable for managing resulting uncertainty emerging properties, functionalities and behaviours, including resilience to failures | Technology frameworks supporting self-adaptability | Failures resilience at SoS level | Automated management of uncertainty and resilience to failures. |
| | **Topic 3.5**: evolvability in SoS supported by virtual engineering (e.g. digital twins) | Virtualisation of IoT and edge services based on open SoS architectures and platforms | Automated virtualisation of IoT and edge services based on open SoS architectures and platforms | Dynamic and scalable virtualisation of IoT and edge services based for run-time optimisation on open SoS architectures and platforms |
| | **Topic 3.6**: methods and tools to manage | Technology frameworks supporting emergent self-adaptability | Automated technology and tools supporting emergency self- | Autonomous technology and tools supporting emergency self- |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| | emergencies in embedded and composable SoS. | | adaptability | adaptability |
| | **Topic 3.7**: service-based vertical and horizontal evolvability to enable high-level, and potentially cross-domain, evolvability of SoS | Open services enabling technology and data evolvability cross-domain | Open services and integration platforms enabling technology and data evolvability cross-domain | Open services and integration platforms enabling automated technology and data evolvability cross-domain |
| **Major Challenge 4: SoS integration along the life cycle.** | **Topic 4.1**: efficient and flexible engineering processes | SoA-inspired engineering processes, toolchains and tools | Engineering support for SoS emergent behaviours | Engineering support for emergent behaviours of very large SoS |
| | **Topic 4.2**: model based engineering | Partial automated generation of SoS software using model-based engineering and AI tools | Full automated generation of SoS software using model-based engineering | Model based engineering support providing engineering automation for very complex SoS solutions |
| | **Topic 4.3**: engineering tools supporting the complete engineering process along the system's lifecycle | Engineering tools enabling run-time engineering | Multi-stakeholders and multi-domains automated engineering process | Highly automated solution engineering in a multi-stakeholders and multi-domains SoS environment |
| | **Topic 4.4**: support for key automation requirements | SoS engineering process and tools partial support for fundamental automation requirements like e.g. real time, security, safety | SoS engineering process and tools full support for fundamental automation requirements like e.g. real time, security, safety | |
| | **Topic 4.5**: automated engineering | Automation of SoS software engineering from requirements to deployment | Technologies and tool for highly automated design time control analysis in SoS environments | Technologies and tool for autonomous run-time control analysis in SoS environments |
| | **Topic 4.6**: automated testing validation and verification (TV&V) | Automated and runtime SoS TV&V for parts of the engineering process | Automated runtime SoS TV&V for the entire engineering process | Autonomous runtime SoS TV&V |
| **Major Challenge 5: control in SoS composed of embedded and cyber-physical** | **Topic 5.1**: tools for control system analysis of SoS | Technologies and tool for design time control analysis in SoS environments | Automated technologies and tool for efficient and robust control design in SoS environments | Autonomous technologies and tool for efficient and robust control design in SoS environments |
| | **Topic 5.2**: considering humans, environment and the economy in the loop | Technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact | Automated technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact | Autonomous technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact |
| | **Topic 5.3**: support in SoS control design | Technologies and tool for efficient and robust control design in SoS environments | Automated technologies and tool for efficient and robust control designed TV&V in SoS environments | Autonomous technologies and tools for efficient and robust control run-time design and TV&V in SoS environments |
| | **Topic 5.4**: dynamic optimisation of communication effort, control architecture | Technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation | Model based technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation | Fully automated run-time technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation |
| | **Topics 5.5**: control system testing, validation and verification (TV&V) | Technologies and tools enabling design time and run-time TV&V in complex SoS solutions. | Model based technologies and tools enabling design time and run-time TV&V in complex SoS solutions | Automated technologies and tools enabling design time and run-time TV&V in complex SoS solutions |
| **Major Challenge 6: SoS monitoring and management** | **Topic 6.1**: Monitoring and management strategies and architectural concepts in OT-IT environments | Real time monitoring and management of evolving OT.IT environments | Scalable monitoring architecture applicable to large scale SoS | SoS integration platforms including scalable, and manageable monitoring capabilities |
| | **Topic 6.2**: Methodologies and technologies for monitoring and management of multiple and interrelated SoS dimensions | Functional, security and safety interrelations monitoring and management | Manageable monitoring architecture of multiple SoS dimensions | SoS management based on multi-dimensional monitoring |
| | **Topic 6.3**: Processes and technology for life cycle monitoring and | Approaches to life cycle monitoring and management for multiple SoS | SoS monitoring architecture along its life cycle | SoS integration platforms supporting SoS monitoring and management evolution along its life cycle |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
|  | management over SoS dimensions | dimensions. Like e.g. functionality, security and safety |  |  |

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**2.1**
EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

**2.2**
CONNECTIVITY

**2.3**
ARCHITECTURE AND DESIGN: METHODS AND TOOLS

**2.4**
QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

# 2

*Strategic Research and Innovation Agenda 2024*

# CROSS-SECTIONAL TECHNOLOGIES

# 2.1

*Cross-Sectional Technologies*

# EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

# 2 CROSS-SECTIONAL TECHNOLOGIES

## 2.1

## Edge Computing and Embedded Artificial Intelligence

### 2.1.1 Scope

### 2.1.1.1 **Introduction**

Our world is drastically changing with the deployment of digital technologies that provide ever increasing performance and autonomy to existing and new applications at a constant or decreasing cost but with a big challenge concerning energy consumption. Especially cyber-physical systems (CPS) place high demands on efficiency and latency and Artificial Intelligence (AI) on computing and memory. Distributed computing systems have diverse architectures and in addition tend to form a continuum between extreme edge, fog, mobile edge[1] and cloud. Nowadays, many applications need computations to be carried out on spatially distributed devices, generally where it is most efficient. This trend includes edge computing, edge intelligence (e.g. Cognitive CPS, Intelligent Embedded Systems, Autonomous CPS) where raw data is processed close to the source to identify the insight data as early as possible bringing several benefits such as reduce latency, bandwidth, power consumption, memory footprint, and increase the security and data protection.

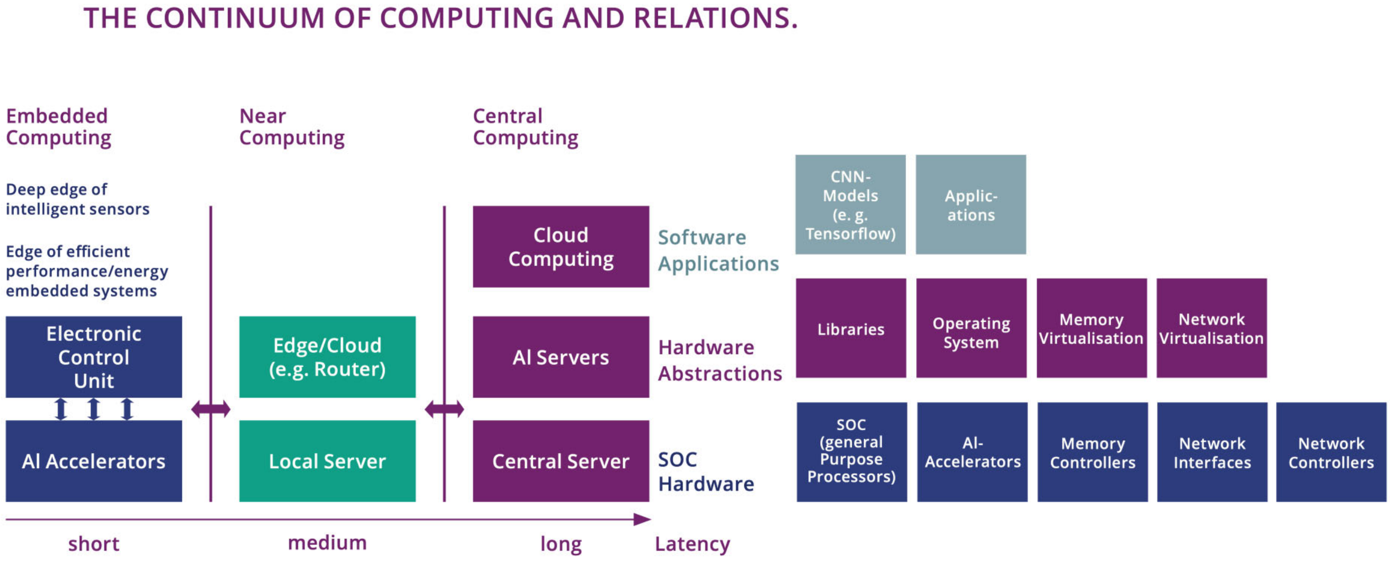


*Figure 2.1.1 - The continuum of computing and relations between the elements constituting an embedded AI system (figure from Gerd Teepe)*

The introduction of Artificial Intelligence (AI) at the edge for data analytics brings important benefits for a multitude of applications. New advanced, efficient, and specialized processing architectures (based on CPU, embedded GPU, accelerators, neuromorphic computing, FPGA and ASICs) are needed to increase, for several orders of magnitude, the edge computing performances and to drastically reduce the power consumption.

One of the mainstream uses of AI is to allow an easier and better interpretation of the data (unstructured data such as image files, audio files, or environmental data) coming from the physical world. Being able to interpret data from the environment locally triggers new applications such as autonomous vehicles. The use of AI in the edge will contribute to automate complex and advanced tasks and represents one of the most important innovations being introduced by the digital transformation. Important examples are its contribution in the recovery from the Covid-19 pandemic as well as its potential to ensure the required resilience in future crises[8]. Chat-GPT from OpenAI (released for use only on November 30th, 2022) triggered a lot of interest for Large Language Models (LLMs), likewise for Llama 1 (released for use and for researchers on February 2023), followed by the work of Stanford (Alpaca) on fine-tuning of models with limited resources. This allowed the emergence of a multiplicity of open-source models tuned with various datasets and publicly available on HuggingFace[2]. Llama 2 (released for download on July 2023), with a possibility of use for commercial purposes, enabled the effective utilisation of fine-tuned models on consumer grade devices, without requiring access to large datacenters for using them (training of the foundation models to create them still requires a large amount of computing power). Right after that, Qualcomm announced that they are working to optimise the execution on Llama 2 (certainly the 7G parameters models) on-device, opening the door for use of LLMs locally on phones and other devices. This paves the way of using LLMs on markets such as automotive, smartphones, home, robots, etc.

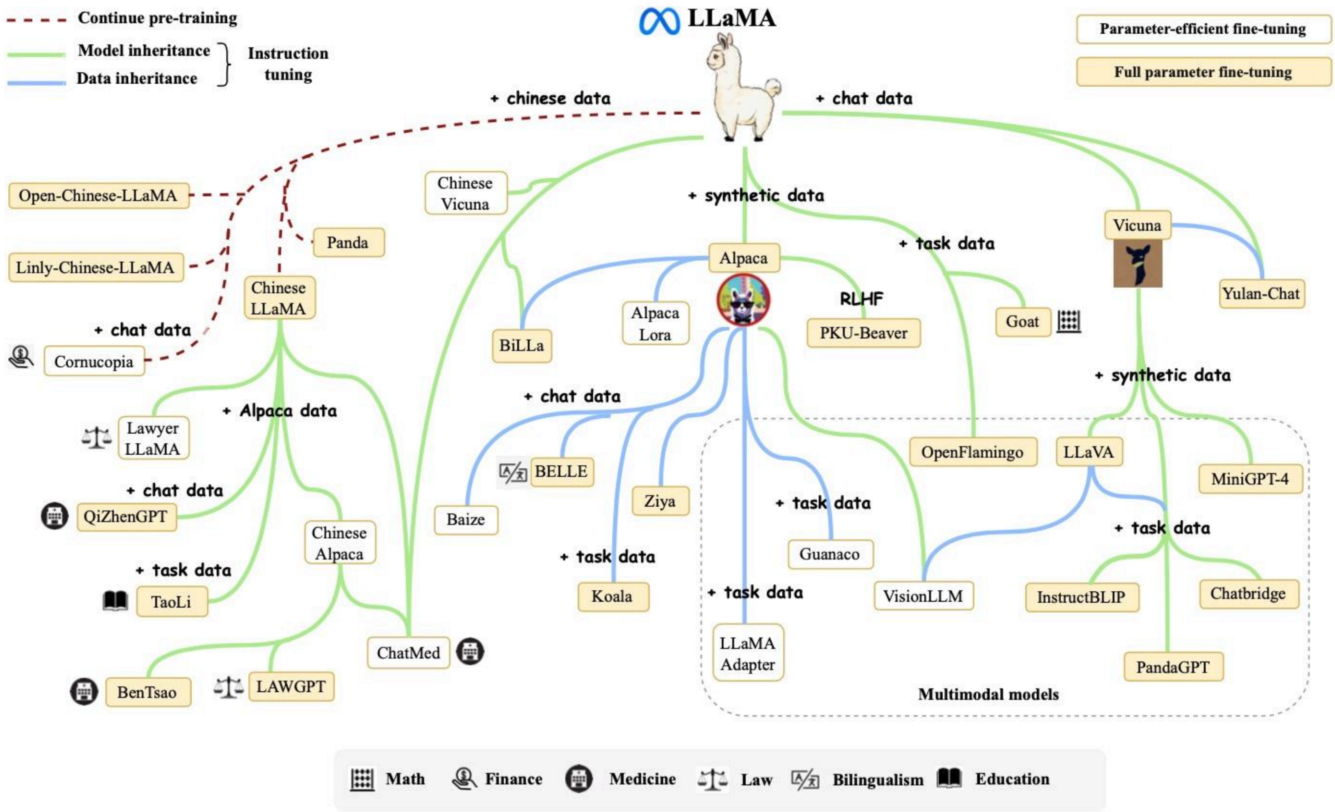


*Figure 2.1.2 - The family of fine-tuned models originating from LLaMa (from [2])*

This Chapter focuses on computing components, and more specifically on embedded architectures, edge computing devices and systems using artificial intelligence at the edge. These elements rely on process technology and embedded software, and have constraints on quality, reliability, safety, and security. They also rely on system composition (systems of systems) and design and tools techniques to fulfil the requirements of the various application domains.

**Furthermore, this chapter focuses on the trade-off between performances and power consumption reduction, and managing complexity (including security, safety, and privacy[3]) for embedded architectures to be used in different applications areas, which will spread edge computing and artificial intelligence use and their contribution to European sustainability.**

### 2.1.1.2 Positioning edge and cloud solutions

The centralised cloud computing model, including data analysis and storage for the increasing number of devices in a network, is limiting the capabilities of many applications, creating problems regarding interoperability, latency and response time, connectivity, privacy, and data processing.

Another issue is dependability that creates the risk of a lack of data availability for different applications, a large cost in energy consumption, and the solution concentration in the hands of a few cloud providers that raise concerns related to data security and privacy.

The increased number of intelligent IoT devices provides new opportunities for enterprise data management, as the applications and services are moving the developments toward the edge. Therefore, most of the IoT data generated and processed by enterprises could be processed at the edge, or on premises, rather than in the traditional data centre in the cloud.

Edge computing enhances the features and the capabilities (e.g. real-time) of IoT applications, embedded, and mobile processor landscape by performing data analytics through high-performance circuits using AI/ML techniques and embedded security. Edge computing allows the development of real-time applications, considering the processing is performed close to the data source. It can also reduce the amount of transmitted data by transforming an extensive amount of raw data into few insightful data with the benefits of decreasing communication bandwidth and data storage requirements, but also increasing security, privacy data protection, and reducing energy consumption. Moreover, edge computing provides mechanisms for distributing data and computing, making IoT applications potentially more resilient to malicious events. Edge computing can also provide distributed deployment models to address more efficient connectivity and latency, solve bandwidth constraints, provide higher and more "specialised" processing power and storage embedded at the network's edge. Other benefits are scalability, ubiquity, flexibility, and lower cost.

In this chapter, **edge computing** is described as a paradigm that can be implemented using different architectures built to support a distributed infrastructure of data processing (data, image, voice, etc.) as close as possible to the points of collection (data sources) and utilisation. In this context, the edge computing distributed paradigm provides computing capabilities to the nodes and devices of the edge of the network (or edge domain) to improve the performance (energy efficiency, latency, etc.), operating cost, reliability of applications and services, and contribute significantly to the sustainability of the digitalisation of the European society and economy. Edge computing performs data analysis by minimizing the distance between nodes and devices and reducing the dependence on centralised resources that serve them while minimizing network hops. Edge computing capabilities include a consistent operating approach across diverse infrastructures, the ability to perform in a distributed environment, deliver computing services to remote locations, application integration, and orchestration. It also adapts service delivery requirements to the hardware performance and develops AI methods to address applications with low latency and varying data rates requirements – in systems typically subject to hardware limitations and cost constraints, or with limited or intermittent network connections.

For intelligent embedded systems, the edge computing concept is reflected in the development of edge computing levels (micro, deep, meta, explained in the next paragraphs) that covers the computing and intelligence continuum from the sensors/actuators, processing, units, controllers, gateways, on-premises servers to the interface with multi-access, fog, and cloud computing.

A description of the micro, deep and meta edge concepts is provided in the following paragraphs (as proposed by the AIoT community).

The **micro-edge** describes intelligent sensors, machine vision, and IIoT devices that generate insight data and are implemented using microcontrollers built around processors architectures such as ARM Cortex M4, or recently RISC-V, which are focused on minimizing costs and power consumption. The distance from the data source measured by the sensors is minimised. The compute resources process this raw data in line and produce insight data with minimal latency. The hardware devices of the micro-edge physical sensors/actuators generate from raw data insight data and/or actuate based on physical objects by integrating AI-based elements into these devices and running AI-based techniques for inference and self-training.

**Intelligent micro-edge** allows IoT real-time applications to become ubiquitous and merged into the environment where various IoT devices can sense their environments and react fast and intelligently with an excellent energy-efficient gain. Integrating AI capabilities into IoT devices significantly enhances their functionality, both by introducing entirely new capabilities, and, for example, by replacing accurate algorithmic implementations of complex tasks with AI-based approximations that are better embeddable. Overall, this can improve performance, reduce latency, and power consumption, and at the same time increase the devices usefulness, especially when the full power of these networked devices is harnessed – a trend called AI on edge.

The **deep-edge** comprises intelligent controllers PLCs, SCADA elements, connected machine vision embedded systems, networking equipment, gateways and computing units that aggregate data from the sensors/actuators of the IoT devices generating data. Deep edge processing resources are implemented with performant processors and microcontrollers such as Intel i-series, Atom, ARM M7+, etc., including CPUs, GPUs, TPUs, and ASICs. The system architecture, including the deep edge, depends on the envisioned functionality and deployment options considering that these devices' cores are controllers: PLCs, gateways with cognitive capabilities that can acquire, aggregate, understand, react to data, exchange, and distribute information.

The **meta-edge** integrates processing units, typically located on-premises, implemented with high-performance embedded computing units, edge machine vision systems, and edge servers (e.g. high-performance CPUs, GPUs, FPGAs, etc.) that are designed to handle compute-intensive tasks, such as processing, data analytics, AI-based functions, networking, and data storage.

This classification is closely related to the distance between the data source and the data processing, impacting overall latency. A high-level rough estimation of the communication latency and the distance from the data sources are as follows. With micro-edge the latency is below 1millisecond (ms), and the distances are from zero to max 15 meters (m). For deep-edge distances are under 1 km and latency below 2-5 ms, meta-edge shows latencies of under 10 ms and distances under 50 km, and up to 50 km (also) for fog computing. MEC concepts are combined with near-edge, with 10-20 ms latency and 100 km distance, while far-edge is 20-50ms and 200 km, and cloud and data centres are more than 50 ms and 1000 km.

| | Latency | Distance |
|---|---|---|
| Micro-edge | Below 1ms | From 0 cm to 15 m |
| Deep-edge | Below 2-5 ms | Below 1km |
| Meta-edge | Below 10 ms | Below 50 km |
| Fog | 10-20 ms | Up to 50 km |
| MEC[4] + near-edge | 10-20 ms | 100 km |
| Far-edge | 20-50 ms | 200 km |
| Cloud/data centres/HPC | More than 50 -100 ms | 1000 km and beyond |

Deployments "at the edge" can contribute, thanks to its flexibility, to be adapted to the specific needs, to provide more energy-efficient processing solutions by integrating various types of computing architectures at the edge (e.g. neuromorphic, energy-efficient microcontrollers, AI processing units), reduce data traffic, data storage and the carbon footprint. One way to reduce the energy consumption is to know which data and why it is collected, which targets are achieved and to optimise all levels of processes, both at hardware and software levels, to achieve those targets, and finally to evaluate what is consumed to process the data. Furthermore, edge computing reduces the latency and bandwidth constraints of the communication network by processing locally and distributing computing resources, intelligence, and software stacks among the computing network nodes and between the centralised cloud and data centres.

In general, the edge (in the peripheral of a global network as the Internet) includes compute, storage, and networking resources, at different levels as described above, that may be shared by several users and applications using various forms of virtualisation and abstraction of the resources, including standard APIs to support interoperability.

More specifically, an edge node covers the edge computing, communication, and data analytics capabilities that make it smart/intelligent. An edge node is built around the computing units (CPUs, GPUs/FPGAs, ASICs platforms, AI accelerators/processing), communication network, storage infrastructure and the applications (workloads) that run on it.

The edge can scale to several nodes, distributed in distinct locations and the location and the identity of the access links is essential. In edge computing, all nodes can be dynamic. They are physically separated and connected to each other by using wireless/wired connections in topologies such as mesh. The edge nodes can be functioning at remote locations and operate semi-autonomously using remote management administration tools.

The edge nodes are optimised based on the energy, connectivity, size, cost, and their computing resources are constrained by these parameters. In different application cases, it is required to provide isolation of edge computing from data centres in the cloud to limit the cloud domain interference and its impact on edge services.

Finally, the edge computing concept supports a dynamic pool of distributed nodes, using communication on partially unreliable network connections while distributing the computing tasks to resource-constrained nodes across the network.

### 2.1.1.3 Positioning Embedded Artificial Intelligence

Thanks to the fast development in Machine Learning during the last decade, Artificial Intelligence is nowadays widely used. However, it demands huge quantity of data, especially for supervised learning using Deep Learning techniques, to get accurate result levels. According to the application complexity, neuronal deep learning architectures are becoming more and more complex and demanding in terms of calculation time. As a result of the huge AI success, its perversive deployment and its computing costs, the worldwide energy consumed will be increased dramatically to levels that will be unsustainable in the near future. However, for a similar performance, due to increase of the efficiency of the algorithm and various quantisation and pruning techniques, the computing and storage need tends to decrease over time. Complex tasks such as voice recognition which required models of 100 GB in the cloud are now reduced to less than half a gigabyte and can be run on local devices, such as smartphones.

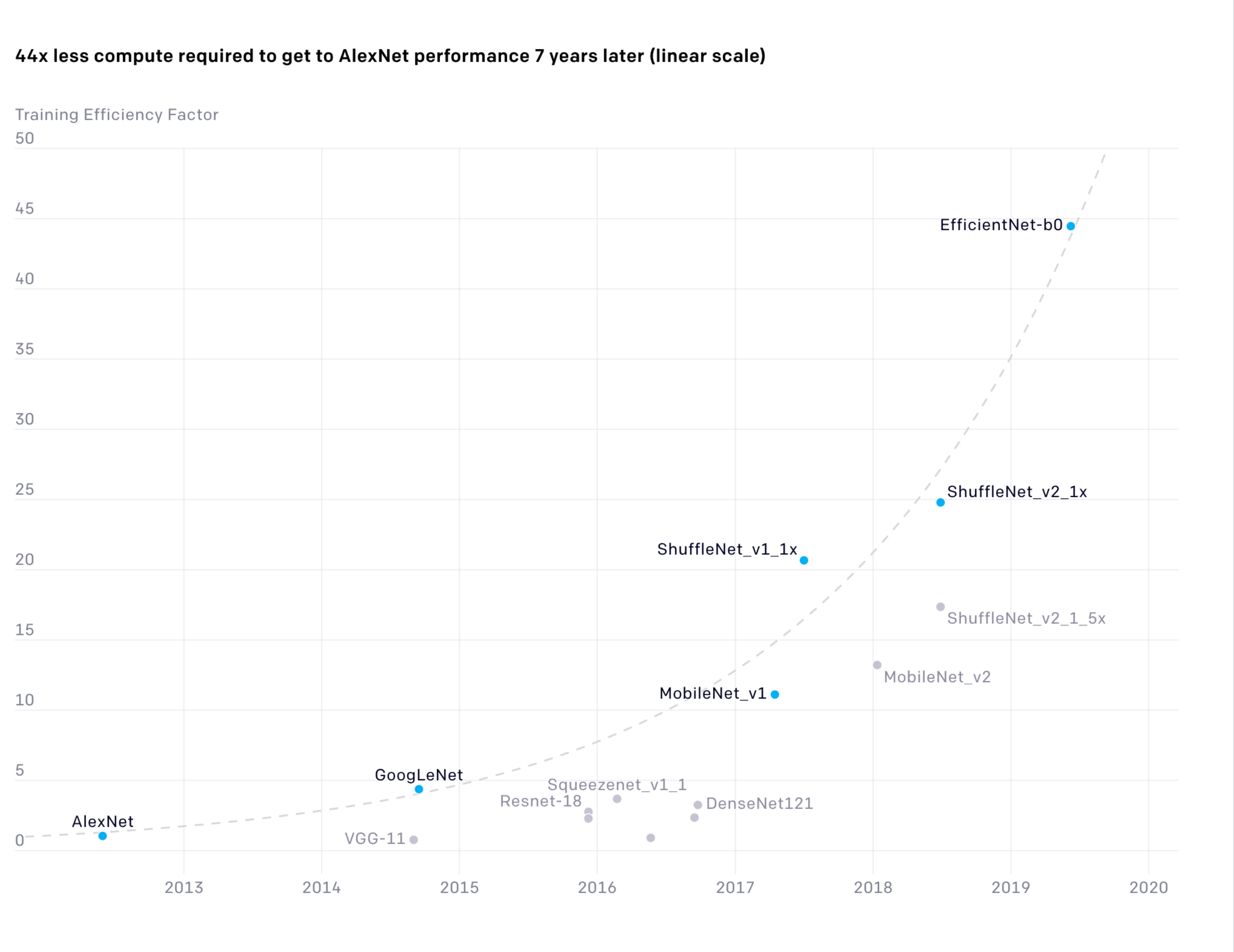


*Figure 2.1.3 - Increase of efficiency used to train to AlexNet level performance (from [11])*

Artificial Intelligence is a very efficient tool for several applications (e.g. image recognition and classifications, natural language understanding, complex manufacturing optimisation, supply chain improvements, etc.) where pattern detection and process optimisation can be done. The recent boom of LLMs allows for a more natural interface between machines and humans. Machines can now process natural language requests locally. These LLMs seem also good for multimodality, e.g. for explaining pictures or dynamically controlling robots (Palm 2 - **https://ai.google/discover/palm2/** ). First examples show abilities to generate code, or more precisely, “glue” code to use an existing API, making “programming” in natural language even accessible to people without programming skills. LLMs can also help programmers to be more efficient, and they just started to also help in the circuit design. More details are given in the Methodology and Tools chapter. Of course, using these LLMs on embedded devices induces more challenges in terms of complexity, power efficiency and costs. They can be used for voice controlling devices or doing high-level tasks, such as answering questions on a vehicle's condition, but this will only be applied on a large scale once their performance, energy consumption and cost is affordable for the use case. New architectures and approaches will be required to achieve these goals in a cost-efficient manner.

As a side effect, data collection is exploding with high heterogeneity levels, coming from numerous and very various sensors. On top, the bandwidth connecting data centres is limited and not all data need to be processed in the cloud.

Naturally, systems are evolving from a centralised to a distributed architecture. Then, artificial Intelligence is a crucial element that allows for soft and optimised operation of distributed systems. Therefore, it is increasingly more embedded in the various network nodes even down to the very edge. Approaches like federated learning allows for consolidation of the data learnt from various local devices, thus preserving privacy of data; only the results of the partial learning are communicated for consolidation into global models that then will be distributed into the edge devices to update their behavior.

Such powerful tool allows edge computing to be more efficient in treating the data locally, while also minimizing the necessary data transmission to the upper network nodes. Another advantage of Embedded Artificial Intelligence is its capacity to self-learn and adapt to the environment through the data collected. Today's learning techniques are still mostly based on supervised learning, but semi-supervised, self-supervised, unsupervised, or federative learning techniques are being developed. LLMs training is self-supervised, often also with human feedback. They show interesting properties for few-shot or zero-shot learning (only few examples, or no examples at all, are required to do a new task proposed by a "prompt").

At the same time, semiconductor technologies, hardware architectures, algorithms and software are being developed and industrialised to reduce memory size, time for data treatment and energy consumption, thus making Embedded AI an important pillar for edge computing. Tools for Embedded AI are also rapidly evolving leading to faster and easier implementation at all levels of the network.

### 2.1.1.4 Scope of the chapter

The scope of this Chapter is to cover the hardware architectures and their realisations (Systems of Chip, Embedded architectures), mainly for edge and "near the user" devices such as IoT devices, cars, ICT for factories and local processing and servers. Data centres and electronic components for data centres are not the focus of the chapter, except when the components can be used in local processing units or local servers (local clouds, swarm, fog computing, etc.). We therefore also cover this "edge" side of the "continuum of computing" and the synergies with the cloud. Hardware for HPC centres is also not the focus, even if the technologies developed for HPC systems are often found in high end embedded systems a few years (decades?) after. Each Section of this chapter is split into 2 sub-Sections, from the generic to the more specific:

- Generic technologies for compute, storage, and communication (generic Embedded architectures technologies) and technologies that are more focused towards edge computing.
- Technologies focused on devices using Artificial Intelligence techniques (at the edge).

The technological aspects, at system level (PCB, assembly, system architecture, etc.), and embedded and application software are not part of this chapter as they are covered in other chapters. Software is important for these programmable or configurable embedded devices, but will be handled in the "embedded software" chapter.

This chapter mainly covers the elements foreseen to be used to compose AI or edge systems:

- **Processors** with high energy efficiency,
- **Accelerators** (for AI and for other tasks, such as security),
- **DPU** (Data processing Unit, e.g. logging and collecting information for automotive and other systems) and processing data early (decreasing the load on processors/accelerators),
- **Memories and associated controllers**, specialised for low power and/or for processing data locally (e.g. using non-volatile memories such as PCRAM, CBRAM, MRAM for synaptic functions, and In/Near Memory Computing), etc.
- **Power management**.

Of course, all the elements to build a SoC are also necessary, but not specifically in the scope of this chapter:

- **Security infrastructure** (e.g. Secure Enclave) with placeholder for customer-specific secure elements (PUF, cryptographic IPs…). Security requirements are dealt with details in the corresponding chapter. The appearance of LLMs / Generative AI calls for security measures, e.g. proof of origin/authenticity etc. will have an impact on the hardware. They should also run efficiently, in a protected environment without consuming too much resources.
- **Field connectivity IPs** (see connectivity Chapter, but the focus here is on field connectivity) (all kinds, wired, wireless, optical), ensuring interoperability.
- Integration using chiplet and interposer interfacing units will be detailed in the technology chapter.
- And all other elements such as coherent cache infrastructure for many-cores, scratchpad memories, smart DMA, NoC with on-chip interfaces at router level to connect cores (coherent), memory (cache or not) and IOs (IO coherent or not), SerDes, high speed peripherals (PCIe controllers and switches, etc.), trace and debug hardware and low/medium speed peripherals (I2C, UART, SPI etc.).

However, the chapter will not detail the challenges for each of these elements, but only the generic challenges that will be grouped in 1) Edge computing and 2) Embedded Artificial Intelligence domains.

In a nutshell, the main recommendation is a paradigm shift towards distributed low power architectures/topologies:

- Distributed computing
- AI using distributed computing, leading to distributed intelligence.

#### 2.1.1.5 State of the Art

This paragraph gives an overview of the importance that AI and embedded intelligence is playing in the sustainable development, the market perspectives for the AI components and the indication of some semiconductor companies providing components and key IPs.

**Impact of AI and embedded intelligence in sustainable development**

AI and particularly embedded intelligence, with its ubiquity and its high integration level having the capability “to disappear” in the environment (ambient intelligence), is significantly influencing many aspects of our daily life, our society, the environment, the organisations in which we work, etc. AI is already impacting several heterogeneous and disparate sectors, such as companies’ productivity [4], environmental areas like nature resources and biodiversity preservation [5], society in terms gender discrimination and inclusion[13] [14], smarter transportation systems[15], etc. just to mention a few examples. The adoption of AI in these sectors is expected to generate both positive and negative effects on the sustainability of AI itself, of the solutions based on AI and on their users[16] [17]. It is difficult to extensively assess these effects and there is not, to date, a comprehensive analysis of their impact on sustainability. A recent study[18] has tried to fill this gap, analyzing AI from the perspective of 17 Sustainable Development Goals (SDGs) and 169 targets internationally agreed in the 2030 Agenda for Sustainable Development[19]. From the study it emerges that AI can enable the accomplishment of 134 targets, but it may also inhibit 59 targets in the areas of society, education, health care, green energy production, sustainable cities, and communities.

From a technological perspective AI sustainability depends, at first instance, on the availability of new hardware[20] and software technologies. From the application perspective, automotive, computing and healthcare are propelling the large demand of AI semiconductor components and, depending on the application domains, of components for embedded intelligence and edge AI. This is well illustrated by car factories being on hold because of the shortage of electronic components. Research and industry organisations are trying to provide new technologies that lead to sustainable solutions redefining traditional processor architectures and memory structure. We already saw that computing near, or in-memory, can lead to parallel and high-efficient processing to ensure sustainability.

The second important component of AI that impacts sustainability concerns software and involves the engineering tools adopted to design and develop AI algorithms, frameworks, and applications. The majority of AI software and engineering tools adopt an open-source approach to ensure performance, lower development costs, time-to-market, more innovative solutions, higher design quality and software engineering sustainability. However, the entire European community should contribute and share the engineering efforts at reducing costs, improving the quality and variety of the results, increasing the security and robustness of the designs, supporting certification, etc.

The report on “Recommendations and roadmap for European sovereignty on open-source hardware, software and RISC-V Technologies” [21] discusses these aspects in more details.

Sustainability through open technologies extends also to open data, rules engines[22] and libraries. The publication of open data and datasets is facilitating the work of researchers and developers for ML and DL, with the existence of numerous images, audio and text databases that are used to train the models and become benchmarks[23]. Reusable open-source libraries[24] allow to solve recurrent development problems, hiding the technical details and simplifying the access to AI technologies for developers and SMEs, maintaining high-quality results, reducing time to market and costs.

In the field of generative AI, some companies provide new models, but often not the training data set. For example, the foundation models Llama 2 from Meta are available in various size, and the same goes for Bloom. Also Phi from Microsoft, Mistral 7B from Mistral AI or stable-diffusion XL from Stability AI are easily accessible. These models are often fine-tuned by the community to shape them for various applications. Hugging Face has more than 490 000 models that can be downloaded. Some data sets are also available in open-source, but mainly for fine-tuning those LLMs. The source code of the software required to run those models is also available in open-source (on GitHub mainly).

Eventually, open-source initiatives (being so numerous, heterogeneous, and adopting different technologies) provide a rich set of potential solutions, allowing to select the most sustainable one depending on the vertical application. At the same time, open source is a strong attractor for applications developers as it gathers their efforts around the same kind of solutions for given use cases, democratises those solutions and speeds up their development. However, some initiatives should be developed, at European level, to create a common framework to easily develop different types of AI architectures (CNN, ANN, SNN, LLM, etc.). This initiative should follow the examples of GAMAM (Google, Amazon, Meta, Apple, Microsoft). GAMAM have greatly understood its value and elaborated business models in line with open source, representing a sustainable development approach to support their frameworks[25]. It should be noted that open-source hardware should not only cover the processors and accelerators, but also all the required infrastructure IPs to create embedded architectures. It should be ensured that all IPs are interoperable and well documented, are delivered with a verification suite, and remain maintained constantly to keep up with errata from the field and to incorporate newer requirements. The availability of automated SoC composition solutions, allowing to build embedded architectures design from IP libraries in a turnkey fashion, is also a desired feature to quickly transform innovation into PoC (Proof of Concept) and to bring productivity gains and shorter time-to-market for industrial projects.

The extended GAMAM and the BATX also have large in-house databases required for the training and the computing facilities. In addition, almost all of them are developing their chips for DL (e.g. Google with its line of TPUs) or made announcements that they will. The US and Chinese governments have also started initiatives in this field to ensure that they will remain prominent players in the field, and it is a domain of competition.

It will be a challenge for Europe to excel in this race, but the emergence of AI at the edge, and its know-how in embedded systems, might be winning factors. However, the competition is fierce and the big names are in with big budgets and Europe must act quickly, because US and Chinese companies are already also moving in this "intelligence at the edge" direction (e.g. with Intel Compute Stick, Google's Edge TPU, NVIDIA's Jetson Nano and Orin Nano, and multiples start-ups both in US and China, etc.). Qualcomm already announced that its new generation systems will support LLMs (Llama 2, certainly a quantised version of the 7B parameter model).

Recently, the attention to the identification of sustainable computing solutions in modern digitalisation processes has significantly increased. Climate changes and an initiative like the European Green Deal[26] are generating more sensitivity to sustainability topics, highlighting the need to always consider the technology impact on our planet, which has a delicate equilibrium with limited natural resources[27]. The computing approaches available today, as cloud computing, are in the list of the technologies that could potentially lead to unsustainable impacts. A recent study[28] has clearly confirmed the importance of edge computing for sustainability but, at the same time, highlighted the necessity of increasing the emphasis on sustainability, remarking that "research and development should include sustainability concerns in their work routine" and that "sustainable developments generally receive too little attention within the framework of edge computing". The study identifies three sustainability dimensions (societal, ecological, and economical) and proposes a roadmap for sustainable edge computing development where the three dimensions are addressed in terms of security/privacy, real-time aspects, embedded intelligence and management capabilities.

**Market perspectives**

Several market studies, although they don't give the same values, show the huge market perspectives for AI use in the next years.

According to ABI Research, it is expected that 1.2 billion devices capable of on-device AI inference will be shipped in 2023, with 70% of them coming from mobile devices and wearables. The market size for ASICs responsible for edge inference is expected to reach US$4.3 billion by 2024 including embedded architectures with integrated AI chipset, discrete ASICs, and hardware accelerators.

The market for semiconductors powering inference systems will likely remain fragmented because potential use cases (e.g. facial recognition, robotics, factory automation, autonomous driving, and surveillance) will require tailored solutions. In comparison, training systems will be primarily based on traditional CPUs, GPUs, FPGAs infrastructures and ASICs.

According to McKinsey, it is expected by 2025 that AI-related semiconductors could account for almost 20 percent of all demand, which would translate into about $65 billion in revenue with opportunities emerging at both data centres and the edge.

According to a recent study, the global AI chip market was estimated to USD 9.29 billion in 2019 and it is expected to grow to USD 253.30 billion by 2030, with a CAGR of 35.0% from 2020-2030.

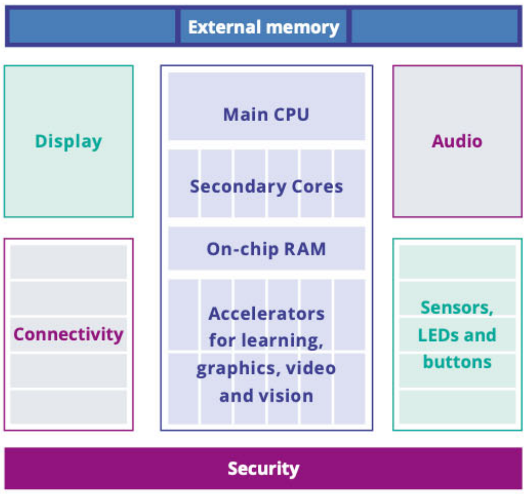
**AI components vendors**

In the next few years, the hardware is serving as a differentiator in AI, and AI-related components will constitute a significant portion of future demand for different applications.

Qualcomm has launched the fifth generation Qualcomm AI Engine, which is composed of Qualcomm Kyro Central Processing Unit (CPU), Adreno Graphics Processing Unit (GPU), and Hexagon Tensor Accelerator (HTA). Developers can use either CPU, GPU, or HTA in the AI Engine to carry out their AI workloads. Qualcomm also launched the Qualcomm Neural Processing Software Development Kit (SDK) and Hexagon NN Direct to facilitate the quantisation and deployment of AI models directly on the Hexagon 698 Processor. Qualcomm also announced to support Meta's Llama 2 models in future chips. Samsung's Exynos 2400 (mobile processor for smartphones) shows AI performance that is 14.7 times better than those of its predecessor, the Exynos 2200, launched in January 2022. Text-to-image AI running locally was demonstrated on this chip.

Huawei and MediaTek incorporate their embedded architectures into IoT gateways and home entertainment, and Xilinx finds its niche in machine vision through its Versal ACAP SoC. NVIDIA has advanced the developments based on the GPU architecture, NVIDIA Jetson AGX platform, a high performance SoC that features GPU, ARM-based CPU, DL accelerators and image signal processors. NXP and STMicroelectronics have begun adding AI HW accelerators and enablement SW to several of their microprocessors and microcontrollers.

ARM is developing the new Cortex-M55 core for machine learning applications and used in combination with the Ethos-U55 AI accelerator. Both are designed for resource-constrained environments. The new ARM's cores are designed for customised extensions and for ultra-low power machine learning.



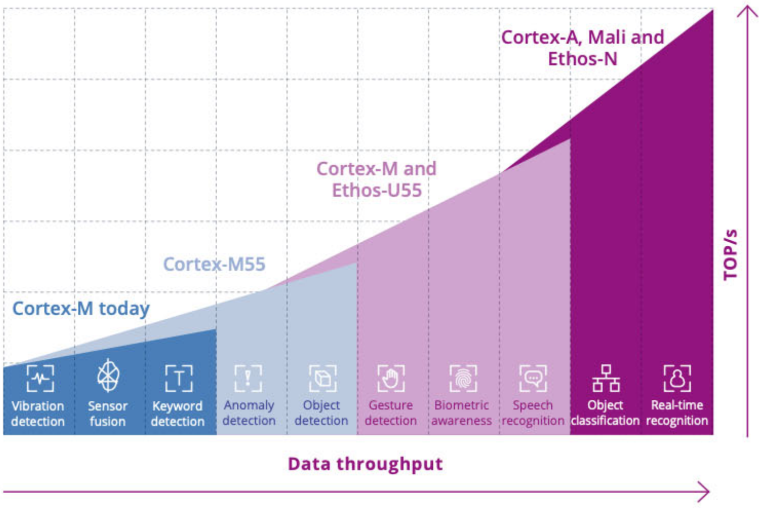


*Figure 2.1.4 - Example of architecture of a modern SoC (from Paolo Azzoni, see also Chapter 1.3) / Arm's Cortex-M55 and Ethos-U55 Tandem. Provide processing power for gesture recognition, biometrics, and speech recognition applications (Source: Arm).*

Open-source hardware, championed by RISC-V, will bring forth a new generation of open-source chipsets designed for specific ML and DL applications at the edge. French start-up GreenWaves is one of European companies using RISC-V cores to target the ultra-low power machine learning space. Its devices, GAP8 and GAP9, use 8- and 9-core compute clusters, the custom extensions give its cores a 3.6x improvement in energy consumption compared to unmodified RISC-V cores.

The development of the neuromorphic architectures is accelerated as the global neuromorphic AI semiconductor market size is expected to grow.

## 2.1.2 Technology Enabled Benefits

Driven by Moore's Law over the last 40 years[5], computing and communication brought important benefits to society. Complex computations in the hands of users and hyper-connectivity have been at the source of significant innovations and improvements in productivity, with a significant cost reduction for consumer products at a global level, including products with a high electronic content, traditional products (e.g. medical and machinery products) and added value services.

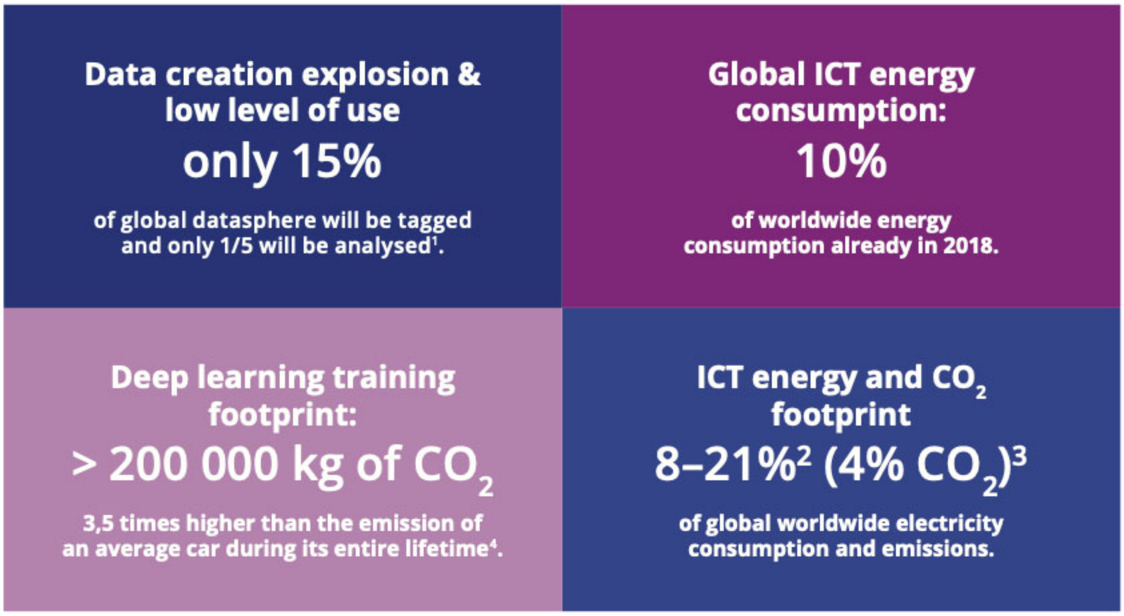
Computing is at the heart of a wide range of fields by controlling most of the systems with which humans interact. It enables transformational science (Climate, Combustion, Biology, Astrophysics, etc.), scientific discovery and data analytics. But the advent of edge computing and of AI on the edge, enabling complete or partially autonomous cyber-physical systems, requires tremendous improvements in terms of semantics and use case knowledge understanding, and of new computing solutions to manage it. Even if deeply hidden, these computing solutions directly or indirectly impact our ways of life: consider, for example, their key role in solving the societal challenges listed in the application chapters, in optimizing industrial processes costs, and in enabling the creation of cheaper products (e.g. delocalised healthcare).

They will also enable synergies between domains: e.g. self-driving vehicles with higher reliability and predictability will directly benefit medical systems, consumer smart bracelets or smart watches for lifestyle monitoring reduce the impact of health problemss[30] with a positive impact on the healthcare system costs. First-aid and insurance services are simplified and more effective thanks to cars localization and remote-control functionalities.

These computing solutions introduce new security improvements and threats. Edge Computing allows a better protection of personal data, being stored, and processed only locally, and this ensures the privacy rights required by GDPR. But at the same time, the easy accessibility to the devices and new techniques, like AI (and especially generative AI), generates a unique opportunity for hackers to develop new attacks. It is, then, paramount to find interdisciplinary trusted computing solutions and develop appropriate counter measures to protect them in case of attacks. For example, Industry 4.0 and forthcoming Industry 5.0[31] requires new architectures that are more decentralised, new infrastructures and new computational models that satisfy high level of synchronisation and cooperation of manufacturing processes, with a demand of resources optimisation and determinism that cannot be provided by solutions that rely on "distant" cloud platforms or data centres[32], but that can ensure low-latency data analyses, that are extremely important for industrial application[33].

These computing solutions have also to consider the man in the loop: especially with AI, solutions ensuring a seamless connection between man and machine will be a key factor. Eventually, a key challenge is to keep the environmental impact of these computing solutions under control, to ensure the European industry sustainability and competitiveness. LLMs which interface with humans using natural language (voice or text) could facilitate the use of electronic devices for people that are not used to electronic systems. They can even be used in vehicles to control ancillary functions.

The following figure illustrates an extract of the challenges and expected market trend of edge computing and AI at the edge.



**Data creation explosion & low level of use**

**only 15%**

**of global datasphere will be tagged and only 1/5 will be analysed[1].**

**Global ICT energy consumption:**

**10%**

**of worldwide energy consumption already in 2018.**

**Deep learning training footprint:**

**> 200 000 kg of $CO_2$**

**3,5 times higher than the emission of an average car during its entire lifetime[4].**

**ICT energy and $CO_2$ footprint**

**8–21%[2] (4% $CO_2$)[3]**

**of global worldwide electricity consumption and emissions.**

*[1] IDC Data Age 2025 study, sponsored by Seagate, April 2017 | [2] Challenges 2015, 6, 117-157; doi:10.3390/challe6010117, projection from Anders Andrae, https://www.nature.com/articles/d41586-018-06610-y | [3] Internation Energy Agency | [4] https://lejournal.cnrs.fr/articles/numerique-le-grand-gachis-energetique*

*Figure 2.1.5 - Challenges and expected market evolution.*

AI introduces a radical improvement to the intelligence brought to the products through microelectronics and could unlock a completely new spectrum of applications and business models. The technological progress in microelectronics has increased the complexity of microelectronic circuits by a factor of 1000 over the last 10 years alone, with the integration of billions of transistors on a single microchip. AI is therefore a logical step forward from the actual microelectronics control units and its introduction will significantly shape and transform all vertical applications in the next decade. AI will be used to design new and better performing chips. (NVIDIA is already using AI-based techniques to develop their chips; they claim that the latest NVIDIA Hopper GPU architecture has nearly 13,000 instances of AI-designed circuits).

AI and edge computing have become core technologies for the digital transformation and to drive a sustainable economy. AI will allow to analyze data on the level of cognitive reasoning to take decisions locally on the edge (embedded artificial intelligence), transforming the Internet of Things (IoT) into the Artificial Intelligence of Things (AIoT). Likewise, control and automation tasks, which are traditionally carried out on centralised computer platforms will be shifted to distributed computing devices, making use of e.g. decentralised control algorithms. Edge computing and embedded intelligence will allow to significantly reduce the energy consumption for data transmissions, will save resources in key domains of Europe’s industrial systems, will improve the efficient use of natural resources, and will also contribute to improve the sustainability of companies.

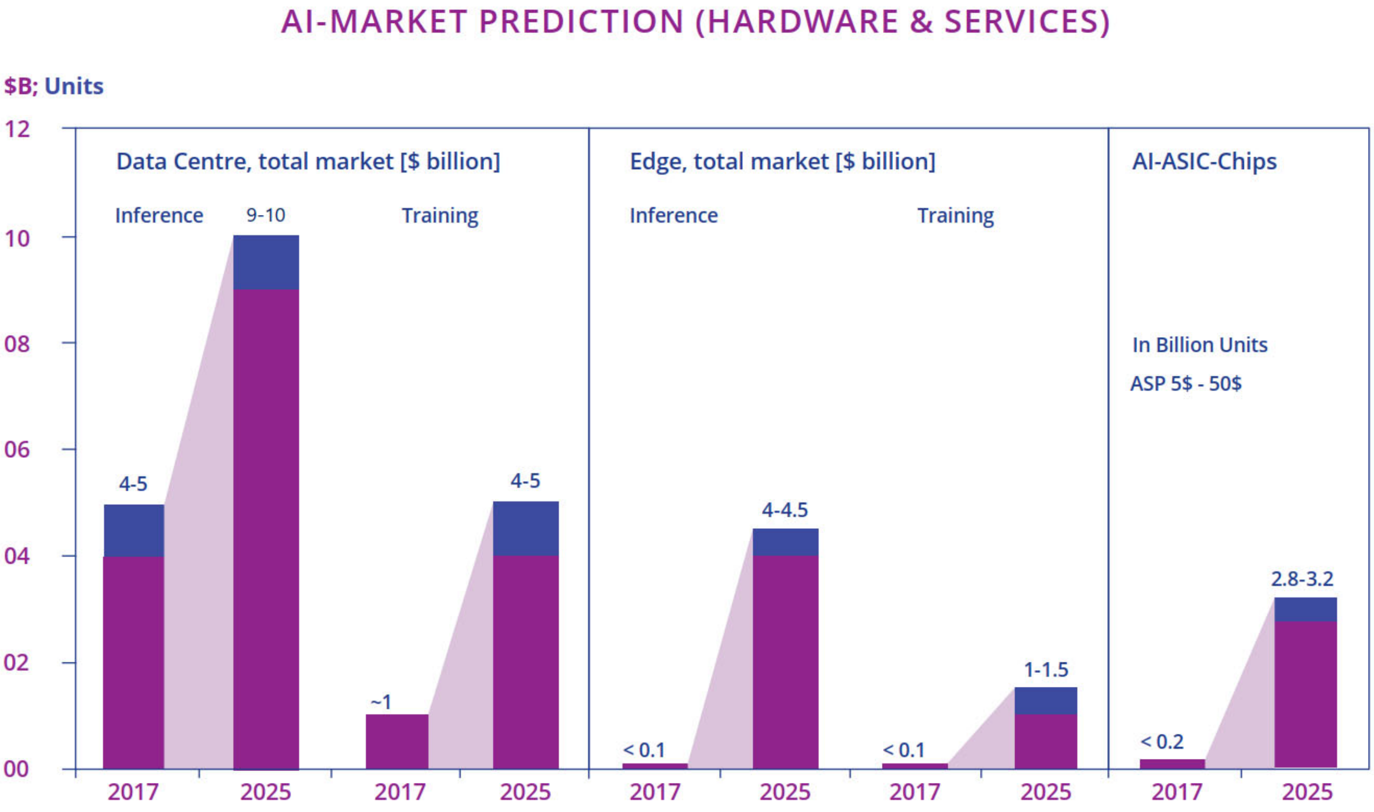


*Figure 2.1.6 - Illustration of an extract of the challenges and the expected market trend for AI and edge computing AI-Market prediction (Hardware & Services) (Source: Tractica, May 2019, McKinsey & Company)*

## 2.1.3 Application Breakthrough

Technologies allowing for low power solutions are almost here. What is now key is to integrate these solutions as close as possible to the production of data and sensors.

The key issues to the digital world are the availability of affordable computing resources and transfer of data to the computing node with an acceptable power budget. Computing systems are morphing from classical computers with a screen and a keyboard to smart phones and to deeply embedded systems in the fabric of things. This revolution on how we now interact with machines is mainly due to the advance in AI, more precisely of machine learning (ML) that allows machines to comprehend the world not only on the basis of various signal analysis but also on the level of cognitive sensing (vision and audio). Each computing device should be as efficient as possible and decrease the amount of energy used.

Low-power neural network accelerators will enable sensors to perform online, continuous learning and build complex information models of the world they perceive. Neuromorphic technologies such as spiking neural networks and compute-in-memory architectures are compelling choices to efficiently process and fuse streaming sensory data, especially when combined with event-based sensors. Event-based sensors, like the so-called retinomorphic cameras, are becoming extremely important especially in the case of edge computing where energy could be a very limited resource. Major issues for edge systems, and even more for AI-embedded systems, is energy efficiency and energy management. Implementation of intelligent power/energy management policies are key for systems where AI techniques are part of processing sensor data and power management policies are needed to extend the battery life of the entire system.

As extracting useful information should happen on the (extreme) edge device, personal data protection must be achieved by design, and the amount of data traffic towards the cloud and the edge-cloud can be reduced to a minimum. Such intelligent sensors not only recognise low-level features but will be able to form higher level concepts as well as require only very little (or no) training. For example, whereas digital twins currently need to be hand-crafted and built bit-for-bit, so to speak, tomorrow's smart sensor systems will build digital twins autonomously by aggregating the sensory input that flows into them.

To achieve intelligent sensors with online learning capabilities, semiconductor technologies alone will not suffice. Neuroscience and information theory will continue to discover new ways[6] of transforming sensory data into knowledge. These theoretical frameworks help model the cortical code and will play an important role towards achieving real intelligence at the extreme edge.

AI systems use the training and inference for providing the proper functions of the system, and they have significant differences in terms of computing resources provided by the AI chips. Training is based on past data using datasets that are analyzed, and the findings/patterns are built into the AI algorithm. Current hardware used for training needs to provide computation accuracy, support sufficient representation accuracy, e.g. floating-point or fixed-point with long word-length, large memory bandwidth, memory management, synchronisation techniques to achieve high computational efficiency and fast write time and memory access to a large amount of data[34]. However, recent research points to increasing training potential for complex CNN models even on constrained edge devices[35].

Reinforcement learning (RL) is a booming area of machine learning and is based on how agents ought to take actions in an environment in order to maximise the notion of cumulative reward. Recent work[36] develops systems that were able to discover their own reward function from scratch. Similarly, Auto-ML allows to determine a "good" structure for a DL system to be efficient in a task. But all those approaches are also very compute demanding.

New deep learning models are introduced at an increasing rate and one of the recent ones, with large applications potential, are transformers, which are the basis of LLMs. Based on the attention model[37], it is a "sequence-to-sequence architecture" that transforms a given sequence of elements into another sequence. Initially used for NLP (Natural Language Processing), where it can translate one sequence in a first language into another one, or complement the beginning of a text with potential follow-up, it is now extended to other domains such as video processing or elaborating a sequence of logical steps for robots. It is also a self-supervised approach: for learning it does not need labelled examples, but only part of the sequence, the remaining part being the "ground truth". The biggest models, such as GPT3, are based on this architecture. GPT3 was in the spotlights in May 2020 because of its potential use in many different applications (the context being given by the beginning sequence) such as generating new text, summarizing text, translating text, answering to questions and even generating code from specifications. This was even amplified by GPT4, and all those capabilities were made visible to the public in November 2022 with Chat-GPT, which triggered a maximum of hype and expectations. Even if today transformers are mainly used for cloud applications, this kind of architecture is rippling down in embedded system. Small to medium size (7 to 13 G parameters models) can be executed on single board computers such as Jetson Orin nano and even Raspberry PI. Quantisation is a very important process to reduce the memory footprint of those models and 4-bit LLMs performs rather well. The new GPUs of NVIDIA support float8 in order to efficiently implement transformers. Supporting LLMs in a low-power and efficient way on edge devices is a new important challenge.

The inference is the application of the learned algorithm to the real devices to solve specific problems based on present data. The AI hardware used for inference needs to provide high speed, energy efficiency, low cost, fixed-point representation, efficient reading memory access and efficient network interfaces for the whole hardware architecture. The development of AI-based devices with increased performance and energy efficiency allows the AI inference "at the edge" (embedded intelligence) and accelerates the development of middleware allowing a broader range of applications to run seamlessly on a wider variety of AI-based circuits. Companies like Google, Gyrfalcon, Mythic, NXP, STMicroelectronics and Syntiant are developing custom silicon for the edge. As an example, Google was releasing Edge TPU, a custom processor to run TensorFlow Lite models on edge devices. NVIDIA is releasing the Jetson Orin Nano range of products, allowing to perform up to 40 TOPS of sparce neural networks within a 15W power range[38].

The Tiny ML community (**https://www.tinyml.org/** ) is bringing Deep Learning to microcontrollers with limited resources and at ultra-low energy budget. The MLPerf allows to benchmark devices on similar applications (**https://github.com/mlcommons/tiny** ), because it is nearly impossible to compare performances on figures given by chips providers.

In summary we see the following disruptions on the horizon, once embedded AI enters the application space broadly:

- Various processing, especially concerning AI functionalities, are moved to local devices, such as voice and environment recognition, allowing privacy preserving functionalities.
- LLMs running on embedded devices in the deep edge (e.g. mobile phones) and meta edge (e.g. autonomous vehicles, industrial on premises processing units) are expected in the near future.
- The latent intelligence of things will be enabled by AI.
- Federated functionalities will emerge (increasing the functionality of a device by using capabilities, resources, or neighboring devices).
- Connected functionalities will also show up: this will extend the control and automation of a single system (e.g. a truck, a car) to a network of systems (e.g. a truck platoon), resulting in networked control of a cyber-physical system. The benefit of this is generally better performance and safety. It will also set the foundation for autonomous machines (including vehicles).
- The detection of events by camera and other long-range sensors (radar, lidar, etc.) is coming into action. Retina sensors will ensure low power operation of the system. Portable devices for blind people will be developed.
- The possibilities for disabled people to move their arms and legs comes into reach, as AI-conditioned sensors will directly be connected to the brain.
- The use of conversational interfaces will be drastically increased, improving the human machine interface with reliable understanding of natural language.

### 2.1.4 Strategic Advantage for the EU

Edge computing and Embedded Artificial Intelligence are key enablers for the future, and Europe should act quickly to play a global role and have a certain level of control of the assets we use in Europe. Further development of AI can be a strategic advantage for Europe, but we are not in a leading position.

Already today AI is being used as a strategic competitive advantage. Tesla is the first car company which is marketing a driving-assistance-system as "auto-pilot". Although it is not qualified to operate without human intervention, it is a significant step forward towards autonomous driving. Behind this feature is one of the strongest AI-processors which can be found in driver assistance systems. However, the chips employed are not freely available on the market but are exclusive for Tesla and they are developed internally now to train their self-learning capabilities. This example clearly shows the importance of system ownership in AI, which must be secured for Europe, if its companies want to be able to sell competitive products when AI is becoming pervasive.

In this context, Europe must secure the knowledge to build AI-systems, design AI-chips, procure the AI-software ecosystem, and master the integration task into its products, and particularly into those products where Europe has a lead today. But the regulations in Europe, which are necessary to control excesses, should not be a stopping factor for the development of the European industry compared to US or China industries.

Adapted to the European industry structure, which is marked by a vibrant and versatile ecosystem of SMEs together with larger firms, we need to build and enhance the AI-ecosystem for the particular strengths but also weaknesses of Europe.

A potential approach could be to:

- To rely on existing application domains where we are strong (e.g. automotive, machinery, chemistry, energy, etc.).
- Good curated databases for training AI models should be available under fair rules.
- Promoting to keep, catch-up and get all expertise in Europe that are required to build competitive edge computing systems and embedded intelligence, allowing us to develop solutions that are adapted to the European market and beyond. All the knowledge is already present in Europe, but not structured and focused and often the target of non-European companies. The European ecosystem is rich and composed of many SMEs, but with little focus on common goals and cooperation.
- Open-source Hardware can be an enabler or facilitator of this evolution, allowing this swarm of SMEs to develop solutions more adapted to the diversity of the market.
- Data-based and knowledge-based modelling combined into hybrid modelling is an important enabler.
- Particular advantage will be cross-domain and cross-technology cooperation between various European vendors combining the best hardware and software know-how and technologies.
- Cooperation along and across value chains for both hardware and software experts will be crucial in the field of smart systems and the AI and IoT community.

**While Europe is recognised for its know-how in embedded systems architecture and software, it should continue to invest in this domain to remain at the state of the art, despite fierce competition from countries like USA, China, India, etc. From this perspective, the convergence between AI and edge computing, what we call embedded intelligence, should be a top priority. Europe should take benefit of its specificities, such as the drive of the "European Green Deal" to make its industry sustainable AND competitive.**

European companies are also in the lead for embedded microcontrollers. Automotive, IoT, medical applications and all embedded systems utilise many low-cost microcontrollers, integrating a complete system, computing, memory, and various peripherals in a single die. Here, pro-active innovation is necessary to upgrade the existing systems with the new possibilities from AI, Cyber-Physical Systems and edge computing, with a focus on local AI. Voice interface and the conversational capabilities of LLMs will be attractive features for consumers. Those new applications will require more processing power to remain competitive, still keeping a low-cost and a low-power budget. In addition, old applications will require AI-components to remain competitive. But power dissipation must not increase accordingly, in fact a reduction would be required. Europe has lost some ground in the processor domain, but AI is also an opportunity to regain parts of its sovereignty in the domain of computing, as completely new applications emerge. Mastering key technologies for the future is mandatory to enforce Europe, and for example, to attract young talents and to enable innovations for the applications.

Europe no longer has a presence in "classical" computing such as processors for laptops and desktop computers, servers (cloud) and HPC, but the drive towards edge computing, part of a computing continuum, might be an opportunity to use the solid know-how in embedded systems and extend it with high performance technology to create Embedded (or Edge) High Performance Computers (eHPC) that can be used in European meta-edge devices. The initiative of the European Commission, "for the design and development of European low-power processors and related technologies for extreme-scale, high-performance big-data and emerging applications, in the automotive sector" could reactivate an active presence of Europe in that field and has led to the launch of the "European Processor Initiative – EPI". New initiatives around RISC-V and Open-source hardware are also key ingredients to keep Europe in the race.

AI-optimised hardware components such as CPUs, GPUs, DPUs, FPGAs, ASICs accelerators and neuromorphic processors are becoming more and more important. European solutions exist, and the knowledge on how to build AI-systems is available mainly in academia. However, more EU action is needed to bring this knowledge into real products in view to enhance the European industry with its strong incumbent products. Focused action is required to extend the technological capabilities and to secure Europe's industrial competitiveness. A promising approach to prevent the dependence on closed processing technologies, relies on Open Hardware initiatives (Open Compute Project, RISC-V, OpenCores, OpenCAPI, etc.). The adoption of an open ecosystem approach, with a globally and incrementally built know-how by multiple actors, prevents that a single entity can monopolise the market or cease to exist for other reasons. The very low up-front cost of open hardware/silicon IP lowers the barrier of innovation for small players to create, customise, integrate, or improve Open IP to their specific needs. Thanks to Open Hardware freely shared, and to existing manufacturing capabilities that still exist in Europe, prototyping facilities and the related know-how, a new wave of European start-ups could come to existence, building on top of existing designs and creating significant value by adding the customisation needed for industries such as automotive, energy, manufacturing or health/medical. Access to affordable design tools and foundry/packaging (e.g. the Design Platform envisioned by the Chips JU) is mandatory for those start-ups to be able to transform their ideas into products. Another advantage of open-source hardware is that the source code is auditable and therefore inspected to ensure quality (and less prone to attack if correctly analyzed and corrected).

In a world, in which some countries are more and more protectionist, not having high-end processing capabilities, (i.e., relying on buying them from countries out of Europe) might become a weakness (leaving for example the learning/training capabilities of AI systems to foreign companies/countries). China, Japan, India, and Russia are starting to develop their own processing capabilities in order to prevent potential shortage or political embargo.

It is also very important for Europe to master the new key technologies for the future, such as AI (in all its forms, including LLMs), the drive for more local computing, not only because it will allow to sustain the industry, but also master the complete ecosystem of education, job creation and attraction of young talents into this field while implementing rapidly new measures as presented in Major Challenge 4.

## 2.1.5 Major Challenges

### 2.1.5.1 For Edge Computing

Four Major Challenges have been identified for the further development of computing systems, especially in the field of embedded architectures and edge computing:

1. **Increasing the Energy Efficiency of Computing Systems:**
    - 1.1 Processing data where it is created.
    - 1.2 **Co-design**: algorithms, HW, SW, and topologies.
2. **Managing the Increasing Complexity of Systems:**
    - 2.1 Balanced mechanisms between performance and **interoperability.**
    - 2.2 Realizing **self-X**: self-optimise, reconfiguration, and self-management.
    - 2.3 Using AI techniques to help in complexity management.
3. **Supporting the Increasing Lifespan of Devices and Systems:**
    - 3.1 HW supporting software upgradability.
    - 3.2 Improving **interoperability** (with the same class of application) and between classes, **modularity**, and complementarity between generations of devices.
    - 3.3 Developing the concept of **2nd life** for components.
    - 3.4 Implementation on the smallest devices, high quality data, meta-learning, neuromorphic computing, and other novel hardware-architectures.
4. **Ensuring European Sustainability in Embedded Architectures Design:**
    - 4.1 **Open-source HW.**
    - 4.2 Energy efficiency improvement.
    - 4.3 Engineering support to improve sustainable AI, edge computing, and Embedded architectures.

### 2.1.5.2 For Embedded Intelligence

The world is more and more connected. Data collection is exploding. Heterogeneity of data and solutions, needs of flexibility in calculation between basic sensors and multiple sensors with data fusion, protection of data and systems, extreme variety of use cases with different data format, connectivity, bandwidth, real time or not, etc. … increase the complexity of systems and their interactions. This leads to systems of systems solutions, distributed between deep edge to cloud and possibly creating a continuum in this connected world.

Ultimately, energy efficiency becomes the key criterium as the digital world is taking a more and more significant percentage of produced electric energy.

Embedded Intelligence is then foreseen as a crucial element to allow a soft and optimised operation of distributed systems.

It is a powerful tool to achieve objectives such as:

- Power energy efficiency by treating data locally and minimizing the necessary data sent to the upper node of network.
- Securing the data (including privacy) keeping them local.
- Central piece for digital identity, trust, and digital finance/transaction systems.
- Securing supply chains, especially for energy and food.
- Allowing different systems to communicate to each other and adapt over time (increasing their lifetime).
- Increasing resilience by learning and becoming more secured, more reliable.
- Europe should lead the adoptation of new AI techniques (like Transformers and LLMs) into edge devices with efficient accelerators and algorithms.
- Europe should push the development of immersive technologies forward (e.g. AR and VR; industrial, metaverses, omniverses) linked / integrated with (hardware based) security (e.g. blockchain) for deep edge and meta edge.
- Europe to lead in autonomous cars and robots.
- Facilitating the access to digital technologies for people (natural language interfaces).
- Keeping systems always on and accessible towards a network continuum.

On top, Embedded Intelligence can be installed at all levels of the chain. However, many challenges must be solved to achieve those goals.

First priority is energy efficiency. The balance between Embedded AI energy consumption and overall energy savings must be carefully reviewed. New innovative architectures and technologies (Near-Memory-Computing, In-Memory-Computing, Neuromorphic, …) need to be developed as well as sparsity of coding and of the algorithm topology (e.g. for Deep Neural Network). It also means to carefully choose which data is collected and for which purposes. Avoiding data transfers is also key for low power: Neural Networks, where storage (the synaptic weights) and computing (the neurons) are closely coupled lead to architectures which may differ from the Von Neumann model where storage and computation are clearly separated. Computing In or Near memory are efficient potential architectures for some AI algorithms.

Secondly, Embedded AI must be scalable and modular all along the distributed chain, increasing flexibility, resilience, and compatibility. Stability between systems must be achieved and tested. Thus, benchmark and validation tools for Embedded AI and related techniques have to be developed.

Thirdly, self-learning techniques (Federative learning, unsupervised learning, etc.) will be necessary for fast and automatic adaptation. Fine tuning allows foundation models to be adapted to particular use cases.

Finally, trust in AI is key for societal acceptance. Explainability and Interpretability of AI decisions for critical systems are important factors for AI adoption, together with certifications processes.

Algorithms for Artificial Intelligence can be realised in stand-alone, distributed (federated, swarm, etc.) or centralised solution (of course, not all algorithms can be efficiently implemented in the 3 solutions). For energy, privacy and all the reasons explained above, it is preferable to have stand-alone or distributed solutions (hence the name “Intelligence at the edge”). The short term might be more oriented towards stand-alone AI (e.g. self-driving car) and then distributed (or connected, like car2car or car2infrastructure).

### 2.1.5.3 Major Challenges

Summarizing, four Major Challenges have been identified:

- Increasing energy efficiency:
    - Development of innovative (and heterogeneous) hardware architectures: e.g. Neuromorphic, including for LLMs.
    - Avoiding moving large quantities of data at all levels: processing at the source of data, sparse data coding, etc.
    - Only processing when it is required (sparse topology, algorithms, etc.).
    - Minimise stand-by power consumption.
    - Interoperability (with the same class of application) and between classes.
    - Scalable and Modular AI.
    - Support of LLMs (hardware and software) at the edge in an affordable manner.
- Managing the increasing complexity of systems:
    - Development of trustable AI (e.g. explainability, interpretability).
    - Verification, validation, testing and certification for intelligent edge devices.
    - Easy adaptation of models.
    - Standardised APIs for hardware and software tool chains, and common descriptions to describe the hardware capabilities.
- Supporting the increasing lifespan of devices and systems:
    - Realizing self-X (unsupervised learning, transfer learning, etc.).
    - Update mechanisms (adaptation, learning, etc.).
- Ensuring European sustainability in AI:
    - Developing solutions that correspond to European needs and ethical principles.
    - Transforming European innovations into commercial successes.
    - Cultivating diverse skillsets and expertise to address all parts of the European embedded AI ecosystem.

Of course, as seen above, all the generic challenges found in Embedded architectures are also important for Embedded AI-based systems, but we will describe more precisely which is specific for each subsection (Embedded architectures/edge computing and Embedded Intelligence).

### 2.1.5.4 Major Challenge 1: Increasing the energy efficiency of computing systems

#### 2.1.5.4.1 State of the art & key focus areas for Edge Computing

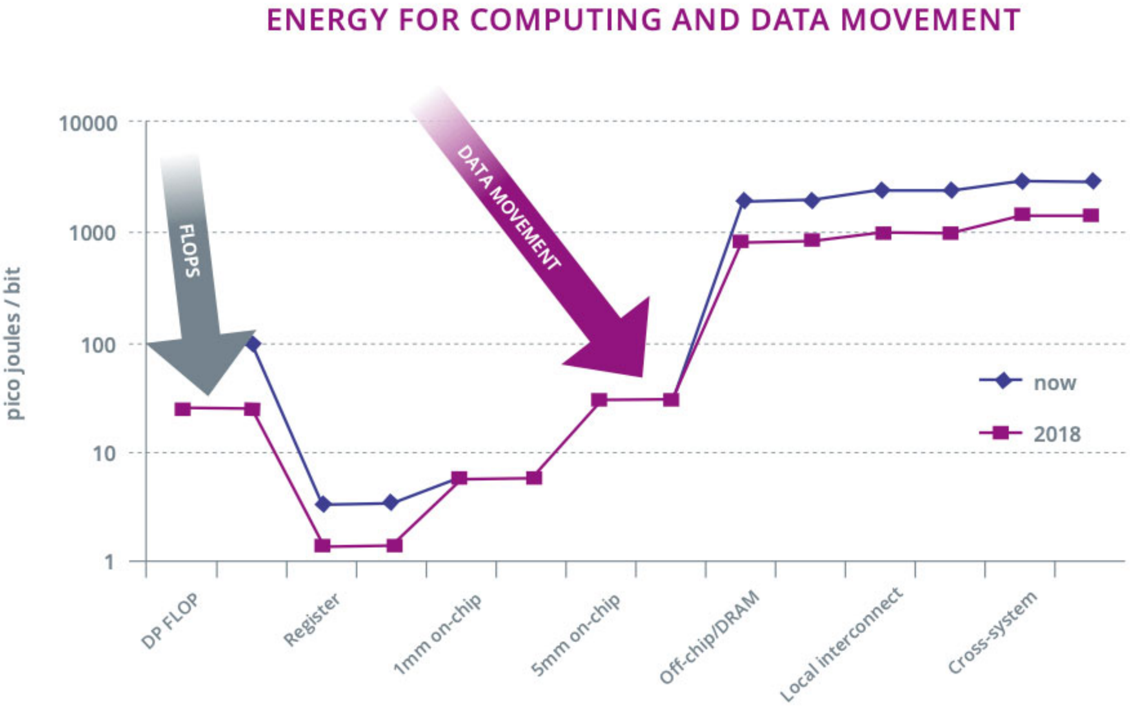
**State of the art**

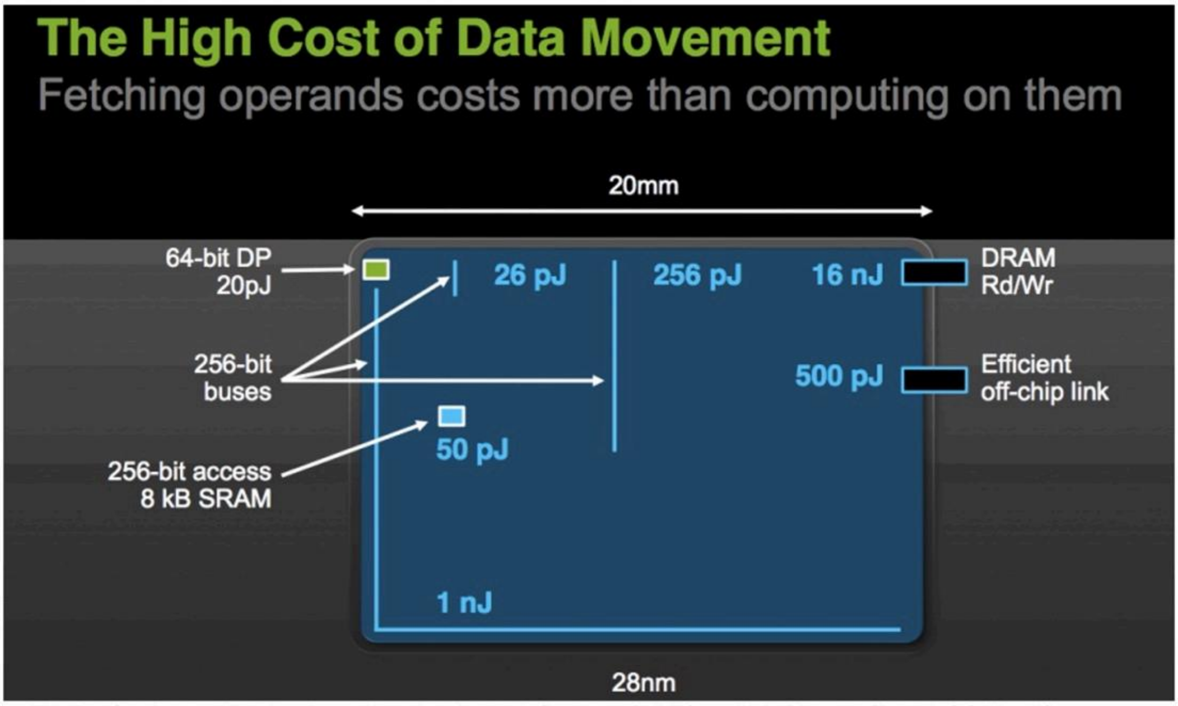
The advantages of using digital systems should not be hampered by their cost in terms of energy. For HPC or data centres, it is clear that the main challenge is not only to reach the "exaflops", but to reach "exaflops" at reasonable energy cost, which impacts the cooling infrastructure, the size of the "power plug" and globally the cost of ownership. At the other extremity of the spectrum, micro-edge devices should work for months on a small battery, or even by scavenging their energy from the environment (energy harvesting). Reducing the energy footprint of devices is the main charter for fulfilling sustainability and the European Green Deal. Multimode energy harvesting (e.g. solar/wind, regenerative braking, dampers/shock absorbers, thermoelectric, etc.) offers huge potential for electrical vehicles andbattery - fuel cells -, operated vehicles in addition to energy efficiency design, real-time sensing of integrity, energy storage and other functions.

Power consumption should not only be seen at the level of the device, but at the level of the aggregation of functions that are required to fulfil a task.

The new semiconductor technology nodes don't really bring improvement to the power per device. Dennard's scaling is ending and going to a smaller node does not anymore lead to a large increase of the operating frequency or a decrease of the operating voltage. Therefore, dissipated energy per surface, so, the power density of devices, is increasing rather than decreasing. Transistor architectures, such as FinFet, FD-SOI, GAA, nanosheets mainly reduce the leakage current (i.e. the energy spent by an inactive device). However, transistors made on FD-SOI substrates achieve the same performance as FinFet transistors at a lower operating voltage, reducing dynamic power consumption.

In addition, comes the memory wall. Today's limitation is not coming from the pure processing power of systems, but rather from the capacity to bring data to the computing nodes within a reasonable power budget fast enough.





The High Cost of Data Movement

Fetching operands costs more than computing on them

**Source: Bill Dally, « To ExaScale and Beyond » www.nvidia.com/content/PDF/sc_2010/theater/Dally_SC10.pdf**

*Figure 2.1.7 - Energy for compute and data movement. This explains the order of magnitude of the problem of data movement, and this problem is still relevant in all technology nodes.*

Furthermore, the system memory is only part of a broader Data Movement challenge which requires significant progress in the data access/storage hierarchy from registers, main memory (e.g. progress of NVM technology, such as the Intel's 3D-xpoint, etc.), to external mass storage devices (e.g. progress in 3D-nand flash, SCM derived from NVM, etc.). In a modern system, large parts of the energy are dissipated in moving data from one place to another. For this reason, new architectures are required, such as computing in or near memory, neuromorphic architectures (also where the physics of the NVM - PCM, CBRAM, MRAM, OXRAM, ReRAM, FeFET, etc. - technology can be used to compute, see figure 2.1.8) and lower bit-count processing are of primary importance. Not only the memories itself, e.g. bitcells, are needed but the complementing libraries and IP for IMC or NMC as well.

| | | Flash reference | MRAM type | PCM type | ReRAM type | FeFET | Hf based FeRAM 1T1C |
|---|---|---|---|---|---|---|---|
| **Performance** | **Programming power** | <200pJ/bit - # 100pJ/bit (eSTM) | ~20pJ/bit | ~90pJ/bit | ~100pJ/bit | <~20pJ/bit | <pJ/bit |
| | **Reading access time** | HV devices<br>~15ns | Core oxide device<br>~1ns | No HV devices<br>~5ns | No HV devices<br>~5ns | No HV devices<br>~5ns | Write after read ( Destr. Read) |
| | **Erasing granularity** | FN mechanism<br>Full page erasing | bit-2-bit erasing<br>Fine granularity | bit-2-bit erasing<br>Fine granularity | bit-2-bit erasing<br>Fine granularity | bit-2-bit?<br>Depend on archi | bit-2-bit erasing |
| **Reliability** | **Endurance** | Mature technology | High capability<br>10^15 ? | 500Kcy | 10^5 trade Off with BER | 10^5<br>Gate stress sensibility | 10^11 #10^6 with write after read |
| | **Retention** | Mature technology | Main weakness<br>Trade-off with Taa | 150°C auto compliant | Demonstrated<br>Trade Off with power | To be proven | To be proven |
| | **Soldering reflow** | Mature technology | High risk<br>To be proven | pass | possible | To be proven | To be proven |
| **Cost** | **Extra masks** | Very high (>10) | Limited (3-5) | Limited (3-5) | Limited (3-5) | Low (1-3) | Low (1-3) |
| | **Process flow** | Complex | Complex | Simple | Simple | Simple | Simple |
| | **New assets vs CMOS** | Shared | New _manufacturable | New _manufacturable | BE High-k material | FE High k material | BE High-k material |

*Figure 2.1.8 - eNVM technologies, strengths and challenges (from Andante: CPS & IoT summer school, Budva, Montenegro, June 6th-10th, 2023*

Power consumption can be reduced by local treatment of collected data, not only at circuit level, but also at system level or at least at the nearest from the sensors in the chain of data transfer towards the data centre (for example: in the gateway). Whereas the traditional approach was to have sensors generate as much data as possible and then leave the interpretation and action to a central unit, future sensors will evolve from mere data-generating devices to devices that generate semantic information at the appropriate conceptual level. This will obviate the need for high bit rates and thus power consumption between the sensors and the central unit. In summary, raw data should be transformed into relevant information (what is useful) as early as possible in the processing continuum to improve the global energy efficiency:

- Only end or middle points equipment are working, potentially with low or sleeping consumption modes.
- Data transfer through network infrastructures is reduced. Only necessary data is sent to the upper level.
- Usage of computing time in data centres is also minimised.
- The development of benchmarks and standardisation for HW/SW and data sets could be an appropriate measure to reduce power consumption. Hence, energy consumption evaluation will be easy and include the complete view from micro-edge to cloud.

**Key focus areas**

To increase the energy efficiency of computing systems, especially in the field of systems for AI and edge computing requires the development of innovative hardware architectures at all levels with their associated software architectures and algorithms:

- At technology level (FinFet, FDSOI, silicon nanowires or nanosheets), technologies are pushing the limits to be ultra-low power. On top, advanced architectures are moving from Near-Memory computing to In-Memory computing with potential gains of 10 to 100 times. Technologies related to advanced integration and packaging have also recently emerged (2.5D, chiplets, active interposers, etc.) that open innovative design possibilities, particularly for what concerns tighter sensor-compute and memory-compute integration.
- At device level, several type of circuit architectures are currently running, tested, or developed worldwide. The list is moving from the well-known CPU to some more and more dedicated accelerators integrated in Embedded architectures (GPU, DPU, TPU, NPU, DPU, etc.) providing accelerated data processing and management capabilities, which are implemented very variously going from fully digital to mixed or full analog solutions:
    - Fully digital solutions have addressed the needs of emerging application loads such as AI/DL workloads using a combination of parallel computing (e.g. SMP and GPU) and accelerated hardware primitives (such as systolic arrays), often combined in heterogeneous Embedded architectures. Low-bit-precision (8-bit integer or less) computation as well as sparsity-aware acceleration have been shown as effective strategies to minimise the energy consumption per each elementary operation in regular AI/DL inference workloads; on the other hand, many challenges remain in terms of hardware capable of opportunistically exploiting the characteristics of more irregular mixed-precision networks. Applications also require further development due to their need for more flexibility and precision in numerical representation (32- or 16-bit floating point), which puts a limit to the amount of hardware efficiency that can be achieved on the compute side.
    - Avoiding moving data: this is crucial because the access energy of any off-chip memory is currently 10-100x more expensive than access to on-chip memory. Emerging non-volatile memory technologies such as MRAM, with asymmetric read/write energy cost, could provide a potential solution to relieve this issue, by means of their greater density at the same technology node. Near-Memory Computing (NMC) and In-Memory Computing (IMC) techniques move part of the computation near or inside memory, respectively, further offsetting this problem. While IMC in particular is extremely promising, careful optimisation at the system level is required to really take advantage of the theoretical peak efficiency potential.
    - Another way is to perform invariant perceptive processing and produce semantic representation with any type of sensory inputs.
- At system level, micro-edge computing near sensors (i.e. integrating processing inside or very close to the sensors or into local control) will allow embedded architectures to operate in the range of 10 mW (milliwatt) to 100 mW with an estimated energy efficiency in the order of 100s of GOPs/Watt up to a few TOPs/Watt in the next 5 years. This could be negligible compared to the energy consumption of the sensor (for example, a MEMS microphone can consume a few mA). On top, the device itself can go in standby or in sleep mode when not used, and the connectivity must not be permanent. Devices currently deployed on the edge rarely process data 24/7 like data centres: to minimise global energy, a key requirement for future edge Embedded architectures is to combine high performance “nominal” operating modes with lower-voltage high compute efficiency modes and, most importantly, with ultra-low-power sleep states, consuming well below 1 mW in fully state-retentive sleep, and less than 1-10 µW in deep sleep. The possibility to leave embedded architectures in an ultra-low power state for most of the time has a significant impact on the global energy consumed. The possibility to orchestrate and manage edge devices becomes fundamental from this perspective and should be supported by design. On the contrary, data servers are currently always on even if they are loaded only at 60% of their computing capability.
- At data level, memory hierarchies will have to be designed considering the data reuse characteristics and access patterns of algorithms, which strongly impact load and store access rate and hence, the energy necessary to access each memory in the hierarchy. For example (but not only), weights and activations in a Deep Neural Network have very different access patterns and can be deployed to entirely separate hierarchies exploiting different combinations of external Flash, DRAM, non-volatile on-chip memory (MRAM, FRAM, etc.) and SRAM.
- At tools level, HW/SW co-design of system and their associated algorithms are mandatory to minimise the data moves and optimally exploit hardware resources, particularly if accelerators are available, and thus optimise the power consumption.

The challenge is not only at the component level, but also at the system and even infrastructure level: for example, the Open Compute Project was started by Facebook with the idea of delivering the most efficient designs for scalable computing through an open-source hardware community.

## 2.1.5.4.2 State of the art & key focus areas for Embedded Intelligence

**State of the art**

Training AI models can be very energy demanding. As an example, according to a recent study, the model training process for natural-language processing (NLP, that is, the sub-field of AI focused on teaching machines to handle human language) could end emitting as much carbon as five cars in their lifetimes[39]. However, if the inference of that trained model is executed billions of times (e.g. by billion users' smartphones), its carbon footprint could even offset the training one. Another analysis[40], published by the OpenAI association, unveils a dangerous trend: "since 2012, the amount of compute used in the largest AI training runs has been increasing exponentially with a 3.5 month-doubling time (by comparison, Moore's law had a 2-years doubling period)". These studies reveal that the need for computing power (and associated power consumption) for training AI models is dramatically widening. Consequently, the AI training processes need to turn greener and more energy efficient.

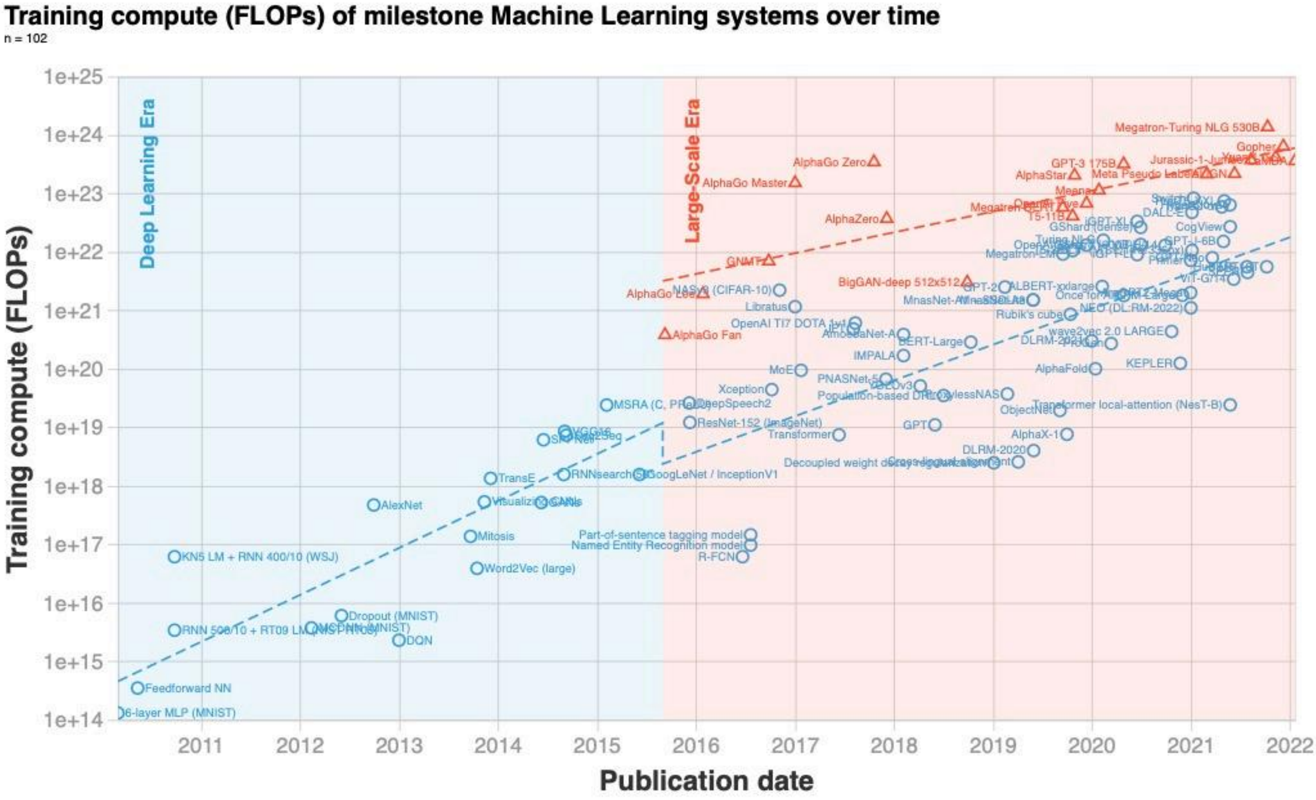


*Figure 2.1.9 - Evolution of the size of the most advanced deep learning networks (from* ***https://arxiv.org/abs/2202.05924*** *)*

For a given use-case, the search for the optimal solution should meet multi-objective trade-offs among accuracy of the trained model, its latency, safety, security, and the overall energy cost of the associated solution. The latter means not only the energy consumed during the inference phase but also considering the frequency of use of the inference model and the energy needed to train it.

In addition, novel learning paradigms such as transfer learning, federated learning, self-supervised learning, online/continual/incremental learning, local and context adaptation, etc., should be preferred not only to increase the effectiveness of the inference models but also as an attempt to decrease the energy cost of the learning scheme. Indeed, these schemes avoid retraining models from scratch all the times or reduce the number and size of the model parameters to transmit back and forth during the distributed training phase.

It is also important to be able to support LLMs at the edge, in a low-cost and low-energy way, to benefit from their features (natural language processing, multimodality, few shot learning, etc..). Applications using transformers (such as LLMs) can run with 4 bit – or less - for storing each parameter, allowing to reduce the amount of memory required to use them in inference mode.

Although significant efforts have been focused in the past to enable ANN-based inference on less powerful computing integrated circuits with lower memory size, today, a considerable challenge to overcome is that non-trivial DL-based inference requires significantly more than the 0.5-1 MB of SRAM, that is the typical memory size integrated on top of microcontroller devices. Several approaches and methodologies to artificially reduce the size of a DL model exist, such as quantizing the neural weights and biases or pruning the network layers. These approaches are fundamental also to reduce the power consumption of the inference devices, but clearly, they cannot represent the definitive solution of the future.

We witness great development activity of computing systems explicitly supporting novel AI-oriented use cases, spanning different implementations, from chips to modules and systems. Moreover, as depicted in the following figure, it covers large ranges of performance and power, from high-end servers to ultra-low power IoT devices.

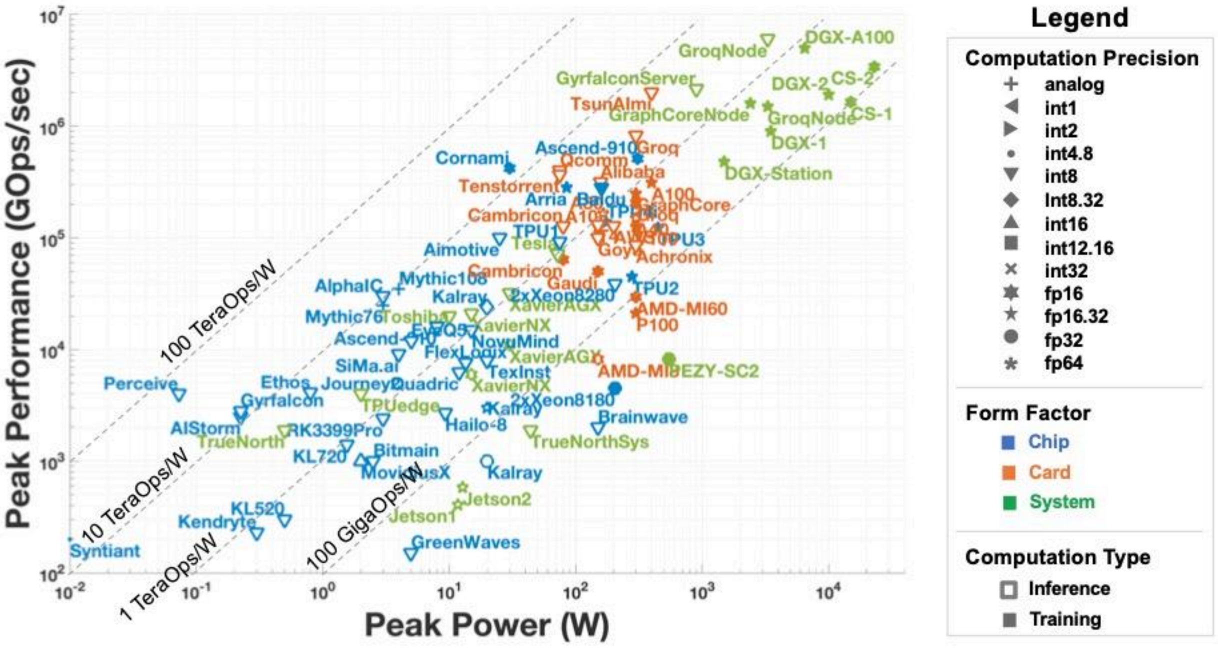


*Figure 2.1.10 - Landscape of AI chips according to their peak power consumption and peak performance*[41].

To efficiently support new AI-related applications, for both, the server and the client on the edge side, new accelerators need to be developed. For example, DL does not usually need a 32/64/128-bit floating point for its learning phase, but rather variable precision including dedicated formats such as bfloats. However, a close connection between the compute and storage parts are required (Neural Networks are an ideal "compute in memory" approach). Storage also needs to be adapted to support AI requirements (specific data accesses, co-location compute and storage), memory hierarchy, local vs. cloud storage. This is particularly important for LLMs which (still) have a large number of parameters (few billions) to be efficient. Quantisation into 4 to 2 bits, new memories and clever architectures are required for their efficient execution at the edge.

Similarly, at the edge side, accelerators for AI applications will particularly require real-time inference, in view to reduce the power consumption. For DL applications, arithmetic operations are simple (mainly multiply-accumulate) but they are done on data sets with a very large set of data and the data access is therefore challenging. In addition, clever data processing schemes are required to reuse data in the case of convolutional neural networks or in systems with shared weights. Computing and storage are deeply intertwined. And of course, all the accelerators should fit efficiently with more conventional systems.

Reducing the size of the neural networks and the precision of computation is key to allow complex deep neural networks to run on embedded devices. This can be achieved either by pruning the topology of the networks, and/or by reducing the number of bits storing values of weight and neuron values. These processes can be done during the learning phase, or just after a full precision learning phase, or can be done (with less performance) independently of the learning phase (example: post-training quantisation). The pruning principle is to eliminate nodes that have a low contribution to the final result. Quantisation consists either in decreasing the precision of the representation (from float32 to float16 or even float8, as supported by the NVIDIA GPUs mainly for transformer networks), or to change the representation from float to integers. For the inference phase, current techniques allow to use 8-bit representations with a minimal loss of performances, and sometimes to reduce the number of bits further, with an acceptable reduction of performance or small increase of the size of the network (LLMs still seem to have a good performance with a 4-bit quantisation). Most major developments environments (TensorFlow Lite[42], N2D2[43], etc) support post-training quantisation, and the Tiny ML community is actively using it. Supporting better tools and algorithms to reduce size and computational complexity of Deep Neural Networks is of paramount importance for allowing efficient AI applications to be executed at the edge.

Fixing and optimizing some parts of the processing (for example feature extraction for CNNs) leads to specialized architectures with very high-performance, as exemplified in the ANDANTE project.

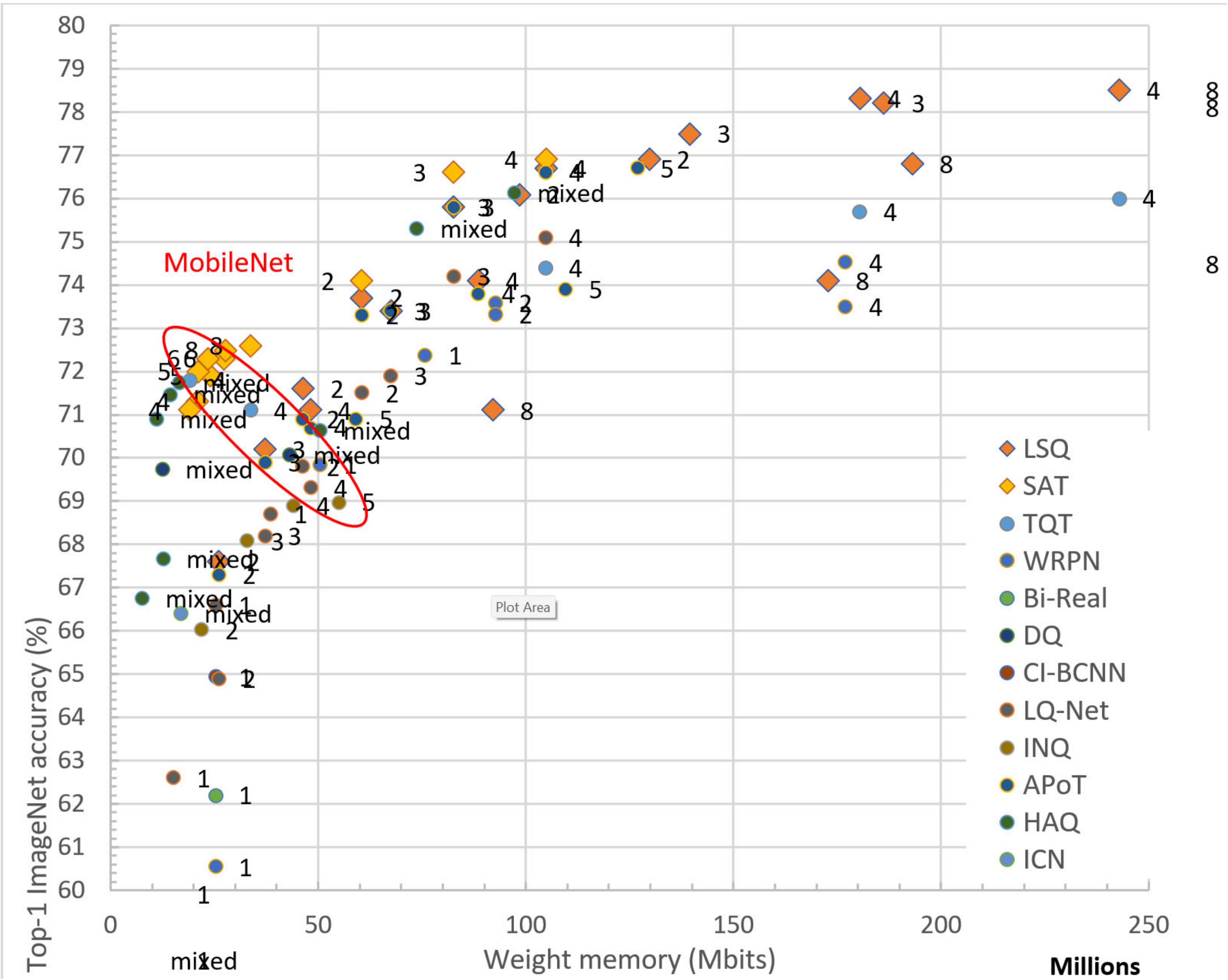


*Figure 2.1.11 - Results of various quantisation methods versus Top-1 ImageNet accuracy*

Finally, new approaches can be used for computing neural networks, such as analogue computing, or using the properties of specific materials to perform the computations (although with low precision and high dispersion, but the neural networks approach is able to cope with these limitations).

Besides DL, the "Human Brain Project", a H2020 FET Flagship Project, targets the fields of neuroscience, computing, and brain-related medicine, including, in its SP9, the Neuromorphic Computing platform SpiNNaker and BrainScaleS. This Platform enable experiments with configurable neuromorphic computing systems.

**Key focus areas**

The focus areas rely on Europe maintaining a leadership role in embedded systems, CPS, components for the edge (e.g. sensors, actuators, embedded microcontrollers), and applications in automotive, electric, connected, autonomous, and shared (ECAS) vehicles, railway, avionics, and production systems. Leveraging AI in these sectors will improve the efficient use of energy resources and increase productivity.

However, running computation-intensive ML/DL models locally on edge devices can be very resource-intensive, requiring, in the worst-case, high-end processing units to be equipped in the end devices. Such stringent requirement not only increases the cost of edge intelligence but can also become either unfriendly or incompatible with legacy, non-upgradeable devices endowed with limited computing and memory capabilities. Fortunately, inferring in the edge with the most accurate DL model is not a standard requirement. It means that, depending on the use case, different trade-offs among inference accuracy, power consumption, efficiency, security, safety, and privacy can be met. This awareness can potentially create a permanently accessible AI continuum. Indeed, the real game-changer is to shift from a local view (the device) to the "continuum" (the whole technology stack) and find the right balance between edge computation (preferable whenever possible, because it does not require data transfer) and data transmission towards cloud servers (more expensive in terms of energy). The problem is complex and multi-objective, meaning that the optimal solution may change over time, needing to consider changing cost variables and constraints. Interoperability/compatibility among devices and platforms is essential to guarantee efficient search strategies in this space.

AI accelerators are crucial elements to improve efficiency and performance of existing systems (to the cost of more software complexity, as described in the next challenge, but one goal will be to automatise this process). For the training phase, the large amount of variable precision computations requires accelerators with efficient memory access and large multi-computer engine structures. In this phase, it is necessary to access large storage areas containing training instances. However, the inference phase requires low-power efficient implementation with closely interconnected computation and memory. In this phase, efficient communication between storage (i.e. the synapses for a neuromorphic architecture) and computing elements (the neurons for neuromorphic) are paramount to ensure good performances. Again, it will be essential to balance the need and the cost of the associated solution. For edge/power-efficient devices, perhaps not ultra-dense technologies are required, cost and power efficiency matter perhaps more than raw computational performances. It is also important to develop better tools and algorithms to reduce size and computational complexity of Deep Neural Networks for allowing efficient AI applications to be executed at the edge.

Other architectures (neuromorphic) need to be further investigated to find the sweet use case spot. One key element is the necessity to save the neuronal network state after the training phase as reinitializing after switch-off will increase the global consumption. The human brain never stops.

It is also crucial to have a co-optimisation of the software and hardware to explore more advanced trade-offs. Indeed, AI, and especially DL, require optimised hardware support for efficient realisation. New emerging computing paradigms such as mimicking the synapses (neuromorphic systems or SNNs), using unsupervised learning like STDP (Spike-timing- dependent plasticity) might change the game by offering learning capabilities at relatively low hardware cost and without needing to access large databases. Instead of being realised by ALU and digital operators, STDP can be realised by the physics of some materials, such as those used in Non-Volatile Memories. These novel approaches need to be supported by appropriate SW tools to become viable alternatives to existing approaches.

Developing solutions for AI at the edge (e.g. for self-driving vehicles, personal assistants, and robots) is more in line with European requirements (privacy, safety) and know-how (embedded systems). Solutions at the extreme edge (small sensors, etc.) will require even more efficient computing systems because of their low cost and ultra-low power requirements.

In conclusion, the Deep learning approach is based on the neural network’s paradigm coming initially from the work of Mc Culloch and Pitts, where a neuron is a small computing element connected to its pairs by weights called synapses. It is a structure where computing and storage are naturally closely mixed. It is therefore important to address memories and topologies in such AI architectures. Sparsity of coding and of the neural network topology are important to reduce energy consumption, both by decreasing data communication and taking benefit of the sparsity of coding and of the topology.

### 2.1.5.5 Major Challenge 2: Managing the increasing complexity of system

#### 2.1.5.5.1 State of the art & key focus areas for Edge Computing

**State of the art**

The increasing complexity of electronic embedded systems, hardware and software algorithms has a significant impact on the design of applications, engineering lifecycle and the ecosystems involved in the product and service development value chain.

The complexity is the result of the incorporation of hardware, software and connectivity into systems, and their design to process and exchange data and information without addressing the architectural aspects. As such, architectural aspects such as optimizing the use of resources, distributing the tasks, dynamically allocating the functions, providing interoperability, common interfaces and modular concepts that allow for scalability are typically not sufficiently considered. Today's complexity to achieve higher automation levels in vehicles and industrial systems is best viewed by the different challenges which need to be addressed when increasing the number of sensors and actuators offering a variety of modalities and higher resolutions. These sensors and actuators are complemented by ever more complex processing algorithms to handle the large volume of rich sensor data. The trend is reflected in the value of semiconductors across different vehicle types. While a conventional automobile contains roughly $330 value of semiconductor content, a hybrid electric vehicle with a full sensor platform can contain up to $1000 and 3,500 semiconductors. Over the past decade, the cost contribution for electronics in vehicles has increased from 18% to 20% to about 40% to 45%, according to Lam Research. The numbers will further increase with the introduction of autonomous, connected, and electric vehicles which make use of AI-based HW/SW components.

This approach necessitates the use of multiple high-performance computing systems to support the cognition functions. Moreover, the current Electrical and Electronic (E/E) architectures impose that the functional domains are spread over separated and dedicated Electronic Control Units (ECUs). This approach hampers upscaling of the automation functionality and obstructs effective reasoning and decision making.

**Key focus areas**

The major recommendations at the Embedded architectures infrastructure level are:

- Improving interoperability of systems: this is mainly covered by design methodology, where tools should be able to build a system from IPs coming from various sources. That means also that the description of the IPs, even if they are proprietary (black box), should contain all the view required to smoothly integrate them together. This is also a requirement for open-source hardware. This can be extended at the level of integration in 2.5D systems based on interposers and chiplets: an ecosystem will only proliferate and flourish if a large catalogue of chiplets (in this case) are available and easily connected. As infrastructure for Embedded architectures, the “common platform” initiated by the European Processor Initiative (EPI) is an example of a template that allows to build different ICs with minimum efforts. For chiplets and interposer ecosystems to really emerge, an agreed standard for interconnect (such as UCIe) will be required, together with physical specifications allowing interoperability between providers.
- Facilitating the easy addition of modules to a system: what is done at the Embedded architectures level can also be promoted at the system levels, where reuse of existing core could simplify the design, but perhaps at the cost of more complex software.

- Developing common interfaces and standards: this is a basic element if we want to increase the productivity by reuse and the efficiency by using interoperability.
- Using AI techniques to help complexity management: existing Embedded architectures are so complex that humans cannot understand all the interactions and corner cases. Tools and techniques using Operational Research or Artificial Intelligence can be used to explore the space of conception and recommend optimum combinations and architectures. Automated Design Space Exploration is an emerging field, and AI is already used in backend tools by the major CAD tools providers (and by Google to design their TPUs). There is emerging research work (like Chip-Chat [48]) to use LLMS in the loop with verification tools to generate "correct" Verilog or VHDL code that can be synthesized into efficient accelerators.

The solutions and recommendations for edge devices are similar of those for embedded computing:

- Improving interoperability of systems.
- Facilitating the easy addition of modules to a system.
- Developing common interfaces and standards, standardised APIs for hardware and software tool chains.
- Using AI techniques to help complexity management.

## 2.1.5.5.2 State of the art & key focus areas for Embedded Intelligence

**State of the art**

To still achieve the required increased level of automation in automotive, transportation and manufacturing, disruptive frameworks are being considered offering a higher order of intelligence. Several initiatives to deliver hardware and software solutions for increased automation are ongoing. Companies like Renesas, NVIDIA, Intel/Mobileye, and NXP build platforms to enable Tier1s and OEMs to integrate and validate automated drive functions. Still, the "vertical" distribution of AI functionality is difficult to manage across the traditional OEM/Tier-1/Tier-2 value chain. Due to the long innovation cycle associated with this chain, vertically integrated companies such as Tesla/Waymo currently seem to hold an advantage in the space of autonomous driving. Closed AI component ecosystems represent a risk as transparency in decision making could prove hard to achieve and sensor level innovation may be stifled if interfaces are not standardised. Baidu (Apollo), Lyft, Voyage and Comma.ai take a different approach as they develop software platforms which are open and allow external partners to develop their own autonomous driving systems through on-vehicle and hardware platforms. Such open and collaborative approach might be the key to accelerate development and market adoption.

Next generation energy and resource efficient electronic components and systems that are connected, autonomous and interactive will require AI-enabled solutions that can simplify the complexity and implement functions such as self-configure to adapt the parameters and the resource usage based on context and real-time requirements. The design of such components and systems will require a holistic design strategy based on new architectural concepts and optimised HW/SW platforms. Such architectures and platforms will need to be integrated into new design operational models that consider hardware, software, connectivity and sharing of information (1) upstream from external sources like sensors to fusion computing/decision processes, (2) downstream for virtualisation of functions, actuation, software updates and new functions, and (3) mid-stream information used to improve the active user experience and functionalities.

Still, it is observed that the strategical backbone technologies to realise such new architectures are not available. These strategical backbone technologies include smart and scalable electronic components and systems (controllers, sensors, and actuators), the AI accelerator hardware and software, the security engines, and the connectivity technologies. A holistic end-to-end approach is required to manage the increasing complexity of systems, to remain competitive and to continuously innovate the European electronic components and systems ecosystem. This end-to-end approach should provide new architecture concepts, HW/SW platforms that allow for the implementation of new design techniques, system engineering methods and leverage AI to drive efficiencies in the processes.

Based on the European's semiconductor expertise and in view of its strategic autonomy, we see an incentive for Europe to build an ecosystem on electronic components, connectivity, and software AI, especially when considering that the global innovation landscape is changing rapidly due to the growing importance of digitalisation, intangible investment and the emergence of new countries and regions. As such, a holistic end-to-end AI technology development approach enables the advances in other industrial sectors by expanding the automation levels in vehicles and industrial systems while increasing the efficiency of power consumption, integration, modularity, scalability, and functional performance.

The new strategy should be anchored into a new bold digitalisation transformation as digital firms perform better and are more dynamic: they have higher labor productivity, grow faster, and have better management practices.

The reference architectures for future AI-based systems need to provide modular and scalable solutions that support interoperability and interfaces among platforms that can exchange information and share computing resources to allow the functional evolution of the silicon-born embedded systems.

The evolution of the AI-based components and embedded systems is no longer expected to be linear and will depend on the efficiency and the features provided by AI-based algorithms, techniques and methods applied to solve specific problems. This allows to enhance the capabilities of the AI-based embedded systems using open architecture concepts to develop HW/SW platforms enabling continuous innovation instead of patching the existing designs with new features that ultimately will block the further development of specific components and systems.

Europe has an opportunity to develop and use open reference architecture concepts for accelerating the research and innovation of AI-based components and embedded systems at the edge, deep-edge and micro-edge that can be applied across industrial sectors. The use of reference open architecture will support the increase of stakeholder diversity and AI-based embedded systems, IoT/IIoT ecosystems. This will result in a positive impact on market adoption, system cost, quality, and innovation, and will support to ensure the development of interoperable and secure embedded systems supported by a strong European R&I&D ecosystem.

The major European semiconductor companies are already active and competitive in the domain of AI at the edge:

- Infineon is well positioned to fully realise AI's potential in different tech domains. By adding AI to its sensors, e.g. utilizing its PSOC microcontrollers and its Modus toolbox, Infineon opens the doors to a range of application fields in edge computing and IoT. First, Predictive Maintenance: Infineon's sensor-based condition monitoring makes IoT work. The solutions detect anomalies in heating, ventilation, and air conditioning (HVAC) equipment as well as motors, fans, drives, compressors, and refrigeration. They help to reduce breakdowns, maintenance costs and extend the lifetime of technical equipment. Second, Smart Homes and Buildings: Infineon's solutions make buildings smart on all levels with AI-enabled technologies, e.g. building's domains such as HVAC, lighting or access control become smarter with presence detection, air quality monitoring, default detection and many other use cases. Infineon's portfolio of sensors, microcontrollers, actuators, and connectivity solutions enables buildings to collect meaningful data, create insights and take better decisions to optimise its operations according to its occupants' needs. Third, Health and Wearables: the next generation health and wellness technology is enabled to utilise sophisticated AI at the edge and is empowered with sensor, compute, security, connectivity, and power management solutions, forming the basis for health-monitoring algorithms in lifestyle and medical wearable devices supplying highest precision sensing of altitude, location, vital signs, and sound while also enabling lowest power consumption. Fourth, Automotive: AI is enabled for innovative areas such as eMobility, automated driving and vehicle motion. The latest microcontroller generation AURIX™ TC4x with its Parallel Processing Unit (PPU) provides affordable embedded AI and safety for the future connected, eco-friendly vehicle.

- NXP, a semiconductor manufacturer with strong European roots, has begun adding AI HW accelerators and enablement SW to several of their microprocessors and microcontrollers targeting the automotive, consumer, health, and industrial market. For automotive applications, embedded AI systems process data coming from the onboard cameras and other sensors to detect and track traffic signs, road users and other important cues. In the consumer space the rising demand for voice interfaces led to ultra-efficient implementations of keyword spotters, whereas in the health sector AI is used to efficiently process data in hearing aids and smartwatches. The industrial market calls for efficient AI implementations for visual inspection of goods, early onset fault detection in moving machinery and a wide range of customer specific applications. These diverse requirements are met by pairing custom accelerators, multipurpose and efficient CPUs with a flexible SW tooling to support engineers implementing their system solution.

- STMicroelectronics integrated edge AI as one of the main pillars of its product strategy plan. By combining AI-ready features in its hardware products to a comprehensive ecosystem of software and tools, ST ambitions to overcome the uphill challenge of AI: opening technology access to all and for a broad range of applications. For the smart building domain, the STM32 microcontrollers embed optimised machine learning algorithms to determine room occupancy, count people in a corridor or automatically read water meters. The AI code compression is performed by users through the low-code STM32Cube.ai optimiser tool which enables a drastic reduction of the power consumption while maintaining the accuracy of the prediction. In anomaly detection for industry 4.0, NanoEdge AI studio, an Auto-ML software for edge-AI, automatically finds and configures the best AI library for STM32 microcontroller or smart MEMS that contain ST's embedded Intelligent Sensor Processing Unit (ISPU) while being able to do learning on device. It results in the early detection of arc-fault or technical equipment failure and extends the lifetime of industrial machines. Designers can now use NanoEdge AI Studio to distribute inference workloads across multiple devices including microcontrollers (MCUs) and sensors with ISPUs in their systems, significantly reducing application power consumption. Always-on sensors that contain an ISPU can perform event detection at very low power, only waking the MCU when the sensor detects anomalies.

Europe can drive the development of scalable and connected HW/SW AI-based platforms. Such platforms will efficiently share resources across platforms and optimise the computation based on the needs and functions. As such, the processing resource will dynamically adjust the type, speed and energy consumption of a processing resource depending on the instantaneously required functionality.

This can be extended at the different layers of the architecture by providing scalable concepts for hardware, software, connectivity, AI algorithms (inference, learning) and the design of flexible heterogenous architectures that optimise the use of computing resources.

It is necessary to optimize the performance parameters of AI-based components, of embedded systems, within an envelope based on energy efficiency, cost, heat dissipation, size, weight using reference architectures that can scale across the information continuum from end-point deep-edge to edge, cloud, and data centre.

**Key focus areas**

- Evolving the architecture, design and semiconductor technologies of AI-based components and systems, integration into IoT/IIoT semiconductor devices with applications in automation, mobility, intelligent connectivity, enabling seamless interactions and optimised decision-making for semi-autonomous and autonomous systems.

- New AI-based HW/SW architectures and platforms with increased dependability, optimised for increased energy efficiency, low cost, compactness and providing balanced mechanisms between performance and interoperability to support the integration into various applications across the industrial sectors.

- Edge, deep-edge and micro-edge components, architectures, and interoperability concepts for AI edge-based platforms for data tagging, training, deployment, and analysis. Use and development of standardised APIs for hardware and software tool chains.

- Deterministic behaviors, low latency and reliable communications are also important for other vertical applications, such as connected cars, where edge computing and AI represent "the" enabling technology, independently from the sustainability aspects. The evolution of 5G is strongly dependent on edge computing and multi-access edge computing (MEC) developments.

- Developing new design concepts for AI born embedded systems to facilitate trust by providing the dependable design techniques, that enable the end-to-end AI systems to be scalable, make correct decisions in a repetitive manner, provide mechanisms to be transparent, explainable, interpretable, and able to achieve interpeatable results and embed features for AI model’s and interfaces' interpretability.

- Linked to the previous point, development of infrastructure for the secure and safe execution of AI.
- Distributed edge computing architecture with AI models running on distributed devices, servers, or gateways away from data centres or cloud servers.
- Scalable hardware agnostic AI models capable of delivering comparable performance on different computing platforms, (e.g. Intel, AMD or ARM architectures).
- Seamless and secure integration at HW/SW embedded systems with the AI models integrated in the SW/HW and APIs to support configurable data integrated with enterprise authentication technologies through standards-based methods.
- Development of AI based HW/SW for multi-tasking and provide techniques to adapt the trained model to produce close or expected outputs when provided with a different but related set of data. The new solutions must provide dynamic transfer learning, by assuring the transfer of training instance, feature representation, parameters, and relational knowledge from the existing trained AI model to a new one that addresses the new target task.
- HW/SW techniques and architectures for self-optimise, reconfiguration and to self-manage the resource demands (e.g. memory management, power consumption, model selection, hyperparameter tuning for automated machine learning scenarios, etc.).
- Edge-based robust energy efficient AI-based HW/SW for processing incomplete information with incomplete data, in real time.
- End-to-end AI architecture including the continuum of AI-based techniques, methods and interoperability across sensor-based system, device-connected system, gateway-connected system, edge processing units, on-premises servers, etc.
- Developing tools and techniques helping in the management of complexity, e.g. using AI methods.
- Environment, tools and platforms to adapt LLMs to edge / embedded targets (and specific accelerators).

### 2.1.5.6 **Major Challenge 3: Supporting the increasing lifespan of devices and systems**

#### 2.1.5.6.1 State of the art & key focus areas for Edge Computing

**State of the art**

Increasing lifetime of an electronic object is very complex and has multiple facets. It covers the life extension of the object itself up to the move of some of its critical parts in other objects and ultimately in the recycling of raw material in new objects. This domain of lifetime extension is very error prone as it is extremely easy to confuse some very different concepts such as upgradability, reuse up to recycling.

The first level of lifetime extension is clearly the upgrade to avoid replacing an object but instead improving its features and performance through either hardware or software update. This concept is not new as it is already applied in several industrial domains for dozens of years.

The second aspect of increasing lifetime is to reuse a system in an application framework less demanding in terms of performance, power consumption, safety, etc.

**Key focus areas**

For re-using something in an environment for which it was not initially designed, it is key to be able to qualify the part in its new environment. To achieve this very challenging goal the main question is “what are the objective parameters to take into account to guarantee that the degraded part is compatible with its new working environment?”

- Intelligent reconfigurable concepts are an essential key technology for increasing the re-use and service life of hardware and software components. Such modular solutions on system level require the consideration of different quality or development stages of sensors, software, or AI solutions. If the resulting uncertainties (measurements, predictions, estimates by virtual sensors, etc.) are considered in networked control concepts, the interoperability of agents/objects of different generations can be designed in an optimal way.
- Distributed monitoring: continuous monitoring and diagnosis also play a crucial role for the optimisation of product lifetime. Where a large amount of data is collected during daily life operation (e.g. usage, environment, sensor data), big data analysis techniques can be used to predictively manipulate the operational strategy, e.g. to extend service life. Similarly, an increase in power efficiency can be achieved by adjusting the calibration in individual agents. For example, consider a fuel cell electric vehicle where the operation strategy decisively determines durability and service life. Distributed monitoring collects data from various interconnected agents in real-time (e.g. a truck platoon, an aircraft swarm, a smart electricity distribution network, a fleet of electric vehicles) and uses these data to draw conclusions about the state of the overall system (e.g. the state of health or state of function). This allows to detect shifting behavior or faulty conditions in the systems and to even isolate them by attributing causes to changes in individual agents in the network or even ageing of individual objects and components. Such detection should be accomplished by analyzing the continuous data stream that is available in the network of agents. A statistical or model-based comparison of the individual objects with each other provides additional insights. Thus, for example, early failures of individual systems could be predicted in advance. This monitoring should also cover the performance of the semiconductor devices themselves, especially to characterise and adjust to ageing and environmental effects and adjust operations accordingly.

- Another essential factor for increasing the lifespan of products is the intelligent use and handling of real-world data from products that are already in use and from previous generations of these. On the one hand, this allows for an optimal adaptation of the operating strategy to, for example, regionally, seasonally, or even individually varying use patterns. On the other hand, the monitoring of all agents (e.g. fleet of vehicles) also enables very precise estimates and predictions of certain conditions. This enables the detection of early failures of individual objects but also the timely implementation of countermeasures. Such approaches can be referred to as distributed monitoring.
- Distributed predictive optimisation is possible, whenever information about future events in a complex system is available. Examples are load predictions in networked traffic control or demand forecasts in smart energy supply networks. In automation, a concept dual to control is monitoring and state observation, leading to safety-aware and reconfigurable automation systems. Naturally, all these concepts, as they concern complex distributed systems, must rely on the availability of vast data, which is commonly associated with the term big data. Note that in distributed systems the information content of big data is mostly processed, condensed, and evaluated locally thus relieving both communication and computational infrastructure.

## 2.1.5.6.2 State of the art & key focus areas for Embedded Intelligence

**State of the art**

The novelty with AI systems is to upgrade while preserving and guaranteeing the same level of safety and performance. For previous systems based on conventional algorithmic approaches, the behavior of the system could be evaluated offline in validating the upgrade with a predefined data set representative enough for the operating conditions, knowing that, more than the data themselves, the way they are processed is important. In the case of AI, things are completely different, as the way data are processed is not typically immediately understandable, but what is key are the data set itself and the results it produces. In these conditions it is important to have frameworks where people could reasonably validate their modification, whether it is hardware or software, in order to guarantee the adequate level of performance and safety, especially for systems which are human-life-critical. Another upgrade-related challenge is that of designing systems with a sufficient degree of architectural heterogeneity to cope with the performance demands of AI and machine learning algorithms, but at the same time to be flexible enough to adapt to the fast-moving constraints of AI algorithms. Whereas the design of a new Embedded architecture or electronic device, even of moderate complexity, takes typically 1-3 years, AI models such as Deep Neural Networks are outdated in just months by new networks. Often, new AI models employ different algorithmic strategies from older ones, outdating fixed-function hardware accelerators and necessitating the design of hardware whose functionality can be updated.

The other area of lifetime extension is how AI could identify very low signal in a noisy data environment. In the case of predictive maintenance for instance it is difficult for complex machinery to identify a potential failing part early in advance. The more complex the machinery, less possible is to have a complete analytic view of the system which would allow for simulation and thus identify potential problems in advance. Thanks to AI and collecting large datasets it is possible to extract some very complex patterns which could allow very early identification of parts with a potential problem. AI could not only identify these parts but also give some advice regarding when an exchange of a part is needed before failure, and then help in maintenance task planning.

Whatever the solution used to extend lifetime of systems, this cannot be achieved without a strong framework regarding standards and, even more important, for AI qualification framework of solutions. AI systems are new and show little standardisation currently. Therefore, it is of high importance to devote effort to this aspect of AI-hardware and -software developments. Europe has a very diverse industrial structure, and this is a strength if all those players have early access to the standards frameworks for AI and its development vectors. Open access is therefore as important for the European AI ecosystem as the ability to upgrade and participate in the development of AI-interfaces. Another very important point is how we qualify an AI solution. Computing systems based on algorithms have a lot of tools and an environment to detect and certify that a system has a given property thanks to static code analysis, formal proof, worst case execution time, etc. In case of AI, most of these solutions are not applicable as the performance of the system depends on the quality of datasets used for training and quality of data used during the inference phases.

For this reason, we suggest a strong and dedicated focus on upcoming AI-standards. Nevertheless, we need to keep in mind the strong business lever of standards and make sure that European companies will be able to build on top of standards and generate value at European level. For instance, Android is open source but no way to make a competitive smartphone without a Google Android license. European legislation should support European companies to gain a strong European market in the emerging areas, like AI.

Interoperability, modularity, scalability, virtualisation, upgradability are well-known in embedded systems and are already widely applied. But they are brand new in AI and nearly non-existent in edge AI. On top, self-x (learning/training, configuration or reconfiguration, adaptation, etc.) are very promising but still under research or low level of development. Federative learning and prediction on the fly will certainly take a large place in future edge AI systems where many similar equipment collect data (Smartphone, electrical vehicles, etc.) and could be improved and refreshed continuously.

One challenge for the AI edge model is upgradability of the firmware and new learning/training algorithms for edge devices. This includes the updates over-the-air and the device management of the updating of AI/ML algorithms based on the training and retraining of the networks (e.g. neural networks, etc.) that for IoT devices at the edge is very much distributed and is adapted to the various devices. The challenge of the AI edge inference model, is to gather data for training to refine the inference model as there is no continuous feedback loop for providing this data. The related security questions regarding model confidentiality, data privacy etc. need to be addressed specifically for such fleets of devices.

At the application level, edge AI has a potential positive impact on ecologic sustainability: consider e.g. the application of AI to optimise and reduce the power consumption in manufacturing plants, buildings, households, etc. The potential impact is evident, but, to ensure a real sustainable development and a real benefit, edge AI solutions will have to ensure that the cost savings are significantly larger than the costs required to design, implement, and train AI.

More generally, the implementation, deployment and management of large-scale solutions based on edge AI could be problematic and unsustainable, if proper engineering support, automation, integration platforms and remote management solutions will not be provided. At this level, the problem of sustainability includes business models, organisational aspects, companies' strategies, partnerships, and it extends to the entire value chain proposing edge AI-based solutions.

**Key focus areas**

- Developing HW/SW architectures and hardware that support software upgradability and extension of software useful life. Secure software upgradability is necessary in nearly all systems now and hardware should be able to support future updates. AI introduces additional constraints compared to previous systems. Multiplicity of AI approaches (Machine learning, DL, semantic, symbolic, etc.), multiplicity of neural network architectures based on a huge diversity of neuron types (CNN, RNN, LLMs, etc.), potential complete reconfiguration of neural networks for a same system (linked to a same use case) with a retraining phase based on an adapted set of data make upgradability much more complex. This this why HW/SW, related stacks, tools, data sets compatible with the edge AI system must be developed in synergy. HW/SW plasticity is necessary whatever the AI background principle of each system is, to make them as much as possible upgradable and interoperable and to extend the system lifetime. HW virtualisation will help to achieve this, as well as standardisation. The key point is that lifespan extensions, like power management, are requirements which must be considered from day one of the design of the system. It is impossible to introduce them near the end without a strong rework.

- Standardisation: standards are very difficult to define as they shouldn't be too restrictive to avoid limitation to innovation, but not too open also to avoid plenty of objects compliant to the standard but not interoperable, because not supporting the same options of the same standard. For this reason, the concept of introducing standards early in the innovation process, must be complemented with a visionary perspective in view to expand the prospective standards for future expansions in function, feature, form, and performance.

- Re-use: One concept called the "2nd life" is actually the re-use of parts of systems. Such re-use could be adapted to edge AI as far as some basic rules are followed. First, it is possible to extract the edge AI HW/SW module which is performing a set of functions. For example, this module performs classification for images, movement detection, sound recognition, etc. Second, the edge AI module can be requalified and recertified downgrading its quality level. A module implemented in aeronautic systems could be reused in automotive or industrial applications. A module used in industrial could be reused in consumer applications. Third, an AI system may be re-trained[7] to fit the "2nd life" similar use case, going for example from smart manufacturing to smart home. Last, the business model will be affordable only if such "2nd life" use is on a significant volume scale. A specific edge AI embedded module integrated in tens of thousands of cars could be removed and transferred in a new consumer product being sold on the market.

- Prediction and improvements: prediction / improvements with pure analytics techniques are always difficult. Very often the analytic behaviors of some system parts are not known and then either approximate models are build-up, or it is just ignored. Thanks to AI, the system will be able to evolve based on data collected during its running phase. AI techniques will allow for a better prediction method based on real data allowing the creation of aggregated and more pertinent indicators not possible with a pure analytic approach.

- Realizing self-X (adaptation, reconfiguration, etc.): for embedded systems self-adaptation, self-reconfiguration has an enormous potential in many applications. Usually in self-reorganizing systems the major issue is how to self-reorganise while preserving the key parameters of a system (performance, power consumption, real time constraints, etc.). For any system, there is an operating area which is defined in the multi-dimensional operating parameter space and coherent with the requirements. Of course, very often the real operating conditions are not always covering the whole operating domain for which the system was initially designed. Thanks to AI, when some malfunctioning parts are identified it could be possible to decide, relying on AI and the data accumulated during system operation, if it affects the behaviors of the system regarding its real operating conditions. If this is not the case, it could be considered that the system can continue to work, with maybe some limitations, but which are not vital regarding normal operation. It would then extend its lifetime "in place". The second case is to better understand the degraded part of a system and then its new operating space. This can be used to decide how it could be integrated in another application making sure that the new operating space of the new part is compatible with the operating requirements of the new hosting system.

- Self-learning techniques are promising. Prediction on Natural Language Understanding (NLU) on the fly or keyboard typing, predictive maintenance on mechanical systems (e.g. motors) are more and more studied. Many domains can benefit of the AI in mobility, smart building, and communication infrastructure. LLMs shows interesting properties in this field, such as few-shot learning.

- Dynamic reconfiguration: a critical feature of the AI circuits is to dynamically change their functions in real-time to match the computing needs of the software, AI algorithms and the data available, and create software-defined AI circuits and virtualise AI functions on different computing platforms. The use of reconfigurable computing technology for IoT devices with AI capabilities allows hardware architecture and functions to change with software providing scalability, flexibility, high performance, and low power consumption for the hardware. The reconfigurable computing architectures, integrated into AI-based circuits can support several AI algorithms (e.g. convolutional neural network (CNN), fully connected neural network, recursive neural network (RNN), etc.) and increase the accuracy, performance and energy efficiency of the algorithms that are integrated as part of software-defined functions.

- From the engineering perspective, leveraging open source will help developing European advanced solutions for edge AI (open-source hardware, software, training datasets, open standards, etc.).

As a summary, intelligence at the edge sustainable engineering will have to face many challenges:

- Supply chain integrity for development capability, development tools, production, and software ecosystems, with support for the entire lifecycle of edge AI based solutions.

- Security for AI systems by design, oriented also to certify edge AI based solutions. European regulations and certification processes would lead to a global compelling advantage.

- Europe needs to establish and maintain a complete R&D ecosystem around AI.

- Europe needs to address the end-to-end value chain and support its SMEs.
- Identification of a roadmap for standardisation that does not hinder innovation: the right balance that ensures European leadership in edge AI.
- Europe must strive for driving a leading and vibrant ecosystem for AI, with respect to R&D, development and production, security mechanisms, certifications, and standards.

### 2.1.5.7 **Major Challenge 4: Ensuring European sustainability**

#### 2.1.5.7.1 State of the art & key focus areas for Edge Computing

**State of the art**

One of the major challenges that need to be accounted for in the next few years is related to the design of progressively more complex electronic systems to support advanced functionalities such as AI and cognitive functionality. This is particularly challenging in the European landscape, which is dominated by small and medium enterprises (SMEs) with only some large actors that can fund and support larger-scale projects. To ensure European competitiveness and sustainability in advanced Embedded architectures it is therefore crucial to create an ecosystem, and the means, in which SMEs can cooperate and increase their level of innovation and productivity. This ecosystem needs to cover all parts of the value chain from concept to design till production. The definition of open industrial standards and a market of Intellectual Properties (IPs) are required to accelerate the designand competitivity, and to create a larger market. Open-source on Software, Hardware and tools can play an extremely important role in this regard. Open-source solutions significantly allow to reduce engineering costs for licensing and verification, lowering the entry barrier to design innovative products.

**Key focus areas**

- Energy efficiency improvement:
    - New materials, new embedded non-volatile memories with high density and ultra-low power consumption, substrates and electronic components oriented to low and ultra-low power solutions.
    - 3D-based device scaling for low power consumption and high level of integration.
    - Strategies for self-powering nodes/systems on the edge.
    - Low and ultra-low power and interoperable communications components.
    - Efficient cooling solutions.
- Improving sustainability in edge computing:
    - Efficient and secure code mobility.
    - Open edge computing platforms, providing remote monitoring and control, security, and privacy protection.
    - Solutions for the inclusion/integration of existing embedded computers on the edge.
    - Policies and operational algorithms for power consumption at edge computing level.
    - New benchmarking approach considering sustainability.
- Leveraging open source to help developing European advanced solutions on the edge:
    - Open-source hardware (and its complete ecosystem of IPs and tools).
    - Open-source software.
    - Europe must address the end-to-end value chain.
- Engineering support to improve sustainable edge computing:
    - Engineering process automation for full lifecycle support.
    - Edge devices security by design.
    - Engineering support for edge computing, verification, and certification, addressing end-to-end edge solutions.

#### 2.1.5.7.2 State of the art & key focus areas for Embedded Intelligence

**State of the art**

First, as Embedded Artificial Intelligence is developing quickly and in many different directions for new solutions, it is crucial that a European ecosystem emerge gathering all steps of the value chain. It has then to include the hardware, the software, the tools chain for AI development and the data sets in a trustable and certifiable environment. Both edge computing and Embedded Artificial Intelligence ecosystems are tied together.

Next, technology is strongly affected by sustainability that, very often, tips the scale between the ones that are promising, but not practically usable, and the ones making the difference. E.g. cloud computing, based on data centres, plays a fundamental role for the digitalisation process. However, data centres consume a lot of resources (energy[37], water, etc.), they are responsible for significant carbon emissions during their entire lifecycle, and generate a lot of electronic and chemical waste.

Today, the percentage of worldwide electricity consumed by data centres is estimated to exceed 3%, while the $CO_2$ emissions are estimated to reach the 2% of worldwide emissions[38] [39], with cloud computing being responsible for half of these emissions. A recent study predicts that, without energy efficient solutions, by 2025 eight data centres will consume 20% percent of the world's energy, with a carbon footprint rising to 5.5% of the global emissions. Data centres are progressively becoming more efficient, but shifting the computing to the edge, for example, allows to temporally reduce data traffic, data centres storage and processing. However, only a new computing paradigm could significantly reduce their environmental footprint and ensure sustainability. Edge computing could contribute to reach this goal by the introduction of ultra-low power and efficient computing solutions.

Indeed, from a wider perspective, digital transformation relies largely on other technologies that could significantly impact sustainability, including edge and fog computing, AI, IoT hyper connectivity, etc. In recent years, artificial intelligence and cloud computing have been the focus of the scientific community, environmental entities, and public opinion for the increasing levels of energy consumption, questioning the sustainability of these technologies and, indirectly, their impact on corporate, vertical applications and societal sustainability. For example, devices are already producing enormous amounts of data and a recent study[40] estimates that by 2025 communications will consume 20% of all the world's electricity. This situation has been worsening with the COVID-19 pandemic that generated a worldwide reduction of power consumption because of global lockdown restrictions, but, at the same time, caused a huge spike in Internet usage: NETSCOUT measured an increase of 25-35% of worldwide Internet traffic in March 2020, just due to remote work, online learning and entertainment. This spike in Internet use provides a flavor of the implications of digitalisation on sustainability. Reducing energy of computing and storage devices is a major challenge (see Major Challenge 1 on "Increasing the energy efficiency of computing systems").

Shifting to green energy is certainly a complementary approach to ensure sustainability, but the conjunction of AI and edge computing, the edge AI, has the potential to provide sustainable solutions with a wider and more consolidated impact. Indeed, a more effective and longer-term approach to sustainable digitalisation implies reconsidering the current models adopted for data storage, filtering, analysis, processing, and communication. By embracing edge computing, for example, it is possible to significantly reduce the amount of useless and wasteful data flowing to and from the cloud and data centres, with architectural and structural more efficient solutions that permanently reduce the overall power consumption and bring other important benefits such as real-time data analysis reducing the amount of data to be stored and better data protection. The edge computing paradigm also makes AI more sustainable: it is evident that cloud-based machine learning inference is characterised by a huge network load, with a serious impact on power consumption and huge costs for organisations. Transferring machine learning inference and data pruning to the edge, for example, could exponentially decrease the digitisation costs and enable sustainable businesses. To avoid this type of drawbacks, new AI components should be developed based on neuromorphic architectures and considering the application areas, in some cases, this could lead to more specialised and very efficient solutions.

Sustainability of edge computing and AI is affected by many technological factors, in which Europe should invest, and, at the same time, they have a positive impact on the sustainability of future digitalisation solutions and related applications.

GAMAM already master these technologies and are progressively controlling the complete value chain associated with them. To follow this trend and aim at strategic autonomy, Europe has to fill the technology gaps and address the value chain end to end, with a particular attention to SMEs (which generate a large part of European revenues) and leveraging on the cooperation between the European stakeholders in the value chain to develop successful products and solutions. From this perspective, European coordination to develop AI, edge computing and edge AI technologies is fundamental to create a sustainable value chain, based on alliances, and capable to support the European key vertical applications.

It will be a challenge for Europe to be in this race, but the emergence of AI at the edge, and its know-how in embedded systems, might be winning factors. However, the competition is fierce, and the big names are in with big budgets and Europe must act quickly, because US and Chinese companies are already also moving in this "intelligence at the edge" direction.

**Key focus areas**

On top of the key focus area for Edge computing, Embedded Artificial Intelligence also requires:

On top of the key focus areas for edge computing, Embedded Artificial Intelligence also requires:

- Energy-efficiency improvement:
  - New memories used to mimic synapses.
  - Advanced Neuromorphic components.
- Improving sustainability of AI:
  - Re-use and sharing of knowledge and models generated by embedded intelligence.
  - Energy- and cost-efficient AI training.
  - New benchmarking AI approach considering sustainability.

- Leveraging open-source to help developing European AI advanced solutions on the edge:
    - Open-source training datasets.
    - Open-source foundation models for LLMs (such as the result of the “Bloom” collaboration).
    - Open Frameworks including AI tools.
    - Europe must address the end-to-end Embedded Intelligence value chain.
- Engineering support to improve sustainable AI:
    - Edge AI security by design.
    - Engineering support for AI verification and certification.
    - Education and support to deploy edge AI.

## 2.1.6 Timeline

Legend:

- (EC): concern edge computing
- (eAI:) concern Embedded Artificial Intelligence

| MAJOR CHALLENGE | Topic | Short Term | Medium Term | Long term |
|---|---|---|---|---|
| | | 2024-2028 | 2029-2032 | 2033 and beyond |
| **Major Challenge 1:**<br>**Increasing the energy efficiency of computing systems** | **Processing data where it is created (EC and eAI)** | Development of algorithms and applications where processing is performed. Moving processing towards edge when it is possible<br>New memory management | Development of hybrid architectures, with smooth integration of various processing paradigms (classical, neuromorphic, deep learning), including new OSs supporting multiple computing paradigms<br>Advanced memory management | Dynamic instantiation of multi-paradigm computing resources according to the specifications of the task to be performed. Automatic interfacing, discovery, and configuration of resources |
| | **Development of innovative hardware architectures (EC)** | Development of computing paradigms (e.g. using physics to perform computing). Use of other technologies than silicon (e.g. photonics)<br>Use of 2.5D, interposers and chiplets, with efficient interconnection network, e.g. using photonics)<br>Creating an ecosystem around interposers and chiplets, with interoperability standards<br>New In-memory computing accelerators | Supporting tools integrating multiple computing paradigms.<br>Advanced In-memory computing accelerators<br>Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs | Integration in the same package of multiple computing paradigms (classical, Deep Learning, neuromorphic, photonic, etc.) |
| | **Development of innovative hardware architectures: e.g. neuromorphic (eAI)** | Development of neuromorphic based chips and support of this new computing model.<br>New In-memory computing accelerators for AI<br>Development tools allowing to prune/quantise big networks in order to map them onto embedded devices<br>Development of low-cost and low-energy accelerators for LLMs for embedded applications | Integration of neuromorphic and other computing within classical systems<br>Supporting tools integrating multiple AI computing paradigms.<br>Automatic adaptation of complex networks to embedded systems with a minimum loss of performances<br>Easily upgradable LLM accelerators, fine tuning "on premises". | Integration in the same package of multiple computing paradigms (classical, Deep Learning, neuromorphic, photonic, etc.)<br>Exploring potential use of quantum computing in Artificial Intelligence? |
| | **Developing distributed edge computing systems (EC)** | Development of edge (ex: fog) type of computing (peer to peer) | Edge computing demonstrating high performance for selected applications | |
| | **Developing distributed edge AI systems (eAI)** | Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning)<br>Support of recent Neural networks models such as Transformers, architectures for state-of-the-art Neural Networks algorithms. | Federated learning or similar approach demonstrating high performance for selected applications | |
| | **Interoperability (With the same class of application) and between classes (EC and eAI)** | Create gateways between various solutions, beyond ONNX (for eAI)<br>Developing open architectures (for fast development) with maximum reuse of tools and frameworks<br>Interfaces standards (more than solutions) (could help explainability, with a move from black to grey boxes) | Common interface architecture, with dynamic binding: publishing of capabilities for each device/block, flexible data structure and data converters, dynamic interconnect.<br>Promoting European standard for interoperability cross application silos.<br>Interfaces publishing non-functional properties (latency, bandwidth, energy, etc.) | At all levels (from chips to systems), automatic interoperability, adaptation to the data structure and physical interface, considering the communication characteristics. (Automatic translator of data and data format)<br>Global reconfiguration of the resources to satisfy the functional and non-functional requirements (latency, energy, etc.) |
| | **Scalable and Modular AI (eAI)** | Using the same software development infrastructure from deep edge to edge and possibly HPC applications for AI developments<br>Use of similar building blocks from deep edge to edge AI devices | Scalable architecture (in 3 dimensions). Use of interposer and chiplets to build chips for various applications (for edge and for HPC applications) with the same AI hardware building blocks<br>Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs of AI systems | Linear and/or functional scalability of AI systems |
| | **Scalable and Modular systems (EC)** | Using the same software development infrastructure from deep edge to edge and possibly HPC applications.<br>Use of similar building blocks from deep edge to edge devices | Scalable architecture (in 3 dimensions). Use of interposer and chiplets to build chips for various applications (for edge and for HPC applications) with the same hardware building blocks<br>Complete 2.5D (interposers and chiplets) | Linear and/or functional scalability<br>Digital twin (Functionalities simulation) |

| **MAJOR CHALLENGE** | **Topic** | **Short Term** | **Medium Term** | **Long term** |
|---|---|---|---|---|
| | | **2024-2028** | **2029-2032** | **2033 and beyond** |
| | | | ecosystem, with tools increasing productivity and reuse of chiplets in different designs | |
| | **Co-design: algorithms, HW, SW and topologies (EC)** | Quick implementation and optimisation of HW for the new emerging algorithms | Tools allowing semi-automatic design exploration of the space of configurations, including variants of algorithms, computing paradigms, hardware performances, etc. | Auto-configuration of a distributed set of resources to satisfy the application requirements (functional and non-functional) |
| **Major Challenge 2:**<br>**Managing the increasing complexity of systems** | **Balanced mechanisms between performance and interoperability (EC)** | Exposing the non-functional characteristic of devices/blocks and off-line optimisation when combining the devices/blocks | On-line (dynamic) reconfiguration of the system to fulfil the requirements that can dynamically change (Self-x) | Drive partitioning through standards |
| | **Development of trustable AI (eAI)** | Moved to Chapter 2.4 | Moved to Chapter 2.4 | Moved to Chapter 2.4 |
| | **Developing distributed edge computing systems (EC)** | See items above in *Increasing the energy efficiency of computing systems* | See items above in *Increasing the energy efficiency of computing systems* | See items above in *Increasing the energy efficiency of computing systems* |
| | **Scalable and Modular AI (eAI)** | See items above in *Increasing the energy efficiency of computing systems* | See also items above in *Increasing the energy efficiency of computing systems*<br>Data and learning driven circuits design | See items above in *Increasing the energy efficiency of computing systems* |
| | **Easy adaptation of models (eAI)** | Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning)<br>Create a European training reference database for same class of applications/use cases network learning | Optimisation of the Neural Network topology from a generically learned networks to an application specific one. | Generic model based digital AI development system |
| | **Easy adaptation of modules (EC)** | Easy migration of application on different computing platforms (different CPU – x86, ARM, RISC-V, different accelerators) | Use of HW virtualisation<br>Automatic transcoding of application for a particular hardware instance (à la Rosetta 2) | Generic model based digital development system |
| | **Realizing self-X Self-optimise, reconfiguration and self-management (EC)** | Add self-assessment feature to edge devices<br>Explore what AI techniques (such as LLMs) can do? | Automatic reconfiguration of operational resources following the self-assessment to fulfil the goal in the most efficient way | Modelling simulation tools for scalable digital twins |
| | **Using AI techniques to help in complexity management (EC and eAI)** | Using AI techniques for the assessment of solutions and decrease the design space exploration | Automatic generation of architecture according to a certain set of requirements (in a specific domain) | Modelling simulation tools for scalable digital twins |
| **Major Challenge 3:**<br>**Supporting the increasing lifespan of devices and systems** | **HW supporting software upgradability (eAI)** | Create European training reference databases for same class of applications/use cases network learning<br>Develop European training benchmarks (Methods and methodologies)<br>Build framework tools for HW/SW for fast validation and qualification<br>Establish interfaces standards compatible with most of AI approaches | HW virtualisation based on AI algorithms<br>Generic AI functions virtualisation<br>European training standards (Compliance/Certification)<br>Certifiable AI (and paths towards explainability and interpretability) | Explainable AI |
| | **Realizing self-X** Also partially in **Managing the increasing complexity of systems (eAI)** | Unsupervised learning technics<br>Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning) | HW virtualisation based on AI algorithms<br>Generic AI functions virtualisation<br>Certifiable AI (and paths towards explainability and interpretability) | Explainable AI |

| MAJOR CHALLENGE | Topic | Short Term | Medium Term | Long term |
|---|---|---|---|---|
| | | 2024-2028 | 2029-2032 | 2033 and beyond |
| | **Improving interoperability (with the same class of application) and between classes, modularity, and complementarity between generations of devices.**<br>**(EC)**<br>Also, partially in **Increasing the energy efficiency of computing systems** | Developing open architectures (to quickly develop) with maximum reuse of tools and frameworks<br>Interfaces standards (more than solutions) (could help explainability move from black to grey boxes) | Generic functions modules by class of applications/use cases + virtualisation | |
| | **Improving interoperability of AI functions (with the same class of application) and between classes, modularity, and complementarity between generations of devices.**<br>**(eAI)**<br>Also, partially in **Increasing the energy efficiency of computing systems** | Developing open AI architectures (to fast develop) with maximum reuse of tools and frameworks<br>Interfaces standards (more than solutions) (could help explainability of AI with a move from black to grey boxes)<br>Clarified requirements for embedded AI in industry | Generic AI functions modules by class of applications/use cases + virtualisation | |
| | **Developing the concept of 2<sup>nd</sup> life for components**<br>**(EC)**<br>(Link with sustainability) | Inclusion of existing embedded systems on the edge (huge market opportunity) | Generic set of functions for multi-applications/use cases<br>Library of generic set of functions (Standardisation)<br>Basic data collection for predictive maintenance<br>Global data collections for predictive maintenance by applications/use cases | Standardise flow for HW/SW qualification of generic set of functions (including re-training) which are used in a downgraded application/use case |
| **Major Challenge 4:**<br><br>**Ensuring European sustainability in Edge computing and embedded Artificial Intelligence** | **Energy efficiency improvement**<br>**(EC)** | Materials and electronic components oriented to low and ultralow power solutions<br>Low and ultra-low power communications<br>Strategies for self-powering nodes/systems on the edge<br>Efficient cooling solutions | 3D-based device scaling for low energy consumption | |
| | **Improving sustainability of edge computing**<br>**(EC)** | Inclusion of existing embedded systems on the edge (huge market opportunity) | Efficient and secure code mobility | |
| | **Improving sustainability of embedded Artificial Intelligence**<br>**(eAI)** | Energy and cost-efficient AI training | Reuse of knowledge and models generated by embedded intelligence | |
| | **Leveraging open source to help developing European AI advanced solutions on the edge**<br>**(eAI)** | Open-source software<br>Open-source training datasets<br>Open edge computing platforms<br>Open-source foundation models | Open-source hardware | |

| MAJOR CHALLENGE | Topic | Short Term | Medium Term | Long term |
|---|---|---|---|---|
| | | 2024-2028 | 2029-2032 | 2033 and beyond |
| | **Engineering support to improve sustainable edge computing (EC)** | Sustainability through engineering process automation<br>Continuous engineering across the product life cycle | Holistic development environment<br>Engineering support for verification and certification | |
| | **Engineering support to improve sustainable embedded Artificial Intelligence (eAI)** | Sustainability through engineering process automation<br>Continuous engineering across the product life cycle | Holistic development environment<br>Engineering support for AI verification and certification<br>edge AI security by design | |

## 2.1.7 Synergy with other themes

The scope of this chapter is to focus on computing components, and more specifically towards Embedded architectures/edge computing and intelligence at the edge. These elements rely heavily on Process Technologies, Equipment, Materials and Manufacturing, Embedded Software and Beyond, limits on Quality, Reliability, Safety and Cybersecurity, and are composing systems (System of Systems) that use Architecture and Design techniques to fulfil the requirements of the various application domains. Please refer to all these chapters in this SRIA for more details.

For example, there are close links with the chapter on Quality, Reliability, Safety and Cybersecurity on the topics of increasing “trustworthiness” of computing systems, including those using AI techniques:

- Making AI systems “accepted” by people, as a certain level of explainability is required to build trust with their users.
- Developing approaches to verify, certify, audit and trace computing systems.
- Making systems correct by construction, and stable and robust by design.
- Systems with predictable behavior, including those using deep learning techniques.
- Supporting European principles, such as privacy protection and having “unbiased” databases for learning, for example.

Embedded Software is also important, and the link to this is explained in the corresponding chapter. Systems and circuits used for AI are of course developed applying Architecture and Design and tools techniques, and manufactured based on technologies developed in Process Technologies (e.g. use of non-volatile memories, 3D stacking, etc.). Artificial intelligence techniques can also be used to improve efficiency in several applications.

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# 2.2

*Cross-Sectional Technologies*

# CONNECTIVITY

## 2.2

## Connectivity

### 2.2.1 Scope

Connectivity and interoperability technologies in ECS enabling business and social benefits are tied to layers 1, 5, and 6 of the OSI model. The focus on these ayers is motivated by the Major Challenges that characterise them (see Figure 1).

#### 2.2.1.1 Scope for OSI layer 1

The scope covers the following types of physical layer connectivity.

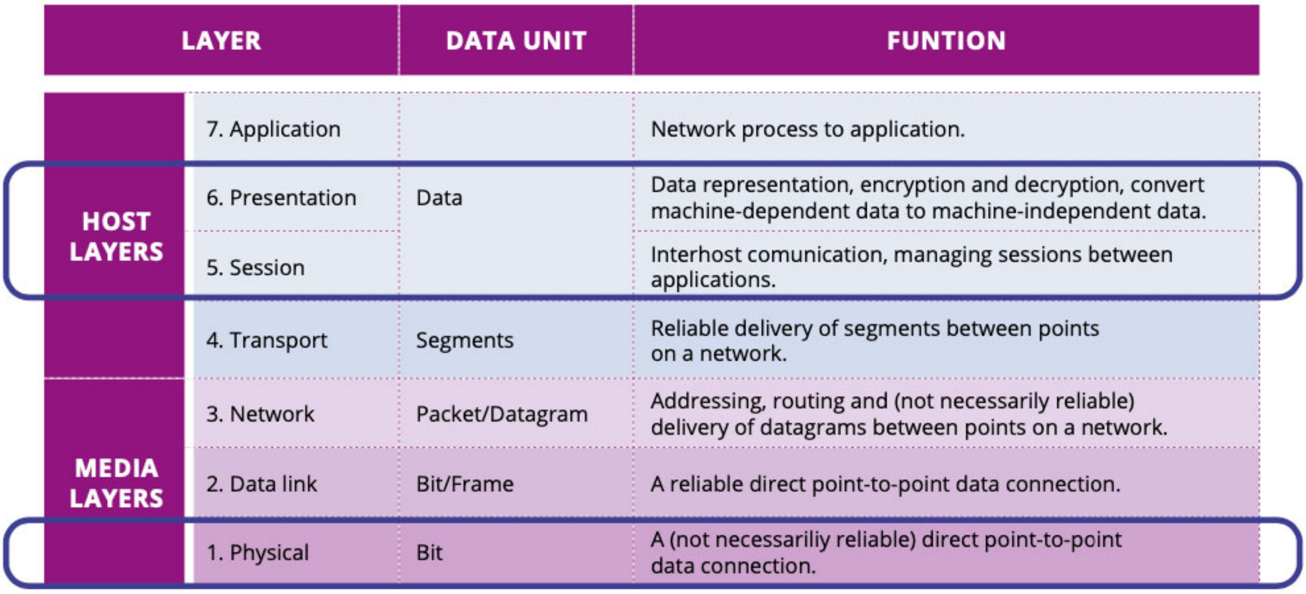
- Cellular:
    - Beyond 5G.
    - Early 6G investigation.
- Low power wide area:
    - Cellular: narrow band IoT, LTE, 6G, etc.
    - Non-cellular: SigFox, LoRa, M-Bus, etc.
- Low power short range:
    - Wireless: existing (Bluetooth, WiFi, etc.) or innovative technologies (mmW, etc.).
    - Wired: covering both high-speed optical glass and plastic fibers, mmW plastic fibers, and copper interconnect (USB, DOCIS, etc.).
- High speed:
    - Wireless: point to point mmW and satellite communication (low earth orbit and geosynchronous equatorial orbits).
    - Wired: high-speed optical (400 Gb+, etc.) and copper interconnect (Ethernet, etc.).

The main challenge will be to ensure European leadership in terms of connectivity technologies (for example, standards) as well as associated software and hardware technology supporting the development of connectivity solutions (e.g. chipset, module, protocols, etc.).

#### 2.2.1.2 Scope for OSI layer 5 and 6

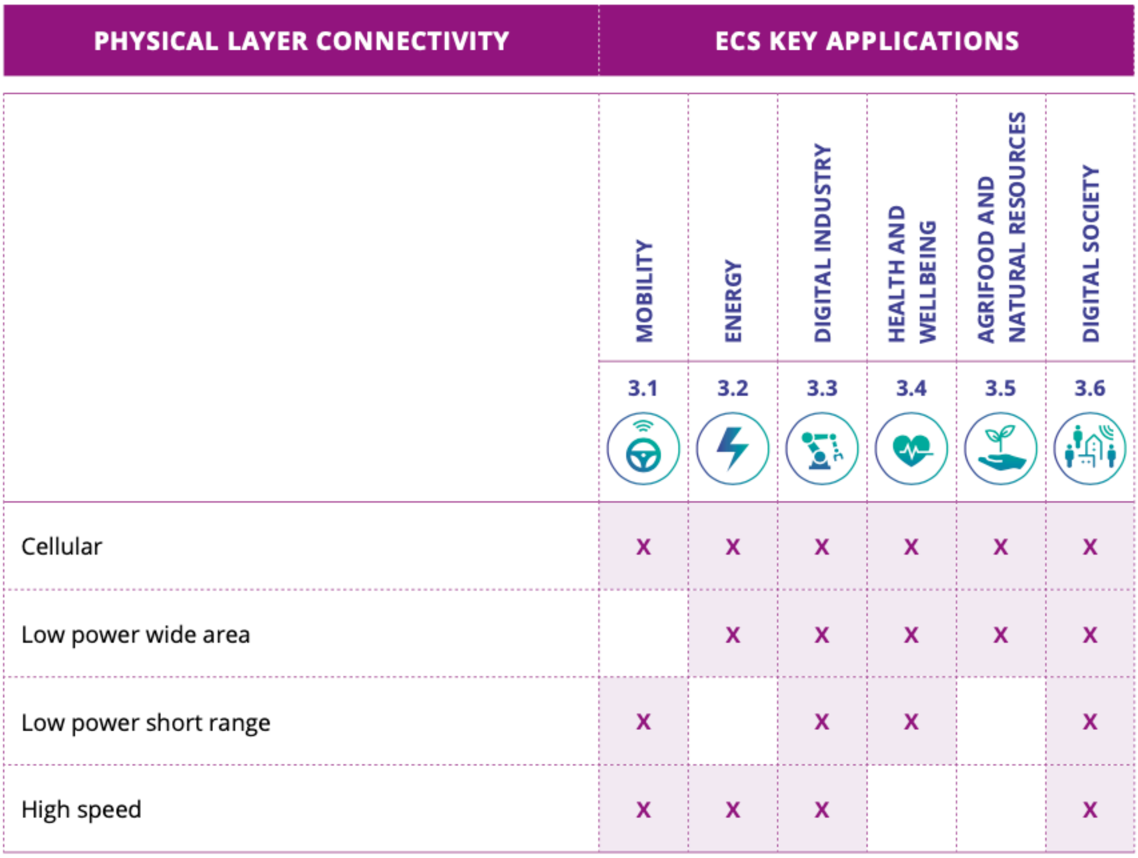
The scope addressed in this context is the interoperability from application to application relying on technologies at OSI layers 5 and 6. This interoperability covers the following underlying aspects:

- Protocols at all technology levels: Internet, operational and legacy.
- Security: such as protocol security, payload encryption, certificates, tokens and key distribution.
- Data semantics: supporting application to application understanding of transferred data/information.



| LAYER | | DATA UNIT | FUNTION |
|---|---|---|---|
| HOST LAYERS | 7. Application | Data | Network process to application. |
| | 6. Presentation | | Data representation, encryption and decryption, convert machine-dependent data to machine-independent data. |
| | 5. Session | | Interhost comunication, managing sessions between applications. |
| | 4. Transport | Segments | Reliable delivery of segments between points on a network. |
| MEDIA LAYERS | 3. Network | Packet/Datagram | Addressing, routing and (not necessarily reliable) delivery of datagrams between points on a network. |
| | 2. Data link | Bit/Frame | A reliable direct point-to-point data connection. |
| | 1. Physical | Bit | A (not necessariliy reliable) direct point-to-point data connection. |

*Figure 2.2.1 - Major Challenges: OSI Model*



| PHYSICAL LAYER CONNECTIVITY | ECS KEY APPLICATIONS | | | | | |
|---|---|---|---|---|---|---|
| | MOBILITY 3.1 | ENERGY 3.2 | DIGITAL INDUSTRY 3.3 | HEALTH AND WELLBEING 3.4 | AGRIFOOD AND NATURAL RESOURCES 3.5 | DIGITAL SOCIETY 3.6 |
| Cellular | X | X | X | X | X | X |
| Low power wide area | | X | X | X | X | X |
| Low power short range | X | | X | X | | X |
| High speed | X | X | X | | | X |

*Figure 2.2.2 - Major Challenge: ensuring European leadership in terms of connectivity technologies*

## 2.2.2 Technology Enabled Benefits

Beyond their economic impact, connectivity and interoperability are also expected to play a key role in many societal challenges to be faced in the coming decades. As will be illustrated in this Section, the societal benefits associated with connectivity are key assets for improving the living standard of European citizens, as well as maintaining Europe leadership in this area.

- Industrial competitiveness: the industrial transition to Industry 4.0/5.0, with its massive usage of automation and digitalization accompanied by AI-supported analytics, puts much higher demands on the availability and reliability of high-speed, secure, low or guaranteed latency connectivity. Given the large amount of legacy connectivity and emerging new connectivity, interoperability over technology generations and between application domains will become an enabler for competitiveness.
- Healthcare improvement: connectivity has the potential to improve medical behaviour for patients and healthcare professionals, as well as the delivery of better medical services. Connected devices can transform the way healthcare professionals operate by allowing remote diagnosis and more efficient means of treatment. For example, patient information could be sent to hospitals via mobile and internet applications, thus saving travel time and service costs, and also substantially improving access to healthcare, especially for rural populations. Connectivity and associated devices and services could complement and improve existing medical facilities. From the citizen side, the monitoring of illnesses can also be enhanced by mobile and internet applications designed to remind patients of their treatments, and to control the distribution of medicinal stocks.
- Energy and environment: one of the projected impacts of digitalisation is an improved ability to optimise energy utilisation and minimise environmental footprints. Connectivity and interoperability are critical elements of the information and communications technology (ICT) infrastructure that is essential to allow such optimisation and minimisation. The size of the energy efficiency market was estimated at US $221 billion in 2015, which was 14% of the global energy supply investments (IEA, 2016b), divided between buildings (53%) transport (29%) and industry (18%) (IEA, 2016a).
- For autonomous and automated driving advanced connectivity solutions are needed with key characteristics ultra-high reliability, extremely low latency and high throughput solutions. Advanced edge solutions that will integrate AI/ML schemes over secure links will be also of paramount importance.
- Improve public services, social cohesion and digital inclusion: ICT technologies have long been recognised as promoting and facilitating social inclusion – i.e. the participation of individuals and groups in society's political, economic and societal processes. One way in which ICT technologies can expand inclusion is through effective public services that rely on ICT infrastructure, and through digital inclusion (i.e. the ability of people to use technology). These three aspects are deeply intertwined, and span dimensions as diverse as disaster relief, food security and the environment, as well as citizenship, community cohesion, self-expression and equality. Public authorities can enhance disaster relief efforts by promoting the spread of information online and by implementing early warning systems. The internet also enables relief efforts through crowd- sourcing: for instance, during Typhoon Haiyan in the Philippines, victims, witnesses and aid workers used the web to generate interactive catastrophe maps through free and downloadable software, helping disseminate information and reduce the vulnerability of people affected by the disaster. Communities can also be strengthened by connectivity, thereby promoting the inclusion of marginalised groups.
- Pandemic and natural disaster management: the growing demand for remote interactions amid the coronavirus pandemic has highlighted a need for connectivity technology, potentially accelerating adoption in the mid-term of new technology such as 5G (and 6G in the 2030 time frame). Lightning-fast speeds, near- instantaneous communications and increased connection density are key to supporting massive remote interactions, which has become of increasing importance for many organisations and enterprises as anxiety rises concerning the management of health or natural disasters. Two key areas – e-health and teleconferencing – are becoming critical for enterprise operations amid pandemics or natural disasters, and an increased dependence on these areas will help strengthen the appeal of improved connectivity (for example, beyond 5G and 6G) and make connectivity a key sovereignty topic for Europe.

Beyond the above benefits to European society and economy, advanced connectivity and associated engineering and operational improvements have the potential to reduce energy and installation material footprints. For example network virtualisation will allow dynamic rearrangements of network traffic to suit changing conditions and requirements regarding e.g. energy, security and real time. In this way connectivity contributes to both the European green deal and sustainability objectives.

### 2.2.3 Application Breakthrough

Improvements in connectivity technology will have an impact on all ECS application areas. For health and well-being, connectivity interoperability issues are addressed by enabling faster translation of ideas into economically viable solutions, which can be further scaled up in daily health practice. Examples of health and well-being application breakthroughs supported here are:

- A shift in focus from acute, hospital-based care to early prevention.
- Strengthening where and how healthcare is delivered, supporting home-based care.
- Stronger participation of citizens in their own care processes, enhancing patient engagement.
- Supporting the clinical workforce and healthcare consumers to embrace technology-enabled care.
- Data communication technology for interoperability of wireless data infrastructure.

Improved, secure and interoperable connectivity will further support healthcare and well-being application breakthroughs regarding, for example:

- Healthcare deployment, enabling digital health platforms.
- Healthcare system paradigm transition from treatment to health prevention, enabling the shift to value-based healthcare.

- Building a more integrated care delivery system, supporting the development of the home as the central location for the patient.
- Enhancing access to personalised and participative treatments for chronic and lifestyle- related diseases.
- Enabling more healthy life years for an ageing population.

In the mobility application area, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding:

- Achieving the Green Deal for mobility, with the 2Zero goals of –37.5% CO2 by 2030.
- Increasing road safety through the CCAM programme.
- Strengthening the competitiveness of the European industrial mobility digitalisation value chain.

In the energy application domain, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding:

- Significant reduction of connectivity energy demand.
- Enabling necessary connectivity to the integration of the future heterogeneous energy grid landscape.
- “Plug and play integration” of ECS into self-organised grids and multimodal systems.
- Solving safety and security issues of self-organised grids and multimodal systems.

In the industry application domain, the provision of improved, robust, secure and interoperable connectivity will support closing gaps such as:

- Preparing for the 5G era in communications technology, especially its manufacturing and engineering dimension.
- Long-range communication technologies, optimised for machine-to-machine (M2M) communication, a large number of devices and low bit rates, are key elements in smart farming.
- Solving IoT cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive in the industry.
- Interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management allowing for the (semi)autonomous deployment and operation of large numbers of devices.

In the digital society application domain, the provision of improved, robust, secure and interoperable connectivity will support the overall strategy regarding:

- Enabling workforce efficiency regardless of location.
- Stimulating social resilience in the various member states, providing citizens with a better work/life balance and giving them freedom to also have leisure time at different locations.
- Ubiquitous connectivity, giving people a broader employability and better protection against social or economic exclusion.
- Enabling European governments, companies and citizens to closer cooperation, and to develop reliable societal emergency infrastructures.

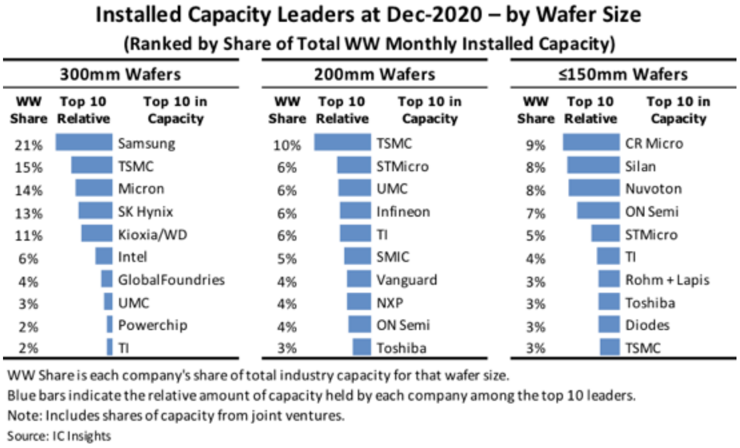
In the agrifood application domain, the provision of improved, robust, secure and interoperable connectivity will support innovations addressing the EU Green Deal regarding:

- Reducing the environmental impact related to transport, storage, packaging and food waste.
- Reducing water pollution and greenhouse gas emission, including methane and nitrous oxide.
- Reducing the European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agriculture and stopping biodiversity erosion.

### 2.2.4 Strategic Advantage for the EU

Connectivity is currently required in almost all application fields (consumer market, automotive, health and wellbeing, smart cities, etc.), but it is worth noting that European players are stronger in terms of the IoT and secured solutions due to hardware leaders such as STMicroelectronics, NXP and Infineon, as well as solution providers such as Gemalto. On the other hand, mass market-oriented businesses such as smartphones is today dominated by the US (Qualcomm, Broadcom, etc.) or Asian players (Huawei, Murata Manufacturing, etc.), with European technology businesses being focused on system integration, digitalisation, analytics, sensors/actuators (Siemens, ABB, Schneider, Valmet, Metso, Ericsson, Nokia, Danfoss, Thales, Dassault, Philips, WV, Airbus, GKN, Skanska, BMW, Daimler, Bosch, SKF, Atlas Copco, STMicroelectronics, etc.).

While Europe is producing only 9% of the overall electronic components (see Figure 2.2.3), its market share is 19% on the market it serves today (industry-grade embedded segments, the wireless infrastructure market being a good example with Ericsson and Nokia). This figure is in line with Europe’s GDP. Since Europe hardly addresses the consumer market, the European ecosystem requires a moderate manufacturing capacity mainly focused on mature or derivative technology. For example: automotive represents today only about 10%, but this is expected to increase in the coming years. The installed European semiconductor manufacturing capability to address Europe’s key verticals is sized accordingly, as illustrated in Figure 3: Europe has a strong presence on 200 mm facilities (with STMicroelectronics and Infineon among the top 5 leaders) which is in line with the technologies required by the European ecosystem and value chain.



**Installed Capacity Leaders at Dec-2020 – by Wafer Size**
(Ranked by Share of Total WW Monthly Installed Capacity)

| 300mm Wafers | | | 200mm Wafers | | | ≤150mm Wafers | | |
|---|---|---|---|---|---|---|---|---|
| WW Share | Top 10 Relative | Top 10 in Capacity | WW Share | Top 10 Relative | Top 10 in Capacity | WW Share | Top 10 Relative | Top 10 in Capacity |
| 21% | | Samsung | 10% | | TSMC | 9% | | CR Micro |
| 15% | | TSMC | 6% | | STMicro | 8% | | Silan |
| 14% | | Micron | 6% | | UMC | 8% | | Nuvoton |
| 13% | | SK Hynix | 6% | | Infineon | 7% | | ON Semi |
| 11% | | Kioxia/WD | 6% | | TI | 5% | | STMicro |
| 6% | | Intel | 5% | | SMIC | 4% | | TI |
| 4% | | GlobalFoundries | 4% | | Vanguard | 3% | | Rohm + Lapis |
| 3% | | UMC | 4% | | NXP | 3% | | Toshiba |
| 2% | | Powerchip | 4% | | ON Semi | 3% | | Diodes |
| 2% | | TI | 3% | | Toshiba | 3% | | TSMC |

WW Share is each company's share of total industry capacity for that wafer size.
Blue bars indicate the relative amount of capacity held by each company among the top 10 leaders.
Note: Includes shares of capacity from joint ventures.
Source: IC Insights

*Figure 2.2.3 - Installed capacity leaders in December 2020 by wafer size*[1].

The higher layer of the OSI communication stack is strongly dominated by software and network management. The European strong hold is clearly with wireless technology, (Ericsson, Nokia, ...) but also automation communication has strong European players like e.g. Siemens, ABB, Schneider, Valmet, Bosch, Endress&Hauser. For the Green deal and circularity, a major concern is the increased amount of data transferred over long distances, which need to be addressed both by technology and with solution architecture and sustainable strategies related to IoT and SoS solutions.

Consequently, to strengthen Europe's position and enable European industry to capture new business opportunities associated with the connected world we live in, it is vital to support European technological leadership in connectivity-supporting digitisation based on IoT and SoS technologies (for example, by being at the forefront of new standard development for the current 5G initiative and the emerging SoS market). Moreover, to bring added value and differentiation compared to US and Asian competitors, European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report[2]).

To illustrate the competitive value for Europe of connectivity and interoperability topics, we will summarize a few of the challenges associated with the connectivity requirement in a market where European industry has been historically strong or has to secure its position for strategic reasons:

- Automotive: the main driver here is the deployment of advanced driver-assistance systems (ADAS), which is a key opportunity for European semiconductor companies. Connectivity technology is consequently a Major Challenge since inter-sensor communication requires high bandwidth, reliability and very low latencies, and therefore innovative solutions will be necessary to prevent network overloads while meeting strict application and services requirements. A B5G and 6G networks with hierarchical architectures will be required to communicate in a reliable way with all the function domains of the car.
- Digital production: production of goods and services already involves a multitude of data obtained from various sources. Digitalisation demands a drastic increase of data sources, ranging from sensors and simulators to models. Such data will be used for control, analytics, prediction, business logics, etc., with receivers such as actuators, decision-makers, sales and customers. Obviously, this will involve a huge number of devices with software systems that are required to be interoperable, and possible to integrate for desired combined functionality. This demands seamless and autonomous interoperability between the devices and systems involved, regardless of the chosen technology. Connectivity technology plays an important role for all application areas of the ECS-SRIA.

## 2.2.5 Major Challenges

Five Major Challenges have been identified in the connectivity domain:

- **Major Challenge 1**: Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain.
- **Major Challenge 2**: Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership.
- **Major Challenge 3**: Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics
- **Major Challenge 4**: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity.
- **Major Challenge 5**: Network virtualisation enabling run-time and evolvable integration, deployment and management of edge and cloud network architectures.

### 2.2.5.1 **Major Challenge 1: Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain**

#### 2.2.5.1.1 State of the art

Today's connectivity solutions require an incredibly complex electronic system comprising various functions integrated into a wide range of technologies.

Note that advanced digital functions such as the application processor and the baseband modem are mastered by a limited number of US and Asian players (Hisilicon, Mediatek, Qualcomm and Samsung), and achieved in advanced complementary metal–oxide–semiconductor (CMOS) technology available at only two Asian businesses (Taiwan Semiconductor Manufacturing Company, TSMC, and Samsung). On this last point, it is worth noting that through the America CHIPS Act, Intel and TSMC will build new advanced logic (3 nm) 300 mm Fabs in Arizona while the European Chips Act should support advanced node fabrication facilities by TSMC in Dresden and by Intel in Magdeburg. The European Chips Act should also support ST and GF plans to build a new 300 mm facility in France to allow for 10 nm and beyond FDSOI technology manufacturing, all this in order to limit the reliance on Asian foundries' manufacturing capabilities.

From their side, European players (Infineon, NXP, ST, etc.) are strong on the analogue and RF front end module markets, mainly due to the availability of differentiated technologies developed and manufactured in Europe. Differentiated technologies are a key strength of the European ECS industry, especially when considering the connectivity market.

Consequently, to maintain Europe's leadership and competitiveness it is vital to ensure that European differentiated semiconductor technologies remain as advanced as possible. This is key to ensure that Europe secures the market share in the connectivity market, and also strengthens its technology leadership by playing a major role in the development and standardisation of future connectivity technologies. This point is crucial to secure Europe's sovereignty on the connectivity topic.

Moreover, over the last year the rising economic tension between the US and China has underlined the value of Europe's ECS supply chain. Once again, this is especially true for differentiated technologies. For example, advanced BiCMOS technologies are currently mastered by a limited number of US (GlobalFoundries and TowerJazz) and European (Infineon, ST and NXP) players. With Chinese companies being forced to move away from US providers, this creates a significant opportunity for Europe as the only viable alternative. Consequently, strengthening Europe's connectivity technology portfolio and associated manufacturing capacity to offer an independent and reliable supply chain is now a key challenge for all European ECS actors.

In addition to being able to provide the differentiated semiconductor technologies supporting the development of innovative connectivity solutions, it is important to note that some European players are proposing connectivity chipset solutions (for example, Sequans Communications and Nordic on the narrowband (NB) IoT topic) or full connectivity solutions. Supporting the growth of these existing actors and helping emerging industry leaders is also a key challenge for Europe to capture a bigger proportion of the value chain, as well as to ensure its sovereignty on the connectivity topic in the long run.

### 2.2.5.1.2 Vision and expected outcome

To address identified connectivity technology challenges, we propose the vision described below, which can be summarised by the following three key points (with associated expected outcomes).

**Strengthening Europe's differentiated technologies portfolio**

As discussed above, Europe's differentiated semiconductor technologies are key assets that should be both preserved and improved upon to secure European leadership in connectivity. Consequently, dedicated research should be encouraged, such as the technologies below (which are also promoted in the Chapter 1.1 on Process Technology, Equipment, Materials and Manufacturing):

- Advanced BiCMOS: targeting RF and sub-THz (i.e., 100-300GHz) and THz front-end modules.
- RF SOI: targeting <7 GHz and mmW front-end modules.
- GaN: targeting the high-power infrastructure and high efficiency/wide bandwidth 6G handset markets (5.925 GHz – 7.125 GHz and 10 GHz – 13.25 GHz bands).
- FD SOI: targeting power-efficient connectivity solutions (for example NB IOT and NTN).
- GaAs: targeting mmW space and defense applications ( W & K bands).
- InP & InP on Si: targeting high-speed optical link (>800 Gb/s), mmW applications (6G sub-THz communication >100 GHz) and ultra-low noise Front End Module in K band.
- RF filters: supporting the development on innovative European based technology (for example POI based TF SAW technologies).
- Advanced packaging: enabling prototyping and medium volume production capability in Europe to enable Heterogeneous integration of differentiated technology manufacture in Europe to move higher in the value chain and capture more value.

The main challenge will be in improving achievable performances. To illustrate this, we have extracted the medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID to serve as a connectivity roadmap (see Figure 2.2.4). We can see that whatever the type of application (device-to-device, D2D, indoor, outdoor), the requirements in analogue RF will mainly consist of achieving Fmax and FT ~500 GHz in 2025 and 1 THz in 2030, while NFmin will be well below 1 dB in the medium term, to reach 0.5dB in the long term. The only parameter that differentiates the types of applications is the output power, which outdoors should reach between 36 and 40 dBm per PA by the end of the decade. The biggest challenge for silicon or hybrid-on-silicon substrate technologies is expected to be the frequency challenge. Technologies such as GaN/Si and RF SOI will deliver power but for applications operating at less than 100 GHz.

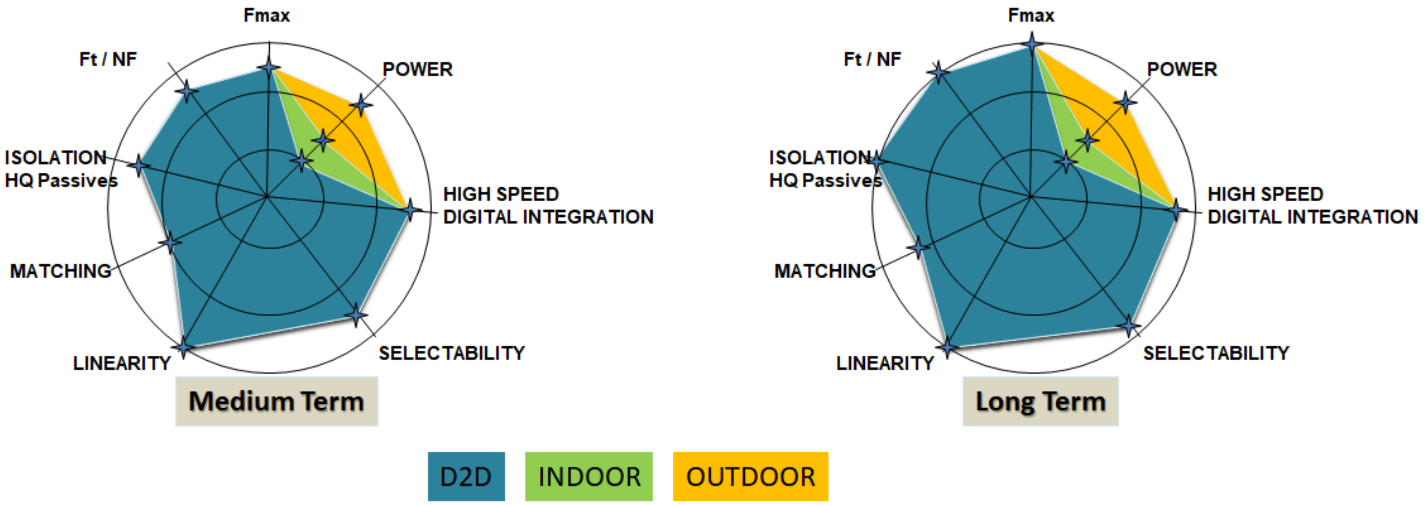


*Figure 2.2.4 - Medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID*[3]

Note that the vision presented in Figure 2.2.4 also applies to packaging and printed circuit board (PCB) technologies. It is also worth noting that while Europe is playing a key role in innovative differentiated semiconductor technologies, there is very little R&D activity or few players in Europe on the packaging and PCB side. This point is clearly a weakness that should be addressed to strengthen Europe's connectivity technology portfolio.

**Securing Europe's differentiated hardware technology manufacturing**

Beyond the development and enablement in Europe of innovative semiconductor technologies targeting the connectivity market, it will be key to safeguard and promote European manufacturing capability to both secure Europe economical interest (in terms of market share) and also address the sovereignty topic (since trade war issues can jeopardise the viability of Europe's industrial actors). To do so, in coordination with chapter 1.1 on Process Technology, Equipment, Materials and Manufacturing, the following topics should be supported:

- The enablement of pilot lines: the objective here is to support the deployment of additional manufacturing capabilities for technology already available in Europe (supporting the transition to 300 mm Fab), or to address new technologies (such as packaging or advanced PCB) to increase the technology portfolio available in Europe.
- The rise of new semiconductor equipment champions: to secure manufacturing capabilities in the long term, it will also be necessary to ensure that the required equipment is provided by European players. This is crucial to prevent any vulnerability in the European supply chain to possible international political or economic issues.
- Nurture a pan-European design ecosystem to tackle the new challenges on transistors in more than Moore, circuits architectures with increased security and trustworthiness and new AI/ML chips raised by the digitalisation era.

**Strengthening Europe's connectivity technology portfolio (hardware, internet protocols and software)**

Leveraging previously discussed differentiated semiconductor technology portfolio, innovative connectivity solutions (hardware, internet protocol (IP) or software) should be encouraged to enable Europe to take full advantage of its technology and manufacturing assets, and to capture market share at the component level. This action is crucial to secure Europe's position beyond 5G and preliminary 6G investigation and standardisation activities. It also enables the development and manufacturing in Europe of highly integrated connectivity module/systems.

Since most of the value of a complex connectivity system will be captured at the module level, it is highly desirable to enable European players to rise the value chain (in coordination with the chapter Components, Modules and Systems Integration).

In targeting systems and applications, it is important to consider the interconnection between subsystems, and focus should be on individual component technology development according to needs identified at the system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key.

Heterogeneous integration refers to the integration of separately manufactured components into a higher- level assembly that cumulatively provides enhanced functionality and improved operating characteristics. In this definition, components should be taken to mean any unit – whether individual die, device, component, and assembly or subsystem – that is integrated into a single system. The operating characteristics should also be taken in their broadest meaning, including characteristics such as system-level cost of ownership.

This is especially true for the hardware side in the context of the end of Moore's law. It is the interconnection of the transistors and other components in the integrated circuit (IC), package or PCB and at the system and global network level where future limitations in terms of performance, power, latency and cost reside. Overcoming these limitations will require the heterogeneous integration of different materials (silicon, III-V, SiC, etc.), devices (logic, memory, sensors, RF, analogue, etc) and technologies (electronics, photonics, MEMS and sensors).

#### 2.2.5.1.3 Key focus areas

To support the vision presented in the previous paragraph, we propose to focus effort on the following key focus areas:

- Innovative materials (GaN, InP, etc.) and large diameter wafers technology (POI, InP on Si, GaN on Si, InP etc.) supporting the development of innovative connectivity technology solution.
- Innovative differentiated semiconductor technology development targeting connectivity application.
- Innovative packaging and PCB technology targeting connectivity application.
- Pilot line enablement to support the strengthening of European manufacturing capability.
- Innovative semiconductor equipment enablement.
- Innovative connectivity solution engineering through virtualisation of the different connectivity layers.
- Enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc.) to help European players capture higher value in the connectivity market.
- Ultra-low power transceivers will be needed, and low eco-footprint.
- Power efficient and cost efficient transceivers including Data conversion (ADC-DAC), up & down frequency conversion (LO & mixers), and RF emission and Reception (PA-LNA).
- Antennas and packages at mm-wave and THz, on-chip antennas.
- Advanced System on Chip design for CMOS and new technologies like e.g. GaN, InP, InP on Si, GaN on Si.
- Meta-materials for antennas, meta-materials for intelligent reflective surfaces and meta-surfaces.

### 2.2.5.2 **Major Challenge 2: Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU’s long-term leadership**

#### 2.2.5.2.1 State of the art

Targeting connectivity solutions beyond 5G, R&D activity is today mainly focused on the three key challenges listed below.

**Evaluating the advantage to use new spectrum (especially 7 GHz – 20 GHz band and mmW frequencies >100 GHz)**

With the ongoing deployment of 5G in the <6 GHz and 28 GHz bands, the current R&D focus is now on the spectrum considered for 6G development targeting the 2030 time horizon. Three main frequency bands are today discussed in the telecommunication industry:

Low band (5.925 GHz – 7.125 GHz):

This band is attracting a lot of attention for 6G (especially in China), we can note that some competition exist with future Wi-Fi development. While China allocated the full band for IMT services, the US did the opposite and the FCC allocated the band for Wi-Fi. Europe is considering an intermediate stance and will likely allocate the 5.925 – 6.425 GHz range to Wi-Fi and the 6.425 GHz – 7.125 GHz range for IMT. Development of wireless system in this band will likely be incremental to previous one <6 GHz, however we can mention that PA efficiency (GaN opportunity on the handset market?) and filtering technology (due to coexistence issues with Wi-Fi) seem the main challenges today.

Mid band (10 GHz – 13.25 GHz):

While no regulation has been enacted yet, the 7 GHz – 20 GHz spectrum is attracting a lot of attention (compared with 3.5 GHz, propagation attenuation will be increased in an acceptable range while path loss will be further reduced by more advanced radio technologies. ). Eliane Semaan, director of spectrum and technology regulation for infrastructure vendor Ericsson, wrote in 2022[4]: "Spectrum from within the 7-20 GHz range is essential to realize the capacity-demanding use cases in future 6G networks". Nokia is pushing the same view, Harri Holma and Harish Viswanathan also wrote in 2022[5]: "Ten years from now we expect new spectrum bands between 7 GHz and 20 GHz to open up for 6G use, which will provide the necessary bandwidth to create these new high-capacity carriers," We can note that Huawei is also pursuing the same strategy but is more specific on the 10 GHz – 13.25 GHz spectrum[6]. This band seems one of the most promising since Jessica Rosenworcel, chairwoman of the FCC, **recently said** she's eyeing the 12.7GHz to 13.25GHz spectrum band as a possible location for the agency's next big spectrum push. From hardware technology point of view, working over 10 GHz will bring several challenges. From PA side, we can wonder if GaAs HBT technology will remain relevant. From filter side, It is not clear if existing filter technologies will provide acceptable performances. More generally, it creates an opportunity for SiGe technology (and consequently for Europe) since this technology is today widely used in the X and Ku bands for satellite communication.

NTN Mid band (Ku band: 12 GHz – 18 GHz & Ka and FWA band: 28 GHz – 40 GHz):

In addition to new spectrum requirements previously mentioned, 6G envision to seamlessly integrate existing satellite communication in cellular connectivity networks. This trend can be seen under the topic Non Terrestrial Networks currently discussed inside 3GPP.

Targeted frequency spectrum is not new (traditional Ku and Ka bands). The main objective is here to leverage under redeployment Low Earth Orbit satellite constellation to complement the cellular network coverage while offering performances (latency & data rate) in line with real-time application.

Two main challenges will have to be addressed: seamless integration and handover of satellite connectivity along with cellular one (network type should be transparent for the user) and the development of cost-effective chipset solutions to enable user terminals in line with mass market constraints (which creates key opportunities for Si-based technology such as SiGe BiCMOS).

High band (>100 GHz):

While the R&D evaluation has been focused on frequencies below 20 GHz to date, there is now some interest in assessing achievable performances with a higher frequency. For regulatory reasons, the 275 GHz – 325 GHz range holds promise as it enables the widest available bandwidth. As an illustration, to play a key role in preliminary 6G investigations, the US has facilitated their research on the 95 GHz – 3 THz spectrum over the coming decade. After a unanimous vote, the Federal Communications Commission (FCC) has opened up the “terahertz wave” spectrum for experimental purposes, creating legal ways for companies to test and sell post-5G wireless equipment. However, we can note that the telecommunication industry is cautious on the use of this spectrum. Magnus Frodigh, Ericsson's chief researcher, for example wrote[7]: "We have thus identified new potential spectrum ranges for 6G, notably in the centimetric range from 7-15 GHz, which we believe will be an essential range, and in the sub-THz range from 92-300 GHz, which will have a complementary role serving niche scenarios". He continued: "Our learnings from 5G are that the mmWave range is a powerful spectrum range which allows operators to provide value to industry and enterprise through high data rates. However, due to limited coverage, it serves as a complement to other ranges that can be used in wider areas but with limited data rates (i.e. mid bands)." Frodigh concluded: "We believe that in order to benefit society, the majority of 6G use cases should be enabled for wide-area coverage, both indoors and outdoors, and not limited to confined areas. This means that – whilst we ought to explore the sub-THz region for entirely novel 6G capabilities – the main value will be in the centimetric 7-15 GHz". At such high frequency, new hardware technology may be required and InP is today a hot topic to enable low noise receivers and power efficient Power Amplifiers > 100 GHz.

**Evaluating the opportunity to use new medium of propagation**

Over the last few years, impressive results have been reported concerning high-speed millimetre wave silicon transceivers coupled to plastic waveguides. The state of art on the data rate is now at 36 Gb/s, with a short distance of 1 m in SiGe 55 nm BiCMOS with 6pJ/b.meter working at 130 GHz. The maximum distance ever reported is 15 m, with 1.5 Gb/s data rate using 40nm CMOS at 120 GHz. In the 10 m distance – which, for instance, is the requirement for data centre applications – the state of the art is given by a data rate of 7.6 Gb/s at 120 GHz for 8m in 40nm CMOS, and a data rate of 6 Gb/s at 60 GHz for 12m in 65 nm CMOS. Although a 10 Gbps data rate, seems feasible, questions remain over whether there is the required energy per bit to deliver this performance. Interesting technologies here is intelligent reflective surfaces and meta surfaces.

**Exploring the benefits that AI could bring to connectivity technologies**

While 5G is being deployed around the world, efforts by both industry and academia have started to investigate beyond 5G to conceptualise 6G. 6G is expected to undergo an unprecedented transformation that will make it substantially different from the previous generations of wireless cellular systems. 6G may go beyond mobile internet and will be required to support ubiquitous AI services from the core to the end devices of the network. Meanwhile, AI will play a critical role in designing and optimising 6G architectures, protocols and operations.

For example, two key 5G technologies are software-defined networking (SDN) and network functions virtualisation (NFV), which have moved modern communications networks towards software-based virtual networks. As 6G networks are expected to be more complex and heterogeneous, advanced softwarisation solutions are needed for beyond 5G networks and 6G networks. Selecting the most suitable computational and network resources and the appropriate dynamic placement of network functions, taking network and application performance as well as power consumption and security requirements into account, will be an important topic. By enabling fast learning and adaptation, AI-based methods will render networks a lot more versatile in 6G systems. The design of the 6G architecture should follow an “AI-native” approach that will allow the network to be smart, agile, and able to learn and adapt itself according to changing network dynamics.

## 2.2.5.2.2 Vision and expected outcome

To address identified connectivity technology challenges, we propose the vision described below, which can be summarised in the following three points (with associated expected outcomes).

**Assess achievable connectivity performances using new spectrums**

To maintain European leadership on connectivity technology and ensure sovereignty, the development of new electronics systems targeting connectivity applications in non-already standardised (or in the process of being standardised) spectrums should be supported. A special focus should be dedicated to the frequency bands listed below.

- Sub-THz connectivity application in the 200 GHz – 300 GHz band: With THz communication being a hot topic in the international community, European activity in the spectrum > 300 GHz should be encouraged. These investigations should help Europe play a role in the development of the new technology and assess its relevance to future 6G standards.
- Unlicensed connectivity in the 6 GHz – 7 GHz band: As Wi-Fi 6 is currently being deployed in the US in the 5 GHz – 6.2 GHz band (on April 23 2020, the FCC approved the opening of 1200 MHz of spectrum to IEEE 802.11ax), this spectrum allocation is also under discussion in Europe. It is vital for Europe to support investigations on this frequency band to ensure that the next generation of Wi-Fi technology is accessible to European citizen and businesses (without any limitation compared to other countries).

- Investigation of the <10 GHz spectrum for 6G: While 5G was initially thought to be mainly linked to the mmW spectrum (for example, at 28 GHz), most of the current deployment effort is happening in the new < 6 GHz frequency bands. To complement the investigation of the above-mentioned THz communication, the evaluation and development of innovative connectivity technology <10 GHz should be encouraged. This may secure European leadership in future 6G proposals and standardisation activities.

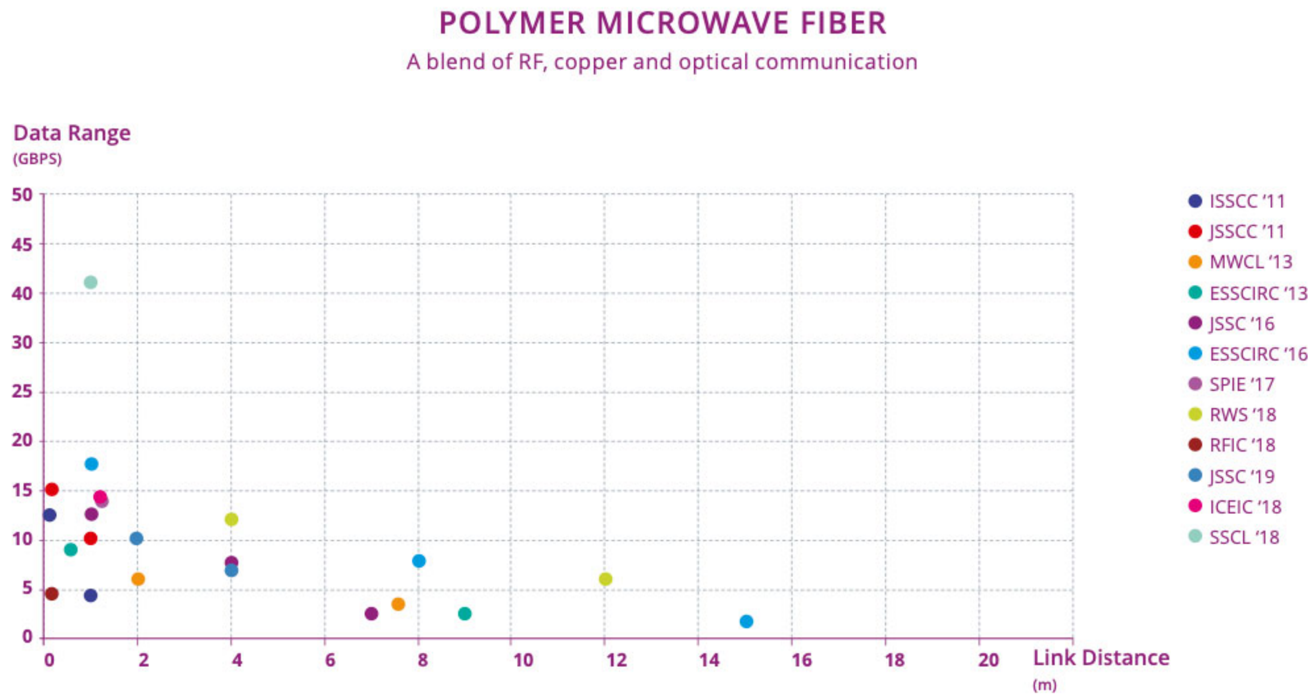


*Figure 2.2.5 - Polymer microwave fiber – A blend of RF, copper and optical communication (Source: **https://www.polymermicrowavefiber.com/** : PMF state of art by KUL Professor Patrick Reynaert)*

**Investigate new propagation medium to enable power-efficient and innovative connectivity technologies**

New applications create the need for new connectivity technology. For example, autonomous driving requires very high-speed communication (currently 10 Gb/s and 40 Gb/s in the future) to connect all the required sensors to the central processing unit (CPU). While Ethernet is today perceived as the technology of choice, its deployment in cars is challenging since the electromagnetic interference (EMI) requirements of the automotive industry impose the use of shielded twisted pairs, which add cost and weight constraints. To address this need, intense R&D activity has been pursued over the last few years to assess the relevance of mmW connectivity using plastic waveguides (as described in the previous section). Consequently, the development of innovative connectivity solutions using new mediums of propagation should be encouraged to enable innovative connectivity technology and ensure European leadership and sovereignty.

**Integrate AI features to make connectivity technology faster, smarter and more power-efficient**

The use of new spectrums or propagation mediums is not the only way to boost innovative connectivity technology. As mentioned, 5G has underlined the role of software to promote virtualisation and reconfigurability, but those concepts may not be sufficient to address the challenges related to the more complex connectivity technology that may be developed (for example, 6G).

To address this challenge, Artificial Intelligence is now perceived as a strong enabler. Consequently, in coordination with the "Edge Computing and Embedded Artificial Intelligence" chapter, the topics below should be supported.

- Investigate AI features at the edge: to improve the power efficiency of mobile devices by reducing the amount of data to be transmitted via the wireless network, the concept of AI at the edge (or edge AI) has been proposed. The idea is to locally process the data provided by the sensor using mobile device computing capability. Moreover, processing data locally avoids the problem of streaming and storing a lot of data to the cloud, which could create some vulnerabilities from a data privacy perspective.

- Use AI to make the connectivity network more agile and efficient: the idea here is to move to an AI-empowered connectivity network to go beyond the concept of virtualisation and achieve new improvements in terms of efficiency and adaptability. For example, AI could play a critical role in designing and optimising 6G architectures, protocols and operations (e.g. resource management, power consumption, improved network performance etc.).

### 2.2.5.2.3 Key focus areas

To support the vision presented in the previous paragraph, we propose that efforts should be focused on the following key focus areas:

- Innovative connectivity system design using new spectrums (especially mmW).
- Investigation and standardisation activity targeting 6G cellular application in the frequency band < 10 GHz.
- Development of innovative connectivity technology using unlicensed frequencies in the 6 GHz – 20 GHz band.
- Development of innovative connectivity systems using new propagation mediums.
- Development of connectivity system leveraging the concept of edge AI.
- Evaluation of the AI concept to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability.

### 2.2.5.3 **Major Challenge 3: Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics**

#### 2.2.5.3.1 State of the art

Europe has a very clear technology lead in automation and digitalisation technology for industrial use. The next generation of automation technology is now being pushed by Industry 4.0 initiatives backed by the EC and most EU countries. In the automotive sector, the autonomous and green car vision is the driver. Here, Europe again has a strong competitive position. In healthcare, the ageing population is the driver. Europe's position in this area is respectable but fragmented. Robust, dependable, secure and interoperable connectivity from application to application and prepared for interaction in System of Systems solution are fundamental to market success in these and other areas.

Interoperability is a growing concern among numerous industrial players. An example here is the formation of industrial alliances and associated interoperability project efforts. One of the directions chosen targets is to gather behind a few large standards. An example of this is showcased in Figure 2.2.6.

To maintain and strengthen the European lead, advances in autonomous interoperability and associated efficient engineering capability are necessary. The game changers are:

- Autonomous interoperability for SoS integration for efficient machine supported engineering at design-time and run-time.
- Open interoperability frameworks and engineering platforms.
- Novel, flexible and manageable security solutions.
- Standardisation of the above technologies.

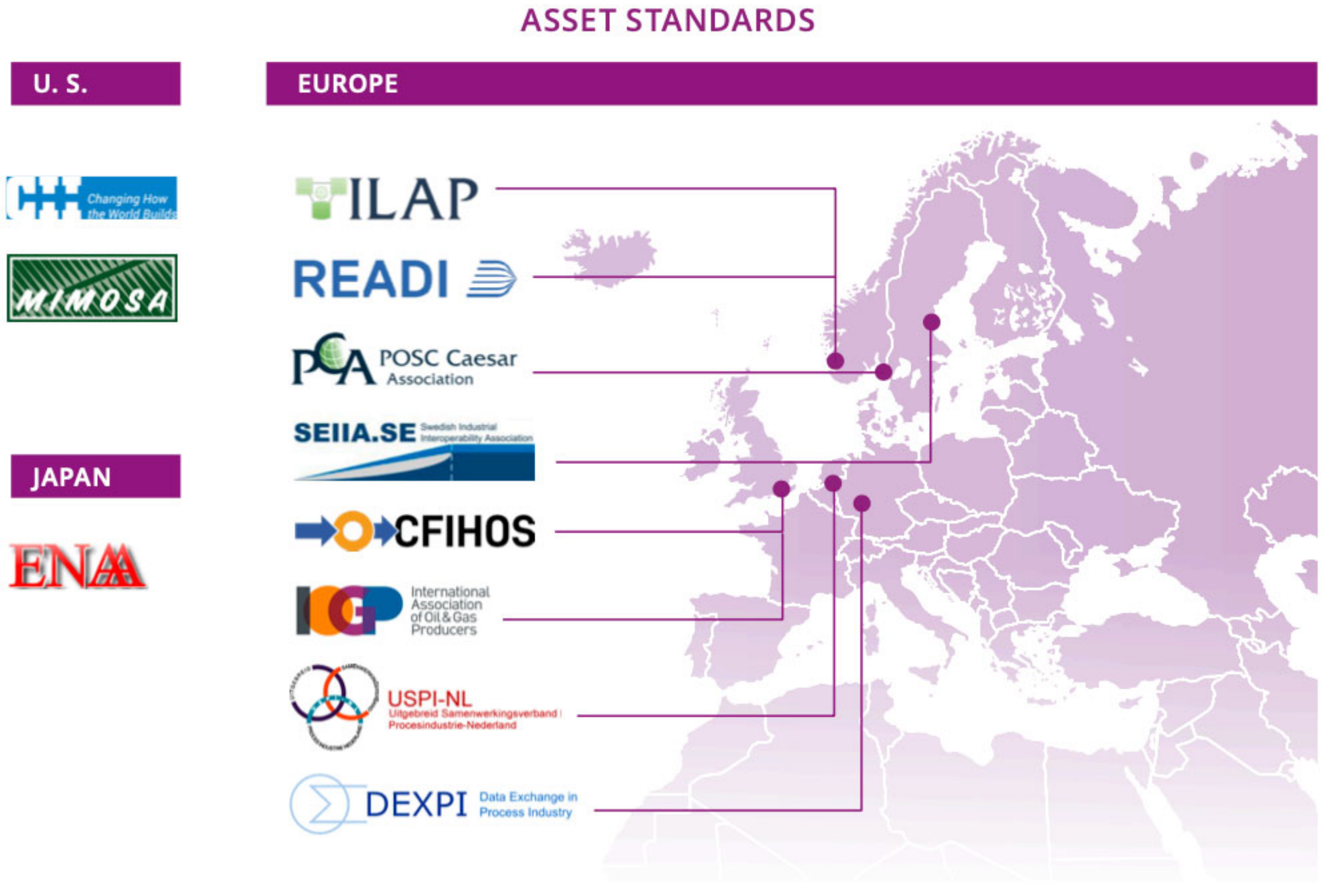


*Figure 2.2.6 ISO 15926 – Asset Standards worldwide (Source: Erik Molin, SEIIA)*

#### 2.2.5.3.2 Vision and expected outcome

To fully leverage heterogeneous integration at the hardware level, software interoperability is a parallel challenge to provide application to application connectivity that allows for autonomous SoS connectivity, from edge to cloud, enabling usage of available data for all areas of application. To do so, dedicated software tools, reference architecture and standardisation are key to supporting autonomous interoperability, thus enabling the provision of a widely interoperable, secure, scalable, smart and evolvable SoS connectivity.

This challenge involves the interoperability of service or agent protocols, including encoding, security and semantics. Here, payload semantics interoperability is a primary focus, leading to architectures, technologies and engineering tools that support application to application integration of SoS for all areas of applications at design- time, in run-time and over life cycle. This will include e.g. translation between different standards used in domains where SoS interaction is necessary to reach business and societal objectives.

The objective here is a technology that enables nearly lossless interoperability across protocols, encodings and semantics, while providing technology and engineering support foundations for the low-cost integration of very large, complex and evolvable SoS.

Expected achievements are:

- Open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, including 5G & 6G.
- Open source engineering and implementation frameworks for the de-facto standard SoS connectivity architecture.
- Architecture reference implementations with performance that meets critical performance requirements in focused application areas.

#### 2.2.5.3.3 Key focus areas

The high-priority technical and scientific challenges in both design-time and run-time are:

- Semantics interoperability from application to application.
- Autonomous translation of protocols, encodings, security and semantics.
- Evolvable SoS connectivity architectures and technologies over time and technology generations.

### 2.2.5.4 **Major Challenge 4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity**

#### 2.2.5.4.1 State of the art

It is clear that the US is the leader when it comes to wired connectivity while Europe is the leader in cellular connectivity. The big potential game changer here is 5G and upcoming 6G. To advance the European position, the establishment of connectivity architecture, reference implementation and associated engineering frameworks supporting 5G/6G and other wireless technologies is required. The primary application markets should connect to European strongholds such as automation, digitalisation and automotive. The game changers are:

- Establishment of connectivity architecture standards with associated reference implementation and related engineering frameworks.
- SoS application to application connectivity being interoperable, secure, scalable, smart and evolvable over technology generations.

#### 2.2.5.4.2 Vision and expected outcomes

The enabling of SoS connectivity is fundamental for capturing the emerging SoS market and its very high growth rate. Efficient engineering and the deployment of interoperable, secure, scalable, smart and evolvable SoS connectivity will be key to this. This will help Europe lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

In certain domains such as automotive and industrial automation, Europe is the major player. Market studies[8] indicate very large to extreme growth in the SoS market over the next five years.

This will provide a very strong market pull for all technologies and products upstream. Here, connectivity interoperability is a very important component, enabling tailored SoS solutions and efficient engineering. The vision is to provide interoperable connectivity architecture, reference implementation and associated engineering support and frameworks spanning technologies from legacy to 5G and 6G and other wireless and wired technologies.

Expected achievements

- Open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, like e.g. 5G/6G, wired and optical connectivity.
- Open source engineering and implementation frameworks for the de-facto standard SoS connectivity architecture.
- Architecture reference implementations which meet critical performance requirements in focused application areas.

#### 2.2.5.4.3 Key focus areas

The high-priority technical and scientific challenges are:

- SoS connectivity architecture as a de-facto standard.
- Reference implementation of de-facto SoS connectivity architectures.
- Engineering frameworks for de-facto standard SoS connectivity architecture.

### 2.2.5.5 **Major Challenge 5: Network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures**

#### 2.2.5.5.1 State of the art

Virtualisation of networks is a main trend for cellular networks. This has to be expanded to other wireless and wired connectivity technology. The game changers are:

- Technologies for network virtualisation across multiple hardware and software layers using heterogeneous devices.
- Engineering and integration tools and management methodologies for efficiently engineering, integration and management of virtualized IoT and SoS networks and service components.
- Intelligent, configurable generic hardware platforms.

#### 2.2.5.5.2 Vision and expected Outcome

The enabling of virtualised networks is fundamental for capturing the emerging SoS market and its very high growth rate. Efficient engineering, deployment and management of connectivity is a key enabler for interoperable, secure, scalable, smart and evolvable SoS. This will help Europe lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

European leadership in certain domains, mentioned above, will provide a very strong market pull for all technologies and products upstream. Here, virtualised connectivity is a very important component, enabling dynamic updates and rearrangements of SoS solutions. The vision is to provide virtualised connectivity across physical and mac layers spanning technologies from legacy to 5G and upcoming 6G.

Expected achievements:

- Open source implementation of reference architectures supporting virtualised connectivity across multiple technology platforms, including 5G, B5G, 6G, wired and optical.
- Open source engineering and management frameworks for virtualised connectivity across multiple technology platforms, including 5G, B5G, 6G, wired and optical.
- Reference implementations with performance that meets critical performance requirements in focused application areas taking into consideration energy efficiency.

#### 2.2.5.5.3 Key focus areas

The high-priority technical and scientific challenges are:

- Virtual connectivity architecture supporting multiple technology platforms.
- Reference implementation of virtual connectivity architecture enabling very efficient application-level usage.

- Engineering, integration and management frameworks with tools for virtual connectivity architectures.

## 2.2.6 Timeline

The timeline for addressing the Major Challenges in this section is provided in the following table.

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain** | **Topic 1.1**: innovative differentiated semiconductor technology development targeting connectivity application | TRL 4–6<br>Enable next generation RF SOI and BiCMOS technology as well as innovative GaN on Si technology | TRL 7–9<br>Industrial transfer of previous technologies from pilot line to Fab | |
| | **Topic 1.2**: innovative packaging and PCB technology targeting connectivity application | TRL 3–4<br>Development of innovative European packaging (such AMP) and PCB technologies | TRL 5–6<br>Pilot line enablement and support of small series | TRL 7–9 |
| | **Topic 1.3**: pilot line enablement to support European manufacturing capability strengthening | TRL 4–6<br>Support the transition from 200 mm to 300 mm for existing technologies | TRL 7–9<br>Add manufacturing capability beyond existing technologies | |
| | **Topic 1.4**: innovative semiconductor equipment enablement | TRL 3–4 | TRL 5–6 | TRL 7–9 |
| | **Topic 1.5**: innovative connectivity solution development targeting hardware, IP and software items | TRL 3–4 | TRL 5–6 | TRL 7–9 |
| | **Topic 1.6**: enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc) to help European players capture higher value in the connectivity market | TRL 4–6<br>Ease the access to existing pilot line and enable associated IP ecosystem | TRL 7–9<br>From pilot line to industrial manufacturing | |
| **Major Challenge 2:**<br>**Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership** | **Topic 2.1**: innovative connectivity system design using new spectrums (especially mmW) | TRL 3–4<br>Assess the specification of wireless systems in the 200 GHz – 300 GHz band | TRL 5–6<br>Achieve preliminary transceiver demonstrator using European technologies | TRL 7–9<br>Transfer to the industry to enable European products |
| | **Topic 2.2**: investigation and standardisation activity targeting 6G cellular application in frequency band < 10 GHz | TRL 3–4<br>Contribute to 6G mid band spectrum standardisation | TRL 5–6<br>Leverage European differentiated technologies to address 6G mid band spectrum challenges | TRL 7–9<br>Enable first 6G connectivity chipset solution |
| | **Topic 2.3**: development of innovative connectivity technology using unlicensed frequency in the 6 GHz – 7 GHz band | TRL 4–6<br>Contribute to Wi-Fi6E and 7 standardisation | TRL 7–9<br>Enablement of European Wi-Fi 6E and 7 chipset solution leveraging European derivative technology | |
| | **Topic 2.4**: development of innovative connectivity systems using new propagation mediums | TRL 3–4 | TRL 5–6 | TRL 7–9 |
| | **Topic 2.5**: development of connectivity systems leveraging the concept of edge AI | TRL 4–6 | TRL 7–9 | |
| | **Topic 2.6**: evaluation of the AI concept to be able to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability | TRL 4–6 | TRL 7–9 | |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 3:**<br>**Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics** | **Topic 3.1**: semantics interoperability | AI-supported translation of payload semantics based on a limited set of ontologies and semantics standards | General translation of payload semantics enabling application information usage | General translation of payload semantics enabling application information usage |
| | **Topic 3.2**: autonomous translation of protocols, encodings, security and semantics | Autonomous and dynamic translation between SOA-based services protocol, data encoding, data compression and data encryption | Dynamic translation between major data model relevant for the ECSEL field of application. | Autonomous and dynamic translation between a large set of data models relevant for the ECSEL field of application |
| | **Topic 3.3**: evolvable SoS connectivity architectures and technologies over time and technology generations | TRL4–6 | TRL 5–7 | TRL6–8 |
| **Major Challenge 4:**<br>**architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity** | **Topic 4.1**: SoS connectivity architecture as a de facto standard | SoS connectivity architecture based on SOA established as a major industrial choice in the application domains of the SRIA | SoS connectivity architecture based on SOA established as the major industrial choice in the application domains of the SRIA | |
| | **Topic 4.2**: reference implementation of de facto SoS connectivity architectures | Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (chapter SoS) reference implementation | Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (chapter SoS) reference implementation at TRL 8–9. | |
| | **Topic 4.3**: engineering frameworks for de facto standard SoS connectivity architecture | Reference implementation of an engineering framework with associated tools for SoS connectivity | Reference implementation of an engineering framework with associated tools for SoS connectivity at TRL 8 | |
| **Major Challenge 5:**<br>**network virtualisation enabling run-time engineering, integration, deployment and management of edge and cloud network architectures** | **Topic 5.1**: Virtual connectivity architecture supporting multiple technology platforms, including 5G, B5G and 6G AI | TRL-3-5<br>a fully distributed edge environment, including hardware accelerators | TRL 5-7 | TRL 6-8 |
| | **Topic 5.2**: Reference implementation of virtual connectivity architecture | TRL 3-5<br>Edge modules, integration of multiple technologies for JCAS, Flexible hardware platforms supporting virtualisation and programmability in a fully distributed edge environment | TRL 5-7<br>Pilot scale demonstrations fully distributed edge environment, including hardware accelerators to significant lower cost levels compared to current industrial SOTA | TRL6-8 |
| | **Topic 5.3**<br>Engineering, integration and management frameworks | Advanced baseband capabilities in open virtualisation platforms from hardware(e.g. RISC-V) to open software integration and virtualisation platforms | TRL 5-7 | TRL6-8 |

## 2.2.7 Link with proposed Design Platform and Pilot Lines included in the Chips for Europe Initiative

In order to speed up the pace at which research results may be brought to the market, clear links can be underlined between the proposed SRIA on connectivity and “innovation accelerators” being currently set up in the frame of the European Chips Act. We refer here specifically to the Design Platform and the Pilot Lines included in the Chips for Europe Initiative, which have the objective of supporting technological capacity building and innovation in the Union by bridging the gap between the Union’s advanced research and innovation capabilities and their industrial exploitation.

Being more specific to the context of this SRIA connectivity chapter, the following synergies can be mentioned (according to ongoing discussions about the Chips for Europe initiative at the time of the writing of this chapter):

- **Heterogeneous Integration and Advanced Packaging Pilot Line**: this initiative should support the R&I efforts in the following key focus areas of Major Challenge 1 (see 2.2.5.1.3 key focus areas).

    - Enable a European ecosystem that can support heterogeneous integration (multi-die system-in-a-package, advanced assembly capability, advanced substrate manufacturing, etc.) to help European players capture higher value in the connectivity market.
    - Enable the development of innovative antenna-in-package solutions at mm-wave and THz frequencies.
    - Enable a sovereign European packaging ecosystem to secure the supply chain of European semiconductor players (especially in key areas such as space were required manufacturing scale limits the possibility to have access to Asian OSAT)
- **FDSOI Pilot Line**: this initiative should support the R&I efforts in the following key focus areas of Major Challenge 1 and 2 (see 2.2.5.1.3 key focus areas).
    - Enable the development of power efficient connectivity solution leveraging European based semiconductor technology.
    - Enable the development of innovative connectivity solution at mmW and THz frequencies.

## 2.2.8 References

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# 2.3

*Cross-Sectional Technologies*

# ARCHITECTURE AND DESIGN: METHODS AND TOOLS

## 2.3

# Architecture and Design: Method And Tools

### 2.3.1 Scope

To strengthen European industry's potential to transform new concepts and ideas cost- and effort-effectively into high- value and high-quality electronic components and systems (ECS)-based innovations and applications, two assets are essential: effective architectures and platforms at all levels of the design hierarchy; and structured and well-adapted design methods and development approaches supported by efficient engineering tools, design libraries and frameworks. These assets are key enablers to produce ECS-based innovations that are: (i) beneficial for society; (ii) accepted and trusted by end-users; and thus (iii) successful in the market.

Future ECS-based systems will be intelligent (using intelligence embedded in components), highly automated up to fully autonomous, and evolvable (meaning their implementation and behaviour will change over their lifetime), cf. Part 3. Such systems will be connected to, and communicate with, each other and the cloud, often as part of an integration platform or a system-of-system (SoS, cf. Chapter 1.4). Their functionality will largely be realised in software (cf. Chapter 1.3) running on high-performance specialised or general-purpose hardware modules and components (cf. Chapter 1.2), utilising novel semiconductor devices and technologies (cf. Chapter 1.1).

This Chapter describes needed innovations, advancements and extensions in architectures, design processes and methods, and in corresponding tools and frameworks, that are enabling engineers to design and build such future ECS-based applications with the desired quality properties (i.e. safety, reliability, cybersecurity and trustworthiness, see also Chapter 2.4, in which these quality requirements are handled from a design hierarchy point of view, whereas here a process oriented view is taken). The technologies presented here are therefore essential for creating innovations in all application domains (cf. Part 3); they cover all levels of the technology stack (cf. Part 1), and enable efficient usage of all cross-cutting technologies (cf. Part 2).

Traditionally, there is a huge variety of design processes and methods used in industry, such as processes based on the V-Model in systems and software design, based on Gajsky and Kuhn's diagram (Y-chart) in hardware design, based on the waterfall model or any other kind of (semi-) formal process definition (see Figure 2.3.1).

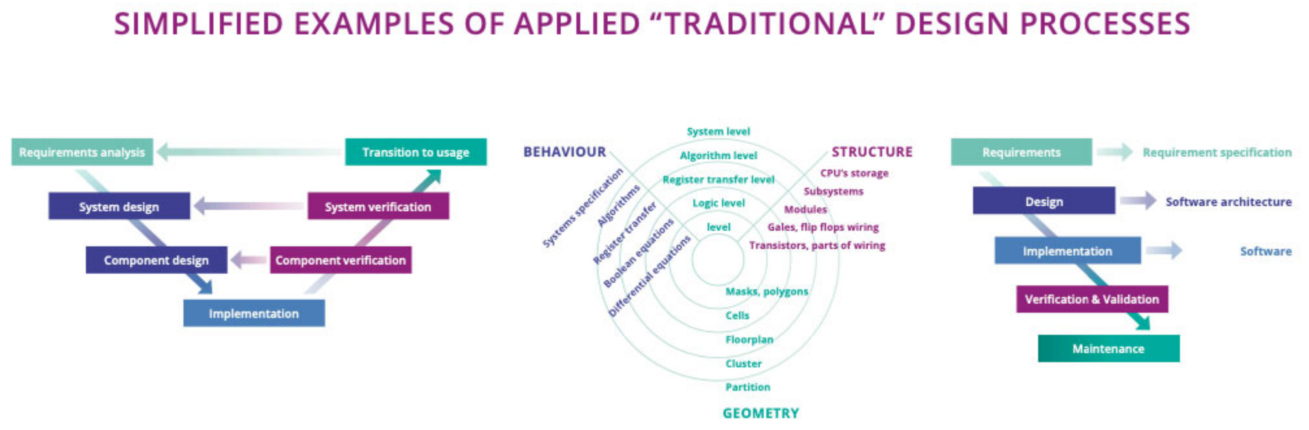


*Figure 2.3.1 - Simplified examples of applied "traditional" design processes: V-Model, Gajsky–Kuhn diagram (Y-chart) and the waterfall model. These are heavily in use, but not sufficient to handle future ECS-based systems and products.*

Adding to the variety of design processes in use, the practical implementation of these processes differs between companies, and sometimes even between different engineering teams within the same company. Nonetheless, most of these processes and their variants have common properties. They comprise several steps that divide the numerous design, implementation, analysis, and validation/verification tasks into smaller parts, which are then processed sequentially and with iterations and loops for optimisation. These steps include: activities and decisions on requirements elicitation and management; technologies used; system Architecture; system decomposition into subsystems, components and modules; hardware/software partitioning and mapping; implementation and integration; and validation and testing on all levels of the design hierarchy.

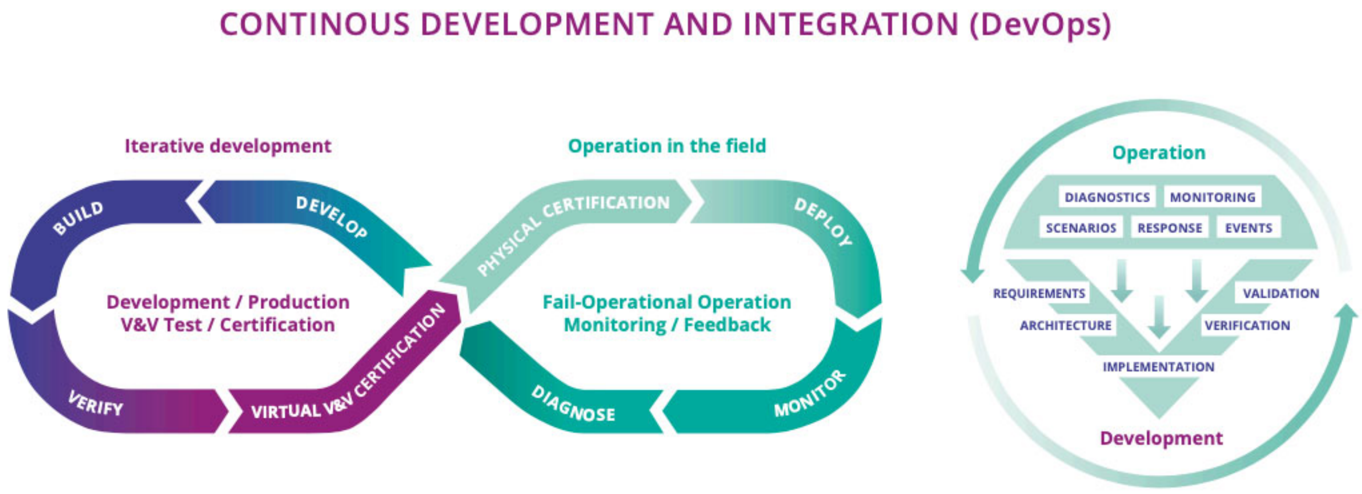


*Figure 2.3.2 - Simplified examples for continuous development processes (DevOps processes). Such processes are essential for building future ECS-based systems and products since they enable data collected during the operation phase to be used in iterative (continuous) development for updates of existing products.*

Due to the sheer size and complexity of current and future ECS-based products, the amount of functionality they perform, and the number and diversity of subsystems, modules and components they comprise, managing complexity and diversity have always been crucial in these processes. The trend of further growing complexity and diversity in future ECS-based applications increases the corresponding challenges, especially in employing model-based and model driven design approaches, and in divide-and-conquer based approaches, both on a technical level – where modular, hierarchical designs need to be integrated into reference architectures and platforms –, and also on an organisational level – i.e. by employing open source solutions like e.g. RISC-V (cf. appendix A) or the various open-source integration platforms (cf. Chapter 1.3 and 1.4), to increase interoperability and thus cooperation.

A further commonality in the different design processes in use today is that almost all of them end after the complete system has been fully tested and validated (and, in some domains, been homologated/certified). Although feedback from production/manufacturing has sometimes been used to increase production quality (e.g. with run-to-run control in semiconductor fabrication), data collected during the lifetime of the system (i.e. from Maintenance, or even from normal operations) is rarely taken into account. If such data is collected at all, it is typically used only for developing the next versions of the system. Again, for future ECS-based applications this will no longer be sufficient. Instead, it is vitally important to extend these processes to cover the complete lifecycle of products. This includes collecting data from system’s operation, and to use this data within the process to: (i) enable continuous updates and upgrades of products; (ii) enable in-the-field tests of properties that cannot be assessed at design-, development- or testing-time; and (iii) increase the effectiveness of validation and test steps by virtual validation methods based on this data (see also Major Challenge 2 and 3 in Chapter 1.3 Embedded Software and Beyond).

Apart from the technical challenges in collecting and analysing this data and/or using it for Maintenance purposes, non-technical challenges include compliance to the appropriate data protection regulations and privacy concerns of system’s owners (Intellectual Property) and users (privacy data). The resulting agile “continuous development processes” will ease quality properties assurance by providing design guidelines, design constraints and practical architectural patterns (e.g. for security, safety, testing), while giving engineers the flexibility and time to deliver the features that those development methodologies support (“quality-by-design solutions”). Last, but not least, the topic of virtual validation is of central importance in these continuous development processes, since both, the complexity of the system under test and the complexity and openness of the environment in which these systems are supposed to operate, are prohibitive for validation based solely upon physical tests. Although considerable advances have been made recently in scenario based testing approaches, including scenario generation, criticality measures, ODD (Operational Design Domain) definitions and coverage metrics, simulation platforms and testing methodologies, and various other topics, further significant research is needed to provide complete assurance cases as needed for certification, which combine evidences gained in virtual validation and verification with evidences generated in physical field testing to achieve the high confidence levels required for safety assurance of highly automated systems.

## 2.3.2 Technology Enabled Benefits

The technologies described in this Chapter (methods and tools for developing and testing applications and their architectures) are the key enabler for European engineers to build future ECS with the desired quality properties (safety, security, reliability, trustworthiness, etc.) with an affordable effort and at affordable cost. As such, these technologies are necessary preconditions for all the achievements and societal benefits enabled by such applications.

ECS-based applications are becoming increasingly ubiquitous, penetrating every aspect of our lives. At the same time, they provide greater functionality, more connectivity and more autonomy. Thus, our dependency on these systems is continuously growing. It is therefore vitally important that these systems are trustworthy – i.e. that they are guaranteed to possess various quality properties (cf. Chapter 1.4). They need to be safe, so that their operation never harms humans or causes damage to human possessions or the environment; even in the case of a system malfunction, safety must be guaranteed. They also need to be secure: on the one hand, data they might collect and compute must be protected from unintended access; on the other hand, they must be able to protect the system and its functionality from access by malicious forces, which could potentially endanger safety. In addition, they must be reliable, resilient, dependable, scalable and interoperable, as well as posess many other quality properties. Most of all, these systems must be trustworthy – i.e. users, and society in general, must be enabled to trust that these systems possess all these quality properties under all possible circumstances.

Trustworthiness of ECS-based applications can only be achieved by implementing all of the following actions.

- Establishing architectures, methods and tools that enable "quality by design" approaches for future ECS-based systems (this is the objective of this Chapter). This action comprises:
    - Providing structured design processes, comprising development, integration and test methods, covering the whole system lifecycle and involving agile methods, thus easing validation and enabling engineers to sustainably build these high-quality systems.
    - Implementing these processes and methods within engineering frameworks, consisting of interoperable and seamless toolchains providing engineers the means to handle the complexity and diversity of future ECS-based systems.
    - Providing reference architectures and platforms that ensure interoperability, enable European Industries to re-use existing solutions and, most importantly, integrate solutions from different vendors into platform economies.
- Providing methodology, modelling and tool support to ensure that all relevant quality aspects (e.g. safety, security, dependability) are designed to a high level (end-to-end trustworthiness). This also involves enabling balancing trade-offs with those quality aspects within ECS parts and for the complete ECS, and ensuring their tool-supported verification and validation (V&V) at the ECS level.
- Providing methodology, modelling and tool support to enable assurance cases for quality aspects – especially safety – for AI-based systems, e.g. for systems in which some functionality is implemented using methods from Artificial Intelligence. Although various approaches to test and validate AI-based functionality are already in place, today these typically fall short of achieving the high level of confidence required for certification of ECS. Approaches to overcome this challenge include, amongst others:
    - Adding quality introspection interfaces to systems to enable engineers, authorities and end-users to inspect and understand why systems behave in a certain way in a certain situation (see "trustworthy and explainable AI" in Chapters 2.1 and 2.4), thus making AI-based and/or highly complex system behaviour accessible for quality analysis to further increase user's trust in their correctness.
    - Adding quality introspection techniques to AI-based algorithms – i.e., to Deep-Neural Networks (DNN) – and/or on-line evaluation of 'distance metrics' of input data with respect to test data, to enable computation of confidence levels of the output of the AI algorithm.
    - Extending Systems Engineering methods – i.e., assurance case generation and argumentation lines – that leverage the added introspection techniques to establish an overall safety case for the system.

The technologies described in this Chapter are thus essential to build high-quality future ECS-based systems that society trusts in. They are therefore key enablers for ECS and all the applications described in Part 3. In addition, these technologies also strengthen the competitiveness of European industry, thus sustaining and increasing jobs and wealth in Europe.

## 2.3.3 Strategic Advantage for the EU

Traditionally, Europe is strong in developing high-quality products. European engineers are highly skilled in systems engineering, including integration, validation and testing, thus ensuring system qualities such as safety, security, reliability, etc, for their products. Nevertheless, even in Europe industrial and academic roadmaps are delaying the advent of fully autonomous driving or explainable AI, for instance. After the initial hype, many highly ambitious objectives have had to be realigned towards more achievable goals and/or are predicting availability with significant delay. The main obstacle, and thus the reason for this technical slowdown, is that quality assurance methods for these kinds of systems are mostly not available at all, while available methods are not able to cover all the complexity of future systems. Worldwide, even in regions and countries that traditionally have taken a more hands-on approach to safety and other system qualities – e.g. a "learning-by-doing" type approach – a market introduction of such systems has failed, mainly due to non-acceptance by users after a series of accidents, with timing goals for market introduction being extended accordingly.

It has to be noted that currently there is a skill gap - a lack of skilled engineers who can drive the innovation process within the European electronics industry. Engineers having the correct skills and in sufficient numbers are crucial for Europe to compete with other regions and exploit the sector's true potential for the European economy. Universities have a vital role in the supply of graduate engineers, and it is essential that graduates have access to industry relevant design tools, leading edge technologies and training. Programs such EUROPRACTICE are essential in providing this access in an affordable manner and ensure that sufficient trained engineers are entering the European industry with relevant skills and experience.

The technologies described in this Chapter will substantially contribute to enabling European Industries to build systems with guaranteed quality properties, thus extending Europe's strength in dependable systems to trustworthy, high-quality system design ("made in Europe" quality), contributing to European strategic autonomy. This in turn will enable Europe to sustain existing jobs and create new ones, as well as to initiate and drive corresponding standards, thus increasing competitiveness.

Design frameworks, reference architectures and integration platforms developed with the technologies described in this Chapter will facilitate cooperation between many European companies, leading to new design ecosystems building on these artefacts. Integration platforms, in particular, will provide the opportunity to leverage a high number of small and medium-sized enterprises (SMEs) and larger businesses into a platform-based economy mirroring the existing highly successful platforms of, for example, Google, Apple, Amazon, etc.

The above holds in particular for EDA Design Platforms, where global, non-European players like Synopsis, Cadence, and others rule an overwhelming part of the market and thus de-facto control if, where and by whom such ecosystems can evolve. Providing European alternatives for such platforms will support technical enhancements e.g. the development of edge AI, embedded AI and embedded computing chips, support of the Open Source Hardware Community (i.e., RISC-V), and many others. It will also facilitate the development of ecosystems, e.g. allowing to have a one-shop entry for start-ups/SMEs and academia to validate their innovations and new architectures into silicon, providing non-differentiating IP's, tool support, and providing a coherent design environment.

In itself, the market for design, development, validation and test tools is already of considerable size, with good growth potential. The DECISION study[1], for example, has put the global market for materials and tools at €141 billion in 2018 (EU share: €24 billion), while Advancy considers the global market for equipment and tools for building ECS-based products at €110 billion in 2016 (EU share: 25%), with an estimated growth to €200 billion by 2025[2]. In addition to this existing and potential market, tools and frameworks are also key enabling technologies facilitating access to the application markets (cf., Part 3), since without them products cannot be built with the required qualities. Furthermore, the existence of cost-efficient processes implemented and supported by innovative development tools and frameworks that guarantee high-quality products typically reduces development time and costs by 20–50% (as shown by previous projects such as ENABLE S3, Arrowhead Tools, and many more). Thus, these technologies contribute substantially to European competitiveness and market access; cost-effectiveness also leads to lower pricing and therefore substantially contributes to making societal-beneficial technologies and applications accessible to everyone.

Last, but not least, the technologies described in this Chapter will contribute significantly to additional strategic goals such as the European Green Deal, while extending design processes to cover the whole lifecycle of products also enables recycling, re-using and a more circular economy.

## 2.3.4 Major Challenges

We identified four **Major Challenges** within the transversal topic "Architecture and Design: Methods and Tools". Together, these four challenges answer the need for Software tools and frameworks for engineering support for future ECS covering the whole lifecycle:

- **Major Challenge 1**: Extending development processes and frameworks to handle connected, intelligent, autonomous and evolvable systems seamlessly vertically – from semiconductor-level to system-of-system-level – and horizontally – from initial requirement analysis via design, test, production, operation, Maintenance, and evolution (updates) to end-of-lifetime. This challenge covers necessary changes in the processes needed to develop, operate, maintain and evolve future ECS- based systems, especially their extensions to cover the whole lifecycle.

- **Major Challenge 2:** Managing new functionality in safe, secure and trustworthy systems. This challenge covers methods and the corresponding tool support to ensure high-quality ECS-based systems, especially with respect to the new capabilities/functions these systems will exploit.

- **Major Challenge 3**: Managing complexity. This challenge deals with methods to handle the ever-increasing complexity of ECS-based systems.

- **Major Challenge 4**: Managing diversity. Handling diversity in all aspects of developing ECS-based systems is a key objective.

Each of the Major Challenges has a number of key focus areas, each of which groups a number of related concrete research and innovation topics to be addressed. Many of these topics are described in a way that they address the same challenge on different levels of the design hierarchy (and thus they must be solved for all addressed levels). However, as a special cross-cutting key focus area, we identified 'support for design platforms' in each of the Major Challenges. This key focus area is therefore discussed in each Major Challenge, collecting those concrete research and innovation topics from the other areas within this Major Challenge that support design platforms.

### 2.3.4.1 Major Challenge 1: Extending development processes and frameworks (to handle connected, intelligent, autonomous, evolvable systems)

#### 2.3.4.1.1 State of the art

There is currently a strict separation between the development and the operation of ECS-based systems. Data collected in any of these phases rarely "crosses the border" into the other phase (cf. section 2.3.1).

Future ECS-based systems need to be connected, intelligent, highly automated, and even autonomous and evolvable (cf. section 2.3.1). This implies a huge variety of challenges, including how to validate autonomous systems (considering that a full specification of the desired behaviour is inherently impossible), how to test them (critical situations are rare events, and the number of test cases implied by the open-world-assumption is prohibitively large), and how to ensure safety and other system quality properties (security, reliability, availability, trustworthiness, etc.) for updates and upgrades.

It is therefore necessary to overcome the "data separation barrier" and to "close the loop" by enabling systems to collect relevant data during the operation phase (Design for Monitoring) and by feeding this data back into the design phase to be used for continuous development within lifecycle-aware holistic design flows. In addition, engineering processes for future ECS-based systems should be extended to shift as much engineering effort as possible from physical to virtual engineering, and include advanced methods for systems and components design as well as new V&V methods enabling safety cases and security measures for future ECS-based systems.

#### 2.3.4.1.2 Vision and expected outcome

The vision is to enable European engineers to extend design processes and methods to a point where they allow handling of future ECS-based systems with all their new functionalities and capabilities for the whole lifecycle. Such extended processes must retain the qualities of the existing processes: (i) efficiency, in terms of effort and costs; (ii) enable the design of trustworthy systems, meaning systems that provably possess the desired quality properties of safety, security, dependability, etc.; and (s) be transparent to engineers, who must be able to completely comprehend each process step to perform optimisations and error correction.

Such extended processes will cover the complete lifecycle of products, including production, Maintenance, decommissioning, and recycling, thereby allowing continuous upgrades and updates of future ECS- based systems that also address the sustainability and environmental challenges (i.e. contribute to the objectives of the Green Deal). As can be derived from the timelines at the end of this Chapter, we expect supply chain-aware digital design flows enabling design for optimised manufacturing and operation (i.e. the "from design phase to operation phase direction" of the continuous design flow) for fail-aware cyber-physical systems (CPS), where selected data from operations is analysed and used in the creation of updates, by 2027. This will be completed through seamless and continuous development processes, including automated digital data flow based on digital twins and AI-based data analysis – online in the system, edge or cloud (run-time digital twin) and offline at the system's designer – as well as data collection at run-time in fail-operational CPS (i.e. "from operation to design phase" direction), by online validation, and by safe and secure deployment, by 2030.

These extended processes also require efficient and consistent methods in each of their phases to handle the new capabilities of future ECS-based systems (cf. Major Challenge 2), as well as their complexity (cf. Major Challenge 3) and diversity (cf. Major Challenge 4).

## 2.3.4.1.3 Key focus areas

This Major Challenge comprises the following key focus areas:

**Virtual engineering of ECS**

Design processes for ECS must be expanded to enable virtual engineering on all hierarchy levels (i.e. from transistor level "deep down", up to complete systems and even System of Systems, cf. "Efficient engineering of embedded software" in Chapter 1.3 and "SoS integration along the lifecycle" in Chapter 1.4 for more details of this software-focused challenge, especially with respect to SoS).

Central to this approach are "digital twins", which capture all necessary behavioural, logical and physical properties of the system under design in a way that can be analysed and tested (i.e. by formal, AI-based or simulation based methods). This allows for optimisation and automatic synthesis (see also Major Challenge 1 and 2 in Chapter 2.4, 'virtual prototypes' in appendix A, and the key focus area "Modelling" in Major Challenge 2 of this Chapter) – for example, of AI- supported, data-driven methods to derive (model) digital twins.

Supporting methods include techniques to visualise V&V and test efforts (including their progress), as well as sensitivity analysis and robustness test methods for different parameters and configurations of the ECS under design. Test management within such virtual engineering processes must be extended to cover all layers of the design hierarchy, and be able to combine virtual (i.e. digital twin and simulation-based) and physical testing (for final integration tests, as well as for testing simulation accuracy).

To substantially reduce design effort and costs, a second set of supporting methods deals with the automated generation of design artefacts such as identification and synthesis of design models, automatic scenario, use-case and test vector generation, generative design techniques, design space exploration, etc. Typically, these build upon AI-supported analysis of field data.

Last, but not least, virtual validation and testing methods must be enhanced considerably in order to achieve a level of realism and accuracy (i.e., conformity to the physical world) that enables their use in safety assurance cases and thus fully enables the shift from physical testing to virtual testing that is needed to cope with the number of test scenarios required. This includes overcoming limitations in realism of models (c.f. Major Challenge 2) and simulation accuracy, as caused for example by sensor phenomenology, vehicle imperfections like worn components, localisation and unlimited diversity in traffic interactions.

**System and component design (methods and tools)**

To fully enable virtual engineering, design processes have to switch completely to model-based processes (including support for legacy components, i.e. 'black box modelling'), where those models may be constructed using data-driven methods. Models are needed for the system and all its components on every level of the design hierarchy, especially for sensors and actuators, as well as the environment of the ECS under design, including humans and their behaviour when interacting with the system. model-based design will also enable: (i) modular and updateable designs that can be analysed, tested and validated both virtually (by formal methods, simulation, etc) and physically; and (ii) consistent integration of all components on all levels of the design hierarchy to allow application-aware HW/SW co-design.

Such processes must be implemented by seamless design and development frameworks comprising interoperable, highly automated yet comprehensible tools for design, implementation, validation and test on all levels of the design hierarchy – from System of Systems down to EDA Design, see e.g. Chapters 1.1, 1.2, and appendix A on open source RISC-V – including support for design space exploration, variability, analysis, formal methods and simulation.

**Lifecycle-aware holistic design flows**

"Closing the loop" – i.e. collecting relevant data in the operation phase, analysing it (using AI-based or other methods) and feeding it back into the development phase (using digital twins, for example) – is the focus of this research topic. It is closely related to the major challenges "Continuous integration and deployment" and "Lifecycle management" in Chapter 1.3, which examines the software part of ECS, and Major Challenges 1, 2 and 4 in Chapter 2.4.

Closing the loop includes data collected during operation of the system on all levels of the hierarchy, from new forms of misuse and cyber-attacks or previously unknown use cases and scenarios at the system level, to malfunctions or erroneous behaviour of individual components or modules. Analysing this data leads to design optimisations and development of updates, eliminating such errors or implementing extended functionality to cover "unknowns" and "incidents".

Data on physical aspects of the ECS must also be collected and analysed. This includes design for optimised manufacturing and deployment, awareness of physical effects and interferences, consideration of end-of- life (EOL) of a product and recycling options within a circular economy.

All of these aspects must be supported by new approaches for multi-level modelling, analysis, verification and formalisation of ECS's operational reliability and service life (c.f. previous challenges), including a consequent usage of open (and inner) source in HW and SW for the complete product lifecycle. As non- (or partly-) technical Challenges, all data collection activities described in this Chapter also need to comply to privacy regulations (e.g. the General Data Protection Regulations GDPR of the EU) as well as in a way that protects the Intellectual Property (IP) of the producers of the systems and their components.

**Integration of new V&V methods**

The required changes of current design processes identified above, as well as the need to handle the new systems capabilities, also imply an extension of current V&V and test methods. First, safety cases for autonomous systems need to rely on an operational design domain (ODD) definition – i.e. characterisation of the use cases in which the system should be operated, as well as a set of scenarios (specific situations that the system might encounter during operation) against which the system has actually been tested. It is inherently impossible for an ODD to cover everything that might happen in the real world; similarly, it is extremely difficult to show that a set of scenarios cover an ODD completely. Autonomous systems must be able to detect during operation whether they are still working within their ODDs, and within scenarios equivalent to the tested ones. V&V methods have to be expanded to show correctness of this detection. Unknown or new scenarios must be reported by the system as part of the data collection needed for continuous development. The same reasoning holds for security V&V: attacks – regardless of whether they are successful or not – need to be detected, mitigated, and reported on. cf. Chapter 1.4 and Chapter 2.4)

Second, the need to update and upgrade future ECS-based systems implies the need to be able to validate and test those updates for systems that are already in the field. Again, corresponding safety cases have to rely on V&V methods that will be applied partly at design-time and partly at run-time, thereby including these techniques into continuous development processes and frameworks. For both of these challenges, energy- and resource-efficient test and monitoring procedures will be required to be implemented.

Third, V&V methods must be enhanced in order to cope with AI-based ECS (i.e., systems and components, in which part of the functionality is based upon Artificial Intelligence methods). This includes, amongst others, adding quality introspection techniques to AI-based algorithms – i.e., to Deep-Neural Networks (DNN) – and/or on-line evaluation of 'distance metrics' of input data with respect to test data, to enable computation of confidence levels of the output of the AI algorithm (compare to 'Explainable AI' in Chapter 2.1) as well as extending Systems Engineering methods – i.e., assurance case generation and argumentation lines – that leverages the added introspection techniques to establish an overall safety case for the system.

**Crosscutting issues: Support for design platforms**

Specific challenges for design platforms:

- Design verification: as designs grow larger and more intricate, exhaustive verification becomes increasingly time-consuming and resource-intensive.
- EDA tools will need to enable designers to optimise designs for lower power consumption, reduced carbon footprint, and efficient resource utilisation (c.f. appendix A on RISC-V).
- Emerging technologies, like quantum computing, neuromorphic, edge AI, and others, impose new demands on design tools. For instance, EDA tools will need to evolve to support quantum circuit design, verification, and optimisation.
- Increased automation and interoperability are required, as increasing complexity has a direct impact on the human effort required to design, validate, test, etc.

Relevant topics from Major Challenge 1 to support design platforms:

- Interoperable Tool chains.
- Test management.
- Integration of AI and AI-based tools that support Engineers in the design and test processes (e.g. in design space elaboration, test (edge) case synthesis, process automation, etc.).
- HW/SW co-design methods.
- Design for optimised manufacturing and operation.
    - Including data collection from the field (both, from operation and maintenance), analysing it and feeding it back into the design loop.
- Open and inner source designs.
- Holistic design flows on all levels of the EDA design hierarchy.
- Energy efficient designs.

- Energy efficient test procedures and equipment.

### 2.3.4.2 **Major Challenge 2: Managing new functionality in safe, secure and trustworthy systems**

#### 2.3.4.2.1 State of the art

Models are abstractions that support technical processes in various forms – for instance, they help systems engineers to accelerate and improve the development process. Specific models represent different aspects of the system under development, and allow different predictions, such as on performance characteristics, temporal behaviour, costs, environmental friendliness or similar. Ideally, models should cover all of these aspects in various details, representing the best trade-off between level of detail, completeness and the limitations listed below:

- Computational complexity and execution performance: models have different levels of complexity, and therefore the computational effort for the simulation sometimes varies considerably. For system considerations, very simple models are sometimes sufficient; for detailed technical simulations, extremely complex multi-physics 3D models are often required. Assessing the needed model fidelity (abstraction resp. granularity level) for each validation task, and balancing it against the needed performance requirements, is therefore essential. To achieve the necessary performance even for high fidelity models, one solution can be the parallel processing of several simulations in the cloud on the other hand super-fast embedded computing and/or edge computing can be good solutions, too. Therefore, cloud and edge computing play an important role for this topic. (cf. Chapter 2.1)

- Effort involved in creating models: very complex physically-based 3D models require considerable effort for their creation. For behavioural models, the necessary parameters are sometimes difficult to obtain or not available at all. For models based on data, including AI-based and ML-based models, extensive data collection and analysis tasks have to be carried out. Further research is urgently needed to reduce the effort for data gathering, model creation and parameterisation.

- Interfaces and integration: often, different models from different sources are needed simultaneously in a simulation. However, these models are frequently created on different platforms, and must therefore be linked or integrated. The interfaces between the models must be further standardised, e.g. FMU, FMI, extensions thereof, or similar. Interoperable models and (open source) integration platforms are needed here; they will also require further cooperation between manufacturers and suppliers. Cloud based simulation platforms require different solutions, which must be uninterrupted and with low latencies.

- Models for software testing, simulation, verification, and for sensors: another very complex field of activity concerns the model-based testing of software in a virtual environment (including virtual hardware platforms and open-source solutions like RISC-V (cf. appendix A)). This implies that sensors for the perception of the environment must also be modelled, resulting in further distortion of reality. The challenge here is to reproduce reality and the associated sensors as accurately as possible, including real-time simulation capacity. Standards for model creation as well as standardised metrics for quality/completeness of models with respect to validation and verification are essential.

For each model it is important to validate that they conform to real world aspects of the system under development, i.e., that they model reality with a sufficient, guaranteed fidelity.

#### 2.3.4.2.2 Vision and expected outcome

Efforts supporting the generation of realistic models for the entire lifecycle of a complex cyber-physical product remain very high, as the requirements for simulation accuracy, the number of influencing parameters of interest and the depth of detail are constantly increasing over time. On the other hand, the application of the highest fidelity models throughout the development process and lifecycle of products with cyber-physical components and software in turn creates numerous opportunities to save development, operating and Maintenance costs. These opportunities arise in cyber-physical components or products such as vehicles, medical devices, semiconductor components, ultra-low-power ECS or any other elements in such complex technical systems. Therefore, research on advanced model-based design, development, and V&V methods and tools for the successful creation of safe, secure and trustworthy products in Europe is of utmost importance, and should be the highest priority of the research agenda. The vision is to derive efficient and consistent methods for modelling, designing, and validating future ECS-based systems, supporting the different steps in the Continuous Development processes derived in Major Challenge 1 by 2026 (resp. by 2029).

#### 2.3.4.2.3 Key focus areas

This challenge comprises the following key focus areas:

**Modelling techniques for new functionalities**

Model generation includes different methods (e.g. data-driven techniques, physics- or rules-based abstraction techniques) for describing (modelling) the behaviour of safety-critical, mixed, physical and logical components on different, hierarchical system levels. Model generation finally results in model libraries that are suitable for different purposes (analysis techniques, simulation, etc.). There are different aspects of the modelled artefact (of the system, component, environment, etc.), such as their physical properties, their (timed) behaviour, and their functional and non-functional properties, which often are modelled with different modelling approaches using different modelling tools. In addition, due to distributed architectures (edge, cloud, IoT, multi-processor architectures, etc.), future systems will become increasingly complex in their interaction and new communication and connection technologies will emerge, which must also be modelled and simulated realistically.

For the design of ECS-based systems, models are required on all levels of the design hierarchy and with different levels of fidelity (cf. Sub-section 2.3.4.2.1 in this Chapter as well as Part 1 and appendix A). These should range from physically-based 3D models of individual components via simplified models for testing component interaction (c.f. e.g. 'compact models' in Major Challenge 1 of Chapter 2.4) to specific models for sensors and the environment, also taking into account statistical scattering from production and system changes during the service life. Latest advances in AI and ML also enable novel data-based modelling techniques that can often, and especially, deliver excellent results in combination with known physical methods (cf. Chapter 2.1). Multi-Scale Modelling is of highest importance here: not only do we need different abstraction levels for the same system, each captured by a model suitable for efficient simulation, analysis and test on that particular abstraction level, we also need formal relations (i.e., refinement relations) between the different abstraction layers that also allow to transfer validation and test results between layers.

Furthermore, it is important to create reusable, validated and standardised models and model libraries for system behaviour, system environment, system structure with functional and non-functional properties, SoS configurations, communication and time-based behaviour, as well as for the human being (operator, user, participant) (cf. Chapter 1.4).

Most importantly, model-based design methods, including advanced modelling and specification capabilities, supported by corresponding modelling and specification tools, are essential. The models must be applicable and executable in different simulation environments and platforms, including desktop applications, real-time applications, multi-processor architectures, edge computing- and hardware-in-the-loop (HiL) platforms as well as cloud (fog) based simulation with heterogeneous access management that includes uninterrupted, wireless and cellular connectivity with low latency.

**Design and V&V methods for ECS evolving during lifetime (including AI-enabled systems)**

The more complex the Architecture of modern ECS systems becomes, the more difficult it is to model its components, their relevant properties and their interactions to enable the optimal design of systems. Classical system theory and modelling often reaches its limits because the effort is no longer economically feasible. AI-supported modelling can be used effectively when large amounts of data from the past or from corresponding experiments are available. Such data-driven modelling methods can be very successful when the exact behaviour of the artefact to be modelled is unknown and/or very irregular. However, the question of determining model accuracy with respect to model fidelity is largely unsolved for these methods.

When AI-based functions are used in components and systems, V&V methods that assure quality properties of the system are extremely important, especially when the AI-based function is safety critical. Experience-based AI systems (including deep learning-based systems) easily reach their limits when the current operating range is outside the range of the training database. There can also be stochastic, empty areas within the defined data space, for which AI is not good at interpolating. Design methods for AI-enabled ECS must therefore take into account the entire operational domain of the system, compensate for the uncertainty of the AI method and provide additional safety mechanisms supervising the AI component (i.e. mechanisms to enable fail-aware and fail-operational behaviour). Advances in V&V methods have to be accompanied by advances in AI-Algorithms, especially those that enable a higher level of introspection and increase the analysability of these algorithms (see 'Explainable AI' in Major Challenge 3 of Chapter 2.1).

A further source of uncertainty results from variabilities (production tolerances, ageing effects or physical processes that cannot be described with infinite accuracy) resulting from human interaction with the system and from other effects. For determining quality properties such as safety and reliability, these effects must be taken into account throughout the designs' V&V. The communication channels in distributed architectures (either in cloud/fog or multi-processor architectures) also fall within the scope of these uncertainties, which can, for example, exhibit certain delays or contain certain disturbances. These effects must also be simulated on the one hand and verified accordingly in the overall simulation and system test.

There are also structured (i.e. foreseeable at design-time) variabilities in technical systems in the form of configurable changes during their lifetime, whether through software updates, user interventions or other updates. For secure systems with structured variability, suitable SW and HW architectures, components and design methods, as well as tools for adaptive, extensible systems, are crucial. This includes (self-)monitoring, diagnosis, update mechanisms, strategies for maintaining functional and data security, and lifecycle management (including End-of-life management, sustainability and possible recycling), as well as adaptive security and certification concepts (c.f. Prognostic and Health Management in Chapter 2.4).

The verification and validation of ECS-based systems can also be carried out with the help of AI-based test methods (cf. Chapter 2.1). This approach allows to benefit from already performed V&V activities and developed methods and to further enhance them substantially. At the same time, the development and application of completely new test methods is also possible, as long as there is sufficient training data available for this task.

The V&V of safety-critical systems does not end with the deployment of the system. Rather, for such systems, the continuous monitoring and safeguarding of adaptive and/or dynamic changes in the system or evolving threads is of utmost importance (cf. Chapter 1.4). Further release cycles might be triggered by problems occurring in operation and the DevOps cycles must be iterated again (e.g. via reinforcement learning).

**Ultra-low power design methods**

The potential application area for ultra-low power electronic systems is very high due to the rapidly advancing miniaturisation of electronics and semiconductors, as well as the ever-increasing connectivity enabled by it. This ranges from biological implants, home automation, the condition-monitoring of materials to location-tracking of food, goods or technical devices and machines. Digital products such as radio frequency/radio frequency identification (RF/RFID) chips, nanowires, high-frequency (HF) architectures, SW architectures or ultra-low power computers with extremely low power consumption support these trends very well (see also appendix A on RISC-V). Such systems must be functional for extended periods of time with a limited amount of energy.

The ultra-low-power design methods comprise the areas of efficiency modelling and low-power optimisation with given performance profiles, as well as the design of energy-optimised computer architectures, energy-optimised software structures or special low-temperature electronics (c.f. Chapters 1.1, 1.2 and 1.3). Helpful here are system-level automatic DSE (design space exploration) approaches able to fully consider energy/power issues (e.g. dark silicon, energy/power/performance trade-offs) and techniques. The design must consider the application-specific requirements, such as the functional requirements, power demand, necessary safety level, existing communication channels, desired fault tolerance, targeted quality level and the given energy demand and energy supply profiles, energy harvesting gains and, last but not least, the system's lifetime.

Exact modelling of the system behaviour of ultra-low power systems and components enables simulations to compare and analyse energy consumption with the application-specific requirements so that a global optimisation of the overall system is possible. Energy harvesting and the occurrence of parasitic effects, must also be taken into account.

**Crosscutting issues: Support for design platforms**

Specific challenges for design platforms:

- Design verification: as designs grow larger and more intricate, exhaustive verification becomes increasingly time-consuming and resource-intensive.
- EDA tools will need to enable designers to optimise designs for lower power consumption, reduced carbon footprint, and efficient resource utilisation.
- Emerging technologies: quantum computing, neuromorphic, edge AI, and others, impose new demands on design toolsFor instance, EDA tools need to evolve to support quantum circuit design, verification, and optimisation.
- Increased levels of automation and interoperability are required, as increasing complexity has a direct impact on the human effort required to design, validate, test, etc.

Relevant topics from Major Challenge 2 supporting design platforms:

- Incremental V&V, re-certification.
- V&V for systems with structural variability.
- Lifetime monitoring and GDPR-compliant data collection.
- Advanced design methods for ultra-low power design.
- Method for comprehensive assessment and optimisation of power management and power consumption.

## 2.3.4.3 Major Challenge 3: Managing complexity

### 2.3.4.3.1 State of the art

The new system capabilities (intelligence, autonomy, evolvability), as well as the required system properties (safety, security, reliability, trustworthiness), each considerably increase complexity (c.f. Part 3 and Sub-section 2.3.1 above). Increasingly complex environments in which these systems are expected to operate, and the increasingly complex tasks (functionalities) that these systems need to perform in this environment, are further sources of soaring system complexity. Rising complexity leads to a dramatic upsurge in the effort of designing and testing, especially for safety-critical applications where certification is usually required. Therefore, an increased time to market and increased costs are expected, and competitiveness in engineering ECS is endangered. New and improved methods and tools are needed to handle this new complexity, to enable the development and design of complex systems to fulfil all functional and non-functional requirements, and to obtain cost-effective solutions from high productivity. Three complexity-related action areas will help to master this change:

- Methods and tools to increase design efficiency.
- Complexity reduction methods and tools for V&V and testing.
- Methods and tools for advanced architectures.

### 2.3.4.3.2 Vision and expected outcome

The connection of electronics systems and the fact that these systems change in functionality over their lifetime continuously drives complexity. In the design phase of new connected highly autonomous and evolvable ECS, this complexity must be handled and analysed automatically to support engineers in generating best-in-class designs with respect to design productivity, efficiency and cost reduction. New methods and tools are needed to handle this new complexity during the design, manufacturing and operations phases. These methods and tools, handling also safety related non functional requirements, should work either automatically or be recommender-based for engineers to have the complexity under control (see also the corresponding challenges in Chapter 1.3. Embedded Software and Beyond).

Complexity increases the effort required, especially in the field of V&V of connected autonomous electronics systems, which depend on each other and alter over their lifetime (cf. Chapter 3.1). The innumerable combinations and variety of ECS must be handled and validated. To that end, new tools and methods are required to help test engineers in creating test cases automatically, analysing testability and test coverage on the fly while optimising the complete test flow regarding test efficiency and cost. This should be achieved by identifying the smallest possible set of test cases sufficient to test all possible system behaviours. It is important to increase design efficiency and implement methods that speed up the design process of ECS. Methods and tools for X-in-the-loop simulation and testing must be developed, where X represents hardware, software, models, systems, or a combination of these. A key result of this major challenge will be the inclusion of complexity-reduction methods for future ECS-based systems into the design flows derived in Major Challenge 1, including seamless tool support, as well as modular architectures that support advanced computation methods (AI, advanced control), system improvements (updates), replacement and recycling by 2026. Building on these, modular and evolvable/extendable reference architectures and (hierarchical, open source-based) chips (i.e., RISC-V, see Appendix A), modules, components, systems and platforms that support continuous system improvement, self-awareness, health and environment monitoring, and safe and secure deployment of updates, will be realised by 2029.

### 2.3.4.3.3 Key focus areas

**Methods and tools to increase design and V&V efficiency**

Design efficiency is a key factor for keeping and strengthening engineering competitiveness. Design and engineering in the virtual world using simulation techniques require increasingly efficient modelling methods of complex systems and components. Virtual design methodology will be boosted by X-in-the-loop, where X (HW, SW, models, systems) are included in the simulation process, which helps to increase accuracy and speed up multi-discipline co-simulation. This starts at the Architecture and design evaluation, where real tests are implemented in a closed loop such as in the exploration process.

**Complexity reduction methods and tools for V&V and testing**

A second way to manage complexity is the complexity-related reduction of effort during the engineering process. Complexity generates most effort in test, and V&V, ensuring compatibility and proper behaviour in networking ECS. Consistent hierarchical design and architectures, and tool-based methods to design those architectures automatically, are needed. Advanced test methods with intelligent algorithms for test termination, as well as automated metrics for testability and diagnosis (including diagnosis during run-time), must be developed and installed. Recommender-based guidance supports where no automated processes can be used. model-based V&V and test supported by AI techniques can help to minimise the efforts driven by complexity. Models and digital twins of ECS can also be used to calculate the test coverage and extract test cases automatically.

**Methods and tools for advanced architectures**

Complexity, and also future complexity, is mainly influenced by the Architecture. Future architectures must support complex, highly connected ECS that use advanced computational methods and AI, as well as machine learning, which lead to a change of ECS over lifetime. Especially for AI (cf. Chapter 2.1), this includes support for V&V of the AI method, for shielding mechanisms and other forms of fault/uncertainty detention resp. for prevention of fault propagations, and for advanced monitoring concepts, that allow deep introspection of components and modules as well as hierarchical 'flagging', merging and handling of monitoring results and detected anomalies. For this, reference architectures and platform architectures are required on all levels of the design hierarchy (for the system and SOS levels, see also the challenges "SoS Architecture and open integration platforms", "SoS interoperability" and related challenges in Chapter 1.4 on System of Systems).

An additional focus of Architecture exploration and optimisation must be architectures that ease the necessary efforts for analysis, test, V&V and certification of applications. Hierarchical, modular architectures that support a divide-and-conquer approach for the design and integration of constituent modules with respect to subsystems have the potential to reduce the demand for analysis and V&V ("correct by design" approach). As integration platforms, they have to ensure interoperability of constituent ECS. For the Architecture exploration and optimisation itself, AI-based methods are needed to achieve a global optimum. Overall, holistic design approaches and tools for architectures of multi-level/multi-domain systems are the goal.

Apart from the benefits that reference architectures and platforms have at a technological level, they are also important economically. As integration platforms for solutions of different vendors, they serve as a focal point for value chain-based ecosystems. Once these ecosystems reach a certain size and market impact, the platforms can serve as the basis for corresponding "platform economies" (cf. Major Challenge "SoS Architecture and open integration platforms" in Chapter 1.4).

**Crosscutting issues: Support for design platforms**

Specific challenges for design platforms:

- Developing highly complex (and heterogeneous, see MC 4) systems-on-chip (SoCs) that integrate diverse functionalities.
- Complexity has an impact on security, safety, reliability, …: design for trustworthiness.
- Increased levels of automation and interoperability are required, as increasing complexity has a direct impact on the human effort required to design, validate, test, etc.

Relevant topics from Major Challenge 3 to support design platforms

- Recommender-(AI-)based guidance in V&V process.
- Automatic generation of test cases (with or without support from AI).
- Test coverage calculation means.
- Reference architectures.
- Architecture exploration support (also AI based).
- Modular and evolvable architectures.

### 2.3.4.4 Major Challenge 4: Managing diversity

#### 2.3.4.4.1 State of the art

In the ECS context, diversity is everywhere – between polarities such as analogue and digital, continuous and discrete, and virtual and physical. With the growing diversity of today's heterogeneous systems, the integration of analogue-mixed signals, sensors, micro-electromechanical systems (MEMS), chiplets, actuators and power devices, transducers and storage devices is essential. Additionally, domains of physics such as mechanical, photonic and fluidic aspects have to be considered at the system level, and for embedded and distributed software. The resulting design diversity is enormous. It requires multi-objective optimisation of systems (and SoS), components and products based on heterogeneous modelling and simulation tools, which in turn drives the growing need for heterogeneous model management and analytics. Last, but not least, a multi-layered connection between the digital and physical world is needed (for real-time as well as scenario investigations). Thus, the ability to handle this diversity on any level of the design hierarchy, and anywhere it occurs, is paramount, and a wide range of applications has to be supported.

#### 2.3.4.4.2 Vision and expected outcomes

The management of diversity has been one of Europe's strengths for many years. This is not only due to European expertise in driving More-than-Moore issues, but also because of the diversity of Europe's industrial base. Managing diversity is therefore a key competence. Research, development and innovation (R&D&I) activities in this area aim at the development of design technologies to enable the development of complex, smart and, especially, diverse systems and services. All these have to incorporate the growing heterogeneity of devices and functions, including its V&V across mixed disciplines (electrical, mechanical, thermal, magnetic, chemical and/ or optical, etc). New methods and tools are needed to handle this growing diversity during the phases of design, manufacturing and operation in an automated way. As in complexity, it is important to increase design efficiency on diversity issues in the design process of ECS. A major consequence of this challenge will be the inclusion of methods to cope with all diversity issues in future ECS-based systems, which have been introduced into the design flows derived in Major Challenge 1, including seamless tool support for engineers.

#### 2.3.4.4.3 Key focus areas

The main R&D&I activities for this fourth major challenge are grouped into the following key focus areas.

**Multi-objective design and optimisation of components and systems**

The area of multi-objective optimisation of components, systems and software running on SoS comprises integrated development processes for application-wide product engineering along the value chain (cf. Part 1 and Appendix A on RISC-V). It also concerns modelling, constraint management, multi-criteria, cross-domain optimisation and standardised interfaces. This includes consistent and complete co-design and the integrated simulation of integrated circuits, package and board in the application context. As well it is also about methods and tools to support multi-domain designs (electronic/electric and hydraulic, etc) and multi-paradigms (different vendors, modelling languages, etc.) as well as HW/SW co-design. Furthermore, it deals with advanced design space exploration and iterative design techniques, the modular design of 2.5 and 3D integrated systems, the upcoming technology around chiplets and flexible substrates, and the trade-offs between performance, cost, space, power and reliability.

**Modelling, analysis, design and test methods for heterogeneous systems considering properties, physical effects and constraints**

The area of modelling, analysis, design, integration and testing for heterogeneous systems considering properties, physical effects and constraints comprises methods and tools for the design, modelling and integration of heterogeneous systems, as well as hierarchical methods for HW/SW hybrid modeling and co-simulation, and co- development of heterogeneous systems (including multi-scale and multi-rate modelling and simulation). All these methods and tools need to consider chiplet technology aspects. Furthermore, it deals with modelling methods to consider operating conditions, statistical scattering and system changes, as well as hierarchical modelling and the early assessment of critical physical effects and properties from SoC up to the system level (cf. Chapter 1.1 and 1.2). Finally, there is a need for analysis techniques for new circuit concepts (regarding new technologies up to the system level), and special operating conditions (voltage domain check, especially for start-ups, floating node analysis, etc.).

**Automation of analogue and integration of analogue and digital design methods**

The area of integration of analogue and digital design methods comprises metrics for testability and diagnostic efficiency, especially for analogue/mixed signal (AMS) designs, harmonisation of methodological approaches and tooling environments for analogue, RF and digital design and automation of analogue and RF design – i.e. high-level description, synthesis acceleration and physical design, modularisation and the use of standardised components (cf. Chapter 1.2).

**Connecting the virtual and physical world of mixed domains in real environments**

The main task in the area of connecting the virtual and physical worlds of mixed domains in real environments is an advanced analysis that considers the bi-directional connectivity of the virtual and physical world of ECS and its environment (including environmental modelling, multimodal simulation, simulation of (digital) functional and physical effects, emulation and coupling with real, potentially heterogenous, hardware, and integration of all of these into a continuous design and validation flow for heterogeneous systems, cf. Major Challenge 1 and 2 above). Furthermore, the key focus area comprises novel more-than-Moore design methods and tools, as well as models and model libraries for chemical and biological systems.

**Crosscutting issues: Support for design platforms**

Specific challenges for design platforms:

- Developing highly complex (and heterogeneous, see MC 3) systems-on-chip (SoCs) that integrate diverse functionalities.
- EDA tools will need to adapt to support the design and optimisation of new advanced packaging solutions for complex heterogeneous systems, incl. chiplets, addressing challenges related to power delivery, thermal management, signal integrity, and testing, etc.
- Design for manufacturability and short time-to-market: EDA tools must evolve to improved yield, reduced variability, and better reliability, to reduce design cycles and facilitate faster design iterations, verification, and optimisation, etc.
- ECS require and will require collaboration across various engineering domains, including electrical, mechanical, thermal, and materials engineering. EDA tools must support seamless integration between different design disciplines.

Relevant topics from Major Challenge 4 to support design platforms

- Consistent & complete co-design & integrated simulation of IC, package and board in the application context.
- Methods and tools to support multi-domain designs (i.e., electronic/electric and hydraulic, etc.) and multi-paradigm designs (different vendors, modelling languages, etc.).
- Advanced Design Space Exploration and iterative design techniques, incl. multi-aspect optimisation (performance vs. cost vs. space vs. power vs. reliability).
- Modular design of 2.5 and 3D integrated systems, as well as chiplet technologies.
- Analysis techniques for new circuit concepts and special operating conditions (voltage domain check, especially for start-up, floating node analysis, etc.).
- Metrics for AMS testability and diagnostic efficiency (including V&V & test).
- Harmonisation of methods and tooling environments for analogue, RF and digital design.
- Automation of analogue and RF design (high-level description, synthesis acceleration and physical design, modularisation, use of standardised components.
- Advanced analysis considering the connection of virtual and physical world and its environment.
- Novel More than Moore design methods and tools.
- Models and model libraries for chemical and biological systems.

### 2.3.5 Timeline

Major Challenge 1:
Extending Development Processes and Frameworks
(to handle connected, intelligent, autonomous, evolvable systems)

2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

**Virtual Engineering of ECS**
Digital twins of the system under development, under test and in use
* Test management, test-cases on all hierarchy layers (from physical sensor input via bitvectors up to concrete scenarios), scenario generation / synthesis.
Visualization techniques to support the V&V and test process and evaluate the progress
Enhance realism and accuracy of virtual Validation and testing methods (models, simulators,...)
(AI-based) Model identification, synthesis, improvement and parameterization with measurement data
* Integration of AI and AI-based tools into engineering and development processes on all levels of the design hierarchy, to shorten development time, incl. metrics for quantification of covered design space, etc.
Operation strategy optimization by means of virtual models and simulation
Complete traceability of products and processes in virtual engineering, supporting sensitivity analysis and robustness investigation, included in the optimization process and the system monitoring process

**System and Component Design (Methods and Tools)**
Model-based design technologies
Data-driven design technologies
Advanced system design processes (e.g., continuous development / DevOps, agile development,...)
Platform based design
Methods and tools for (automatically generated) monitoring of systems (based on their digital twins), including monitoring for anomaly detection (for both security and safety)
Means to process & analyse traces (observations , loggings,...) from tests efficiently to derive tangible knowledge for design improvements
* Consistent Integration of complete, application-aware Co-Design of ECS on all levels of the design hierarchy

**Lifecycle-aware holistic design flows (i.e. 'Close the loop' in development and product lifecycle)**
* Design for optimized manufacturing and operation; awareness of physical effects and interferences; awareness of complete lifecycle, incl. energy, resource, CO2-footprint, recycling, circular economy
Augmented and virtual reality in design, development, manufacturing and maintenance processes
* Open (and inner) source in HW and SW for complete product lifecycle
Exploiting data from the field for V&V and development, design and optimisation tasks – creating a system family with shared learning from operational data
Analysis of ECS systems in operation to improve future design within a continuous development process (DevOps)
Consistent methods and new approaches for (multi-level, multi-paradigm) modeling) , analysis, verification and formalization of ECS's operational reliability and service life
"Supply-chain-aware" design flow: from requirements to optimized system architecture considering supply chain leveraging "seamless digital twin from component to design to manufacturing to operation"
* Holistic design flows taking into consideration and bridging the functional layers and architectural layers with life-cycles and value streams .

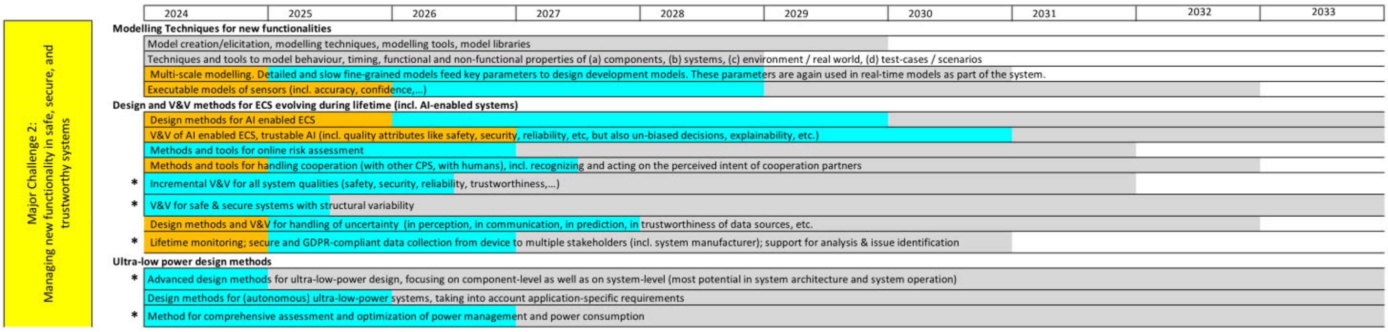
**Integration of new Verification and Validation methods**
Incorporation of V&V methods and technologies into virtual engineering resp. design frameworks, incorporation into continuous development process
Leverage System Engineering Methods -- i.e. assurance cases, V&V techniques, etc. -- to a level that makes them applicable for AI-based components
From offline V&V (@design-time) to online V&V (@runtime)
Usage of AI and AI-based tools for V&V and development task (exploiting AI capabilities)
Model-based and mixed real/virtual testing approaches, incl. V&V of system architecture by simulating system components on different levels of abstraction
* Energy and resource efficient test procedures and equipment
V&V extended by life-time monitoring of security and reliability aspects

🟧 - **Start research activities aiming at** Technology Readiness Level (**TRL**) **2-4** (applied research - validation in laboratory environment ) **or higher**

🟦 - **Start research activities aiming at TRL 4-6** (validation in laboratory ennvironment - demonstration in relevant environment ) **or higher**

⬜ - **Start research activities aiming at TRL 6-8** ( demonstration in relevant environment - prototyping in an operational environment qualified )

* Also related to crosscutting key focus area Support for Design Platforms



Major Challenge 2:
Managing new functionality in safe, secure, and trustworthy systems

2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

**Modelling Techniques for new functionalities**
Model creation/elicitation, modelling techniques, modelling tools, model libraries
Techniques and tools to model behaviour, timing, functional and non-functional properties of (a) components, (b) systems, (c) environment / real world, (d) test-cases / scenarios
Multi-scale modelling. Detailed and slow fine-grained models feed key parameters to design development models. These parameters are again used in real-time models as part of the system.
Executable models of sensors (incl. accuracy, confidence,...)

**Design and V&V methods for ECS evolving during lifetime (incl. AI-enabled systems)**
Design methods for AI enabled ECS
V&V of AI enabled ECS, trustable AI (incl. quality attributes like safety, security, reliability, etc, but also un-biased decisions, explainability, etc.)
Methods and tools for online risk assessment
Methods and tools for handling cooperation (with other CPS, with humans), incl. recognizing and acting on the perceived intent of cooperation partners
* Incremental V&V for all system qualities (safety, security, reliability, trustworthiness,...)
* V&V for safe & secure systems with structural variability
Design methods and V&V for handling of uncertainty (in perception, in communication, in prediction, in trustworthiness of data sources, etc.
* Lifetime monitoring; secure and GDPR-compliant data collection from device to multiple stakeholders (incl. system manufacturer); support for analysis & issue identification

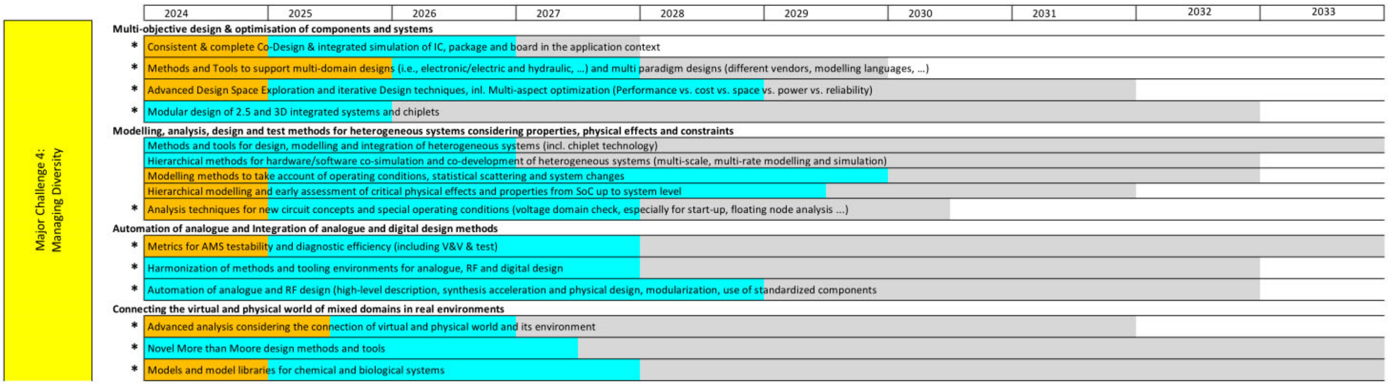
**Ultra-low power design methods**
* Advanced design methods for ultra-low-power design, focusing on component-level as well as on system-level (most potential in system architecture and system operation)
Design methods for (autonomous) ultra-low-power systems, taking into account application-specific requirements
* Method for comprehensive assessment and optimization of power management and power consumption

🟧 - **Start research activities aiming at** Technology Readiness Level (**TRL**) **2-4** (applied research - validation in laboratory environment ) **or higher**

🟦 - **Start research activities aiming at TRL 4-6** (validation in laboratory ennvironment - demonstration in relevant environment ) **or higher**

⬜ - **Start research activities aiming at TRL 6-8** ( demonstration in relevant environment - prototyping in an operational environment qualified )

* Also related to crosscutting key focus area Support for Design Platforms



Major Challenge 4:
Managing Diversity

2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

**Multi-objective design & optimisation of components and systems**
* Consistent & complete Co-Design & integrated simulation of IC, package and board in the application context
* Methods and Tools to support multi-domain designs (i.e., electronic/electric and hydraulic, ...) and multi paradigm designs (different vendors, modelling languages, ...)
* Advanced Design Space Exploration and iterative Design techniques, inl. Multi-aspect optimization (Performance vs. cost vs. space vs. power vs. reliability)
* Modular design of 2.5 and 3D integrated systems and chiplets

**Modelling, analysis, design and test methods for heterogeneous systems considering properties, physical effects and constraints**
Methods and tools for design, modelling and integration of heterogeneous systems (incl. chiplet technology)
Hierarchical methods for hardware/software co-simulation and co-development of heterogeneous systems (multi-scale, multi-rate modelling and simulation)
Modelling methods to take account of operating conditions, statistical scattering and system changes
Hierarchical modelling and early assessment of critical physical effects and properties from SoC up to system level
* Analysis techniques for new circuit concepts and special operating conditions (voltage domain check, especially for start-up, floating node analysis ...)

**Automation of analogue and Integration of analogue and digital design methods**
* Metrics for AMS testability and diagnostic efficiency (including V&V & test)
* Harmonization of methods and tooling environments for analogue, RF and digital design
* Automation of analogue and RF design (high-level description, synthesis acceleration and physical design, modularization, use of standardized components

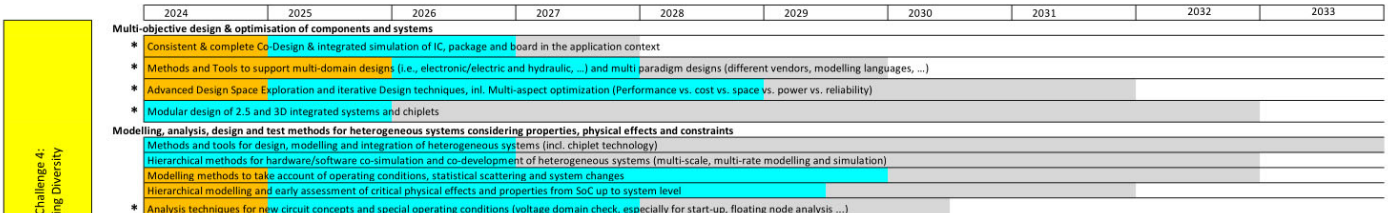
**Connecting the virtual and physical world of mixed domains in real environments**
* Advanced analysis considering the connection of virtual and physical world and its environment
* Novel More than Moore design methods and tools
* Models and model libraries for chemical and biological systems

🟧 - **Start research activities aiming at** Technology Readiness Level (**TRL**) **2-4** (applied research - validation in laboratory environment ) **or higher**

🟦 - **Start research activities aiming at TRL 4-6** (validation in laboratory ennvironment - demonstration in relevant environment ) **or higher**

⬜ - **Start research activities aiming at TRL 6-8** ( demonstration in relevant environment - prototyping in an operational environment qualified )

* Also related to crosscutting key focus area Support for Design Platforms



Challenge 4:
ing Diversity

2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

**Multi-objective design & optimisation of components and systems**
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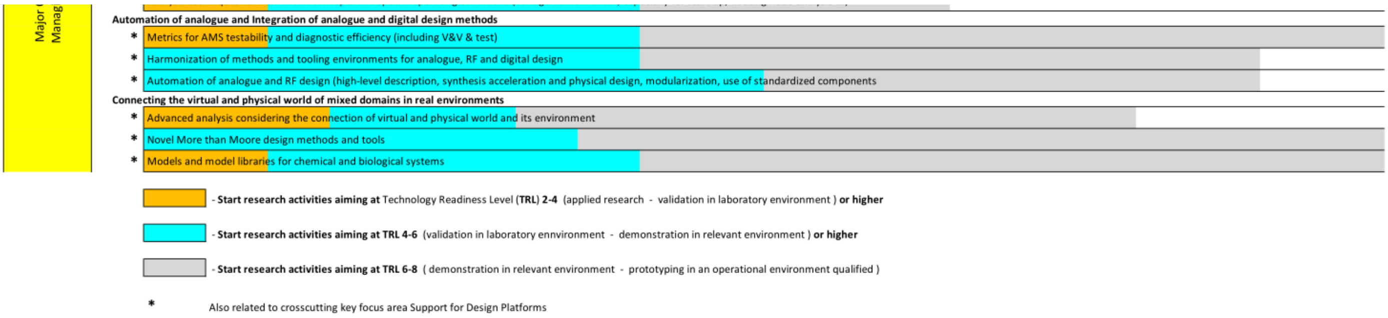


## 2.3.6 Synergy with other themes

The processes, methods and tools addressed in this Chapter relate to all other chapters of the ECS-SRIA. They enable the successful development, implementation, integration and testing of all applications described in Part 3 of the ECS-SRIA, cover all levels of the technology stack (as indicated in Part 1) and enable the sufficient usage of all transversal technologies described in Part 2. Thus, there is a high synergy potential to carry out joint research on these topics. This holds especially true for topics in Chapter 2.4: qualities such as safety and security described there are a driver for the technologies in this Chapter, where we describe processes, methods and tools that enable engineers to design systems guaranteed to possess the required qualities in a cost- and time-efficient way.

Additionally, strong ties exist to the 'engineering challenges' both in Chapter 1.3 (on embedded software) and in Chapter 1.4 (on systems of systems). Finally, especially for our challenge 4 on managing diversity, there is an overlap – and thus an opportunity to synergistically merge key topics from this challenge – with topics from Chapter 1.2 (on components and modules).

There is also a high synergy potential with additional activities outside of the pure funded projects work: reference architectures, platforms, frameworks, interoperable toolchains and corresponding standards are excellent nuclei around which innovation ecosystems can be organised. Such ecosystems comprise large industries, SMEs, research organisations and other stakeholders. They are focused on a particular strategic value chain, certain technology or any other asset for which sustainability and continuous improvement must be ascertained. The main activities of such innovation ecosystems are, first, to bring together the respective communities, implement knowledge exchange and establish pre-competitive cooperation between all members of the respective value chains. Second, they should promote the technology around which they are centred, i.e. by refining and extending the platform, providing reference implementations and making them available to the community, provide integration support, establish the standard, etc. Third, they should ensure greater education and knowledge-sharing. Fourth, they should develop those parts of the Strategic Research and Innovation Agenda and other roadmaps that are related to the respective technology, monitor the implementation of the roadmaps, and incubate new project proposals in this area.

Last, but not least, the technologies described in this Chapter are essential and necessary, but they are also to a large extent domain-agnostic, and can thus also serve as a connection point with activities in other funding programmes (for example Xecs, ITEA and other EUREKA clusters).

## 2.3.7 References

1. *DECISION Etudes & Conseil (Eds). "Emerging Technologies in Electronic Components and Systems (ECS) – Opportunities Ahead". A study conducted for DG-CONNECT, 2019.* ↩
2. *Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.* ↩

# 2.4

*Cross-Sectional Technologies*

# QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

# 2 CROSS-SECTIONAL TECHNOLOGIES

## 2.4

## Quality, Reliability, Safety and Cyber-Security

### 2.4.1 Scope

Modern technologies and new digitised services are key to ensuring the stable growth and development of the European Union and its society. These new technologies are largely based on smart electronic components and systems (ECS). Highly automated or autonomous transportation systems, improved healthcare, industrial production, information and communication networks, and energy grids all depend on the availability of electronic systems. The main societal functions[1] and critical infrastructure are governed by the efficient accessibility of smart systems and the uninterrupted availability of services.

Ensuring the reliability, safety and security of ECS is a Major Challenge since the simultaneous demand for increased functionality and continuous miniaturisation of electronic components and systems causes interactions on multiple levels. This Chapter addresses these complex interdependencies by considering input from, and necessary interaction between, major disciplines. The quality, reliability, safety and cybersecurity of electronic components and systems are, and will be, fundamental to digitised society (see Figure 2.4.1). In addition, the tremendous increase of computational power and reduced communication latency of components and systems, coupled with hybrid and distributed architectures, impose to rethink many “traditional” approaches and expected performances towards safety and security, exploiting AI and ML.

In practice, ensuring reliability, safety, and security of ECS is part of the Design, Implementation, and Validation/Testing process of the respective manufacturers and – for reasons of complexity and diversity/heterogeneity of the systems – must be supported by (analysing and testing) tools. Thus, the techniques described in Chapter 2.3 (Architecture and Design: Method and Tools) are complementary to the techniques presented here: in that Chapter, corresponding challenges are described from the design process viewpoint, whereas here we focus on a detailed description of the challenges concerning reliability, safety, and security within the levels of the design hierarchy.

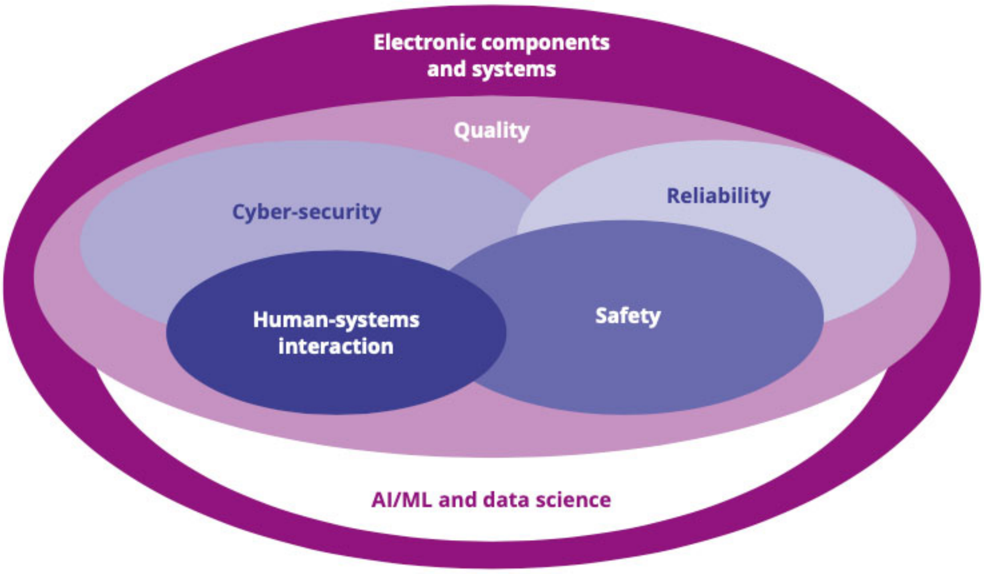


*Figure 2.4.1 - Role of quality, reliability, safety and cybersecurity of electronic components and systems for digitalisation.*

### 2.4.2 Technology Enabled Benefits

“The role of the technology is to allow persons to express their potential”. Hans Rosling, in his book *Factfulness: Ten Reasons We're Wrong About the World – and Why Things Are Better Than You Think*, plots the life quality of the world’s population in groups at successive levels. He shows how such groups, even those at the bottom level, will move forward over time to the next level. Technology can help accelerate that progression. An emblematic example of that is the project launched by Facebook and the Internet Society (ISOC) to develop internet exchange points (IXPs) throughout Africa. Albeit not without difficulty, IXPs help promote e-learning to improve education in the continent, and for connected drones to deliver medicines and other products to remote populations.

The recent Covid-19 pandemic has emphasised the importance of digital technology to the western world, with the recourse to robots in several hazardous situations, from disinfecting airplanes and hospital rooms, to delivering medication to isolated patients. Digital technology that can fit these diverse needs should address holistically concerns such as quality of service, reliability, safety, trustworthy, privacy, cybersecurity and human–system integration. A degraded behaviour in any of these dimensions, or an incorrect integration among them, would affect vital properties and could cause serious damage. In addition, such shortcomings in safety, reliability and security might even outweigh the societal and individual benefits perceived by users, thus lowering trust in, and acceptance of, the technologies. All these topics and features constitute the core of this Chapter.

## 2.4.3 Strategic Advantage for the EU

Europe is internationally known for its high-quality product standards, which enjoy a strong international reputation. The European Union (EU) has a robust and reliable safety and product liability regulatory framework, and a rigorous body of safety standards, complemented by national, non-harmonised liability regulations. In the past, this has been a big success for European embedded systems in almost all industries, including automotive, telecommunications, manufacturing, railway, avionic and military defence, to name but a few of the many sectors where people rely on them.

However, in light of the two main drivers of digitalisation and connectivity, Europe is highly dependent on the supply of hardware and software from countries outside of Europe. Dominating market players in the information and communications technology (ICT) sector – such as those in the expanding sectors of social networks, logistic and e-commerce are expanding their products towards industrial domains. In addition, recent revelations regarding espionage and state-sponsored surveillance have initiated a debate on the protection of core EU values such as security, privacy, data protection and trust. Therefore, digital strategic autonomy – the ability of the EU to maintain a high level of control and security of its products, responding quickly if potential vulnerabilities are noticed – is of utmost importance. A strategic advantage can be achieved by designing reliable, safe and secure products where the dependencies to foreign products are transparently considered. A difference for EU products can also be achieved by treating privacy and necessary human interaction with its own set of independent standards, where technology will keep its limits according to European values when interacting with citizens.

## 2.4.4 Major Challenges

To introduce the topic presented in this Chapter, we first present some definitions that will be useful to clarify the concepts described in the **Major Challenges**.

- Production quality: often defined as “the ability of a system being suitable for its intended purpose while satisfying customer expectations”, this is a very broad definition that basically includes everything. Another widely used definition is “the degree a product meets requirements in specifications” – but without defining the underlying specifications, the interpretation can vary a lot between different stakeholders. Therefore, in this Chapter quality will be defined “as the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (such as burn-in) but no other type of testing”. In this way, reliability, dependability and cybersecurity, which for some would be expected to be included under quality, will be treated separately.
- Reliability: this is the ability or the probability, respectively, of a system or component to function as specified under stated conditions for a specified time.
- Prognostics and health management: a method that permits the assessment of the reliability of the product (or system) under its application conditions.
- Functional safety: the ability of a system or piece of equipment to control recognized hazards to achieve an acceptable level of risk, such as to maintain the required minimum level of operation even in the case of likely operator errors, hardware failures and environmental changes to prevent physical injuries or damages to the health of people, either directly or indirectly.
- Dependability: according to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here (192-01-01) can be an individual part, component, device, functional unit, equipment, subsystem or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01- 27) and maintenance support performance (192-01-29), and in some cases other characteristics such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).
- Safety: freedom from unacceptable risk of harm [CENELEC 50126].
- Security: measures can provide controls relating to physical security (control of physical access to computing assets) or logical security (capability to login to a given system and application) (IEC 62443-1-1):
    - measures taken to protect a system;
    - condition of a system that results from the establishment and maintenance of measures to protect the system;
    - condition of system resources being free from unauthorized access, and from unauthorized or accidental change, destruction or loss;
    - capability of a computer-based system to provide adequate confidence that unauthorized persons and systems can neither modify the software and its data nor gain access to the system functions, and yet ensure that this is not denied to authorized persons and systems;
    - prevention of illegal or unwanted penetration of, or interference with, the proper and intended operation of an industrial automation and control system.

- Cybersecurity: the protection of information against unauthorized disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).
- Robust root of trust systems: these are based on cryptographic functionalities that ensure the authenticity and integrity of the hardware and software components of the system, with assurance that it is resilient to logical and physical attacks.
- Emulation and Forecasting: cybersecurity evolution in parallel to increasing computation power and hybrid threats mixing geopolitical, climate change and any other external threats impose to anticipate the horizon of resilience, safety and security of systems forecasting attacks and incidents fast evolution.

Five Major Challenges have been identified:

- **Major Challenge 1**: ensuring HW quality and reliability.
- **Major Challenge 2**: ensuring dependability in connected software.
- **Major Challenge 3**: ensuring cyber-security and privacy.
- **Major Challenge 4**: ensuring of safety and resilience.
- **Major Challenge 5**: human systems integration.

### 2.4.4.1 Major challenge 1: Ensuring HW quality and reliability

#### 2.4.4.1.1 State of the art

With the ever-increasing complexity and demand for higher functionality of electronics, while at the same time meeting the demands of cutting costs, lower levels of power consumption and miniaturization in integration, hardware development cannot be decoupled from software development. Specifically, when assuring reliability, separate hardware development and testing according to the second-generation reliability methodology (design for reliability, DfR) is not sufficient to ensure the reliable function of the ECS. A third-generation reliability methodology must be introduced to meet these challenges. For the electronic smart systems used in future highly automated and autonomous systems, a next generation of reliability is therefore required. This new generation of reliability assessment will introduce in situ monitoring of the state of health on both a local (e.g. IC packaging) and system level. Hybrid prognostic and health management (PHM) supported by Artificial Intelligence (AI) is the key methodology here. This marks the main difference between the second and the third generation. DfR concerns the total lifetime of a full population of systems under anticipated service conditions and its statistical characterization. PHM, on the other hand, considers the degradation of the individual system in its actual service conditions and the estimation of its specific remaining useful life (RUL).

#### 2.4.4.1.2 Vision and expected outcome

Since embedded systems control so many processes, the increased complexity by itself is a reliability challenge. Growing complexity makes it more difficult to foresee all dependencies during design. It is impossible to test all variations, and user interfaces need greater scrutiny since they have to handle such complexity without confusing the user or generating uncertainties.

The trend towards interconnected, highly automated and autonomous systems will change the way we own products. Instead of buying commodity products, we will instead purchase personalized services. The vision of **Major challenge 1** is to provide the requisite tools and methods for novel ECS solutions to meet ever- increasing product requirements and provide availability of ECS during use in the field. Therefore, availability will be the major feature of ECS. Both the continuous improvement of existing methods (e.g. DfR) and development of the new techniques (PHM) will be the cornerstone of future developments in ECS (see also Challenges 1 and 2, and especially the key focus areas on lifecycle-aware holistic design flows in Chapter 2.3 **Architecture and Design: Methods and Tools**). The main focus of Major challenge 1 will circulate around the following topics.

- Digitization, by improving collaboration within the supply chain to introduce complex ECS earlier in the market.
- Continuous improvement of the DfR methodology through simultaneous miniaturization and increasing complexity.
- Model-based design is a main driver of decreasing time-to-market and reducing the cost of products.
- Availability of the ECS for highly automated and autonomous systems will be successfully introduced in the market based on PHM.
- Data science and AI will drive technology development and pave the way for PHM implementation for ECS.
- AI and PHM based risk management.

#### 2.4.4.1.3 Key focus areas

**Quality: In situ and real-time assessments**

Inline inspection and highly accelerated testing methods for quality and robustness monitoring during production of ECS with ever-increasing complexity and heterogeneity for demanding applications should increase the yield and reduce the rate of early fails (failures immediately following the start of the use period).

- Controlling, beyond traditional approaches, the process parameters in the era of Industry 4.0 to minimize deviations and improve quality of key performance indicators (KPIs).
- Process and materials variabilities will have to be characterized to quantify their effects on hardware reliability, using a combination of empirical studies, fundamental RP models and AI approaches.
- Advanced/smart monitoring of process output (e.g. measuring the 3D profile of assembled goods) for the detection of abnormities (using AI for the early detection of standard outputs).
- Early detection of potential yield/reliability issues by simulation-assisted design for assembly/design for manufacturing (DfM/DfA) as a part of virtual prototyping.

**Digitization: A paradigm shift in the fabrication of ECS from supplier/customer to partnership**

Digitization is not possible without processing and exchange data between partners.

- Involving European stakeholders to resolve the issue of data ownership:
    - Create best practices and scalable workflows for sharing data across the supply chain while maintaining intellectual property (IP).
    - Standardize the data exchange format, procedures and ownership, and create an international legal framework.
    - Conceive and validate business models creating economic incentives and facilitating sharing data, and machine learning algorithms dealing with data.
- Handling and interpreting big data:
    - Realise consistent data collection and ground truth generation via annotation/labelling of relevant events.
    - Create and validate a usable and time-efficient workflow for supervised learning.
    - Standardized model training and model testing process.
    - Standardized procedures for model maintenance and upgrade.
- Make a link between data from Industry 4.0 and model-based engineering:
    - Derive working hypotheses about system health.
    - Validate hypothesis and refine physics-based models.
    - Construct data models-based embedding (new) domain knowledge derived from model-based engineering.
- Identify significant parameters that must be saved during production to be re-used later for field-related events, and vice versa – i.e. feed important insights derived from field data (product usage monitoring) into design and production. This is also mandatory to comply with data protection laws.
- Evaluate methods for the indirect characterization of ECS using end-of-line test data.
- Wafer fabrication (pre-assembly) inline and offline tests for electronics, sensors and actuators, and complex hardware (e.g. multicore, graphics processing unit, GPU) that also cover interaction effects such as heterogeneous 3D integration and packaging approaches for advanced technologies nodes (e.g. thin dice for power application – dicing and grinding).

**Reliability: Tests and modelling**

Continuous improvement of physics of failure (PoF) based methodologies combined with new data-driven approaches: tests, analyses and degradation, and lifetime models (including their possible reconfiguration):

- Identifying and adapting methodology to the main technology drivers.
- Methods and equipment for dedicated third-level reliability assessments (first level: component; second level: board; third level: system with its housing, e.g. massive metal box), as well as accounting for the interactions between the hierarchy levels (element, device, component, sub-module, module, system, application).
- Comprehensive understanding of failure mechanisms, lifetime prediction models (including multi-loading conditions), continuously updating for new failure mechanisms related to innovative technologies (advanced complementary metal–oxide–semiconductor (CMOS), μ-fluidics, optical input/output (I/O), 3D printing, wide bandgap technologies, etc). New materials and production processes (e.g. 3D printing, wide bandgap technologies, etc), and new interdisciplinary system approaches and system integration technologies (e.g. μ-fluidics, optical input/output (I/O), etc).
- Accelerated testing methods (e.g. high temperature, high power applications) based on mission profiles and failure data (from field use and tests):

  - Use field data to derive hypotheses that enable improved prioritization and design of testing.
  - Usage of field, PHM and test data to build models for ECS working at the limit of the technology as accelerating testing is limited.
- Standardize the format of mission profiles and the procedure on how mission profiles are deducted from multimodal loading.
- Design to field – better understanding of field conditions through standardized methodology over supply chain using field load simulator.
- Understanding and handling of new, unforeseen and unintended use conditions for automated and autonomous systems.
- Embedded reliability monitoring (pre-warning of deterioration) with intelligent feedback towards autonomous system(s).
- Identification of the 10 most relevant field-related failure modes based on integrated mission profile sensors.
- Methods to screen out weak components with machine learning (ML) based on a combination of many measured parameters or built-in sensor data.
- New standards/methodologies/paradigms that evaluate the "ultimate" strength of systems – i.e. no longer test whether a certain number of cycles are "pass", but go for the limit to identify the actual safety margin of systems, and additionally the behavior of damaged systems, so that AI can search for these damage patterns.
- Digital twin software development for reliability analysis of assets/machines, etc.
- Comprehensive understanding of the SW influence on HW reliability and its interaction:
  - SW Reliability: start using maturity growth modelling techniques, develop models and gather model parameters.
  - SW/HW Reliability modelling: find ways as to combine the modelling techniques (in other words: scrunch the different time domains).
  - SW/HW Reliability testing: find ways as to test systems with software and find the interaction failure modes.

**Design for reliability: Virtual reliability assessment prior to the fabrication of physical HW**

Approaches for exchanging digital twin models along the supply chain while protecting sensitive partner IP and adaptation of novel standard reliability procedures across the supply chain.

- Digital twin as main driver of robust ECS system:
  - Identifying main technology enablers.
  - Development of infrastructure required for safe and secure information flow.
  - Development of compact PoF models at the component and system level that can be executed in situ at the system level – metamodels as the basis of digital twins.
  - Training and validation strategies for digital twins.
  - Digital twin-based asset/machine condition prediction.
- Electronic design automation (EDA) tools to bridge the different scales and domains by integrating a virtual design flow.
- Virtual design of experiment as a best practice at the early design stage.
- Realistic material and interface characterization depending on actual dimensions, fabrication process conditions, ageing effects, etc., covering all critical structures, generating strength data of interfaces with statistical distribution.
- Mathematical reliability models that also account for the interdependencies between the hierarchy levels (device, component, system).
- Mathematical modelling of competing and/or superimposed failure modes.
- New model-based reliability assessment in the era of automated systems.
- Development of fully harmonized methods and tools for model-based engineering across the supply chain:
  - Material characterization and modelling, including effects of ageing.
  - Multi-domain physics of failure simulations.
  - Reduced modelling (compact models, metamodels, etc.).
  - Failure criteria for dominant failure modes.
  - Verification and validation techniques.
- Standardization as a tool for model-based development of ECS across the supply chain:
  - Standardization of material characterization and modelling, including effects of ageing.

  - Standardization of simulation-driven design for excellence (DfX).
  - Standardization of model exchange format within supply chain using functional mock-up unit (FMU) and functional mock-up interface (FMI) (and also components).
  - Simulation data and process management.
  - Initiate and drive standardization process for above-mentioned points.
  - Extend common design and process failure mode and effect analysis (FMEA) with reliability risk assessment features (“reliability FMEA”).
  - Generic simulation flow for virtual testing under accelerated and operational conditions (virtual ”pass/fail” approach).
- Automation of model build-up (databases of components, materials).
- Use of AI in model parametrization/identification, e.g. extracting material models from measurement.
- Virtual release of ECS through referencing.

**Prognostics and health management of ECS: Increase in functional safety and system availability**

- Self-monitoring, self-assessment and resilience concepts for automated and autonomous systems based on the merger of PoF, data science and ML for safe failure prevention through timely predictive maintenance.
- Self-diagnostic tools and robust control algorithms validated by physical fault-injection techniques (e.g. by using end-of-life (EOL) components).
- Hierarchical and scalable health management architectures and platforms, integrating diagnostic and prognostic capabilities, from components to complete systems.
- Standardized protocols and interfaces for PHM facilitating deployment and exploitation.
- Monitoring test structures and/or monitor procedures on the component and module levels for monitoring temperatures, operating modes, parameter drifts, interconnect degradation, etc.
- Identification of early warning failure indicators and the development of methods for predicting the remaining useful life of the practical system in its use conditions.
- Development of schemes and tools using ML techniques and AI for PHM.
- Implementation of resilient procedures for safety-critical applications.
- Big sensor data management (data fusion, find correlations, secure communication), legal framework between companies and countries).
- Distributed data collection, model construction, model update and maintenance.
- Concept of digital twin: provide quality and reliability metrics (key failure indicator, KFI).
- Using PHM methodology for accelerated testing methods and techniques.
- Development of AI-supported failure diagnostic and repair processes for improve field data quality.
- AI-based asset/machine/robot life extension method development based on PHM.
- AI-based autonomous testing tool for verification and validation (V&V) of software reliability.
- Lifecycle management – modeling of the cost of the lifecycle.

### 2.4.4.2 Major Challenge 2: Ensuring dependability in connected software

#### 2.4.4.2.1 State of the art

Connected software applications such as those used on the Internet of Things (IoT) differ significantly in their software architecture from traditional reliable software used in industrial applications. The design of connected IoT software is based on traditional protocols originally designed for data communications for PCs accessing the internet. This includes protocols such as transmission control protocol/internet protocol (TCP/IP), the re-use of software from the IT world, including protocol stacks, web servers and the like. This also means the employed software components are not designed with dependability in mind, as there is typically no redundancy and little arrangements for availability. If something does not work, end-users are used to restarting the device. Even if it does not happen very often, this degree of availability is not sufficient for critical functionalities, and redundancy hardware and back-up plans in ICT infrastructure and network outages still continue to occur. Therefore, it is of the utmost importance that we design future connected software that is conceived either in a dependable way or can react reliably in the case of infrastructure failures to achieve higher software quality.

#### 2.4.4.2.2 Vision and expected outcome

The vision is that networked systems will become as dependable and predictable for end-users as traditional industrial applications interconnected via dedicated signal lines. This means that the employed connected software components, architectures and technologies will have to be enriched to deal with dependability for their operation. Future dependable connected software will also be able to detect in advance if network conditions change – e.g. due to foreseeable transmission bottlenecks or planned maintenance measures. If outages do happen, the user or end application should receive clear feedback on how long the problem will last so they can take potential measures. In addition, the consideration of redundancy in the software architecture must be considered for critical applications. The availability of a European ecosystem for reliable software components will also reduce the dependence on current ICT technologies from the US and China.

## 2.4.4.2.3 Key focus areas

**Dependable connected software architectures**

In the past, reliable and dependable software was always directly deployed on specialised, reliable hardware. However, with the increased use of IoT, edge and cloud computing, critical software functions will also be used that are completely decoupled from the location of use (e.g. in use cases where the police want to stop self-driving cars from a distance):

- Software reliability in the face of infrastructure instability.
- Dependable edge and cloud computing, including dependable and reliable AI/ML methods and algorithms.
- Dependable communication methods, protocols and infrastructure.
- Formal verification of protocols and mechanisms, including those using AI/ML.
- Monitoring, detection and mitigation of security issues on communication protocols.
- Quantum key distribution (“quantum cryptography”).
- Increasing software quality by AI-assisted development and testing methods.
- Infrastructure resilience and adaptability to new threats.
- Secure and reliable over-the-air (OTA) updates.
- Using AI for autonomy, network behaviour and self-adaptivity.
- Dependable integration platforms.
- Dependable cooperation of System of Systems (SoS).

This Major Challenge is tightly interlinked with the cross-sectional technology of 2.2 Connectivity Chapter, where the focus is on innovative connectivity technologies. The dependability aspect covered within this challenge is complementary to that chapter since dependability and reliability approaches can also be used for systems without connectivity.

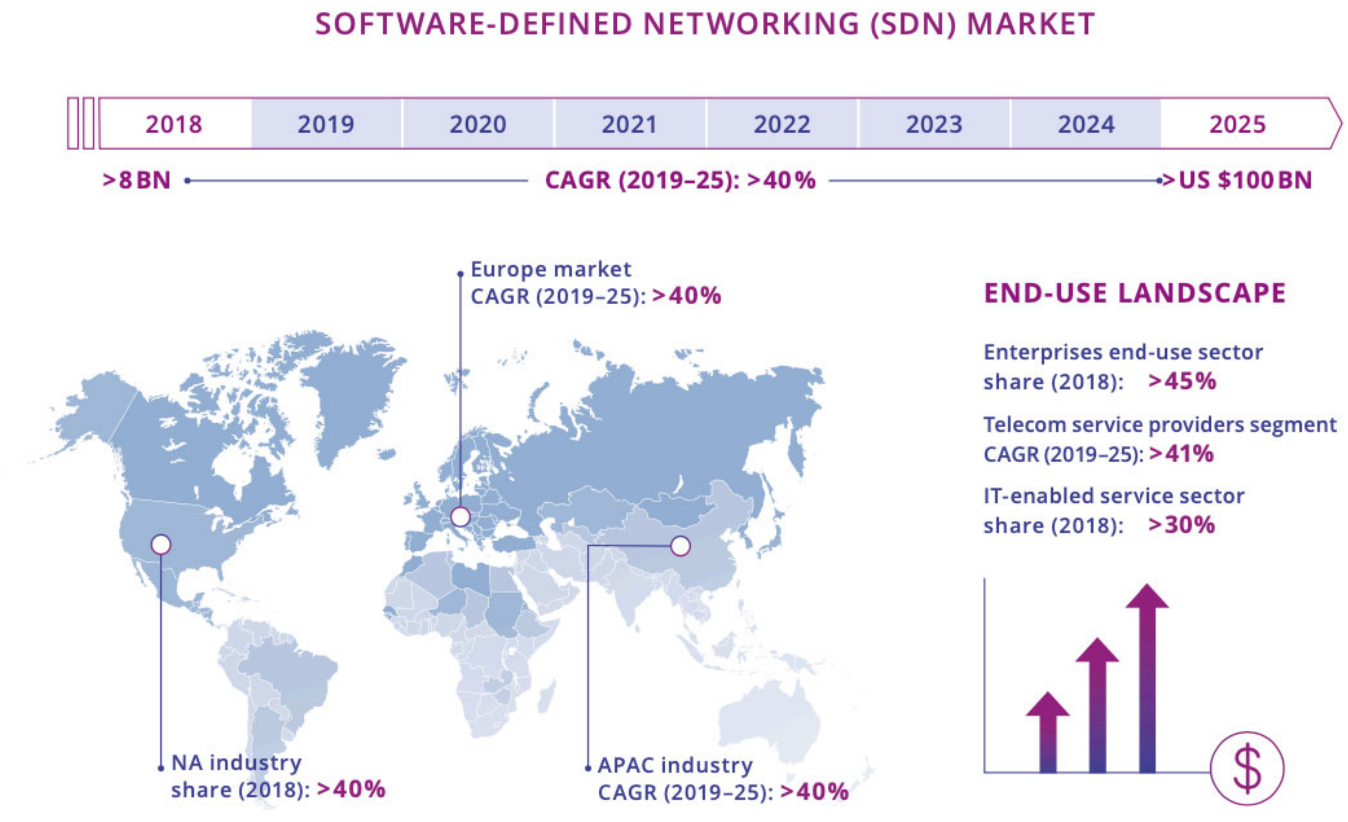


*Figure 2.4.2 - Software-defined networking (SDN) market size by 2025 (Source: Global Markets Insight, Report ID GMI2395, 2018)*

**Dependable softwarisation and virtualisation technologies**

Changing or updating software by retaining existing hardware is quite common in many industrial domains. However, keeping existing reliable software and changing the underlying hardware is difficult, especially for critical applications. By decoupling software functionalities from the underlying hardware, softwarisation and virtualisation are two disruptive paradigms that can bring enormous flexibility and thus promote strong growth in the market (see Figure 2.4.2). However, the softwarisation of network functions raises reliability concerns, as they will be exposed to faults in commodity hardware and software components:

- Software-defined radio (SDR) technology for highly reliable wireless communications with higher immunity to cyber-attacks.
- Network functions virtualisation infrastructure (NFVI) reliability.
- Reliable containerisation technologies.
- Resilient multi-tenancy environments.
- AI-based autonomous testing for V&V of software reliability, including the software-in-the-loop (SiL) approach.
- Testing tools and frameworks for V&V of AI/ML-based software reliability, including the SiL approach.

**Combined SW/HW test strategies**

Unlike hardware failures, software systems do not degrade over time unless modified. The most effective approach for achieving higher software reliability is to reduce the likelihood of latent defects in the released software. Mathematical functions that describe fault detection and removal phenomenon in software have begun to emerge. These software reliability growth models (SRGM), in combination with Bayesian statistics, need further attention within the hardware-orientated reliability community over the coming years:

- HW failure modes are considered in the software requirements definition.
- Design characteristics will not cause the software to overstress the HW, or adversely change failure-severity consequences on the occurrence of failure.
- Establish techniques that can combine SW reliability metrics with HW reliability metrics.
- Develop efficient (hierarchical) test strategies for combined SW/HW performance of connected products.

Dependability in connected software is strongly connected with other chapters in this document. In particular, additional challenges are handled in following chapters:

- Chapter 1.3 Embedded Software and Beyond: Major Challenge 1 (MC1) efficient engineering of software; MC2 continuous integration of embedded software; MC3 lifecycle management of embedded software; and MC6 Embedding reliability and trust.
- Chapter 1.4 System of Systems: MC1 SoS architecture; MC4 Systems of embedded and cyber-physical systems engineering; and MC5 Open system of embedded and cyber-physical systems platforms.
- Chapter 2.1 Edge Computing and Embedded Artificial Intelligence: MC1: Increasing the energy efficiency of computing systems.
- Chapter 2.2 Connectivity: MC4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity.
- Chapter 2.3 Architecture and Design: Method and Tools: MC3: Managing complexity.

### 2.4.4.3 Major Challenge 3: Ensuring cyber-security and privacy

#### 2.4.4.3.1 State of the art

We have witnessed a massive increase in pervasive and potentially connected digital products in our personal, social and professional spheres, enhanced by new features of 5G networks and beyond. Connectivity provides better flexibility and usability of these products in different sectors, with a tremendous growth of sensitive and valuable data. Moreover, the variety of deployments and configuration options and the growing number of sub-systems changing in dynamicity and variability increase the overall complexity. In this scenario, new security and privacy issues have to be addressed, also considering the continuously evolving threat landscape. New approaches, methodologies and tools for risk and vulnerability analysis, threat modeling for security and privacy, threat information sharing and reasoning are required. Artificial intelligence (e.g. machine learning, deep learning and ontology) not only promotes pervasive intelligence supporting daily life, industrial developments, personalisation of mass products around individual preferences and requirements, efficient and smart interaction among IoT in any type of services, but It also fosters automation, to mitigate such complexity and avoid human mistakes.

Embedded and distributed AI functionality is growing at speed in both (connected) devices and services. AI-capable chips will also enable edge applications allowing decisions to be made locally at device level. Therefore, resilience to cyber-attacks is of utmost importance. AI can have a direct action on the behaviour of a device, possibly impacting its physical life inducing potential safety concerns. AI systems rely on software and hardware that can be embedded in components, but also on the set of data generated and used to make decisions. Cyber-attacks, such as data poisoning or adversarial inputs, could cause physical harm and/or also violate privacy. The development of AI should therefore go hand in hand with frameworks that assess security and safety to guarantee that AI systems developed for the EU market are safe to use, trustworthy, reliable and remain under control (C.f. Chapter 1.3 "Embedded Software and beyond" for quality of AI used in embedded software when being considered as a technology interacting with other software components).

The combination of composed digital products and AI highlights the importance of trustable systems that weave together privacy and cybersecurity with safety and resilience. Automated vehicles, for example, are adopting an ever-expanding combination of Advanced Driver Assistance Systems (ADAS) developed to increase the level of safety, driving comfort exploiting different type of sensors, devices and on-board computers (sensors, Global Positioning System (GPS), radar, lidar, cameras, on-board computers, etc.). To complement ADAS systems, Vehicle to X (V2X) communication technologies are gaining momentum. Cellular based V2X communication provides the ability for vehicles to communicate with other vehicle and infrastructure and environment around them, exchanging both basic safety messages to avoid collisions and, according to the 5g standard evolutions, also high throughput sensor sharing, intent trajectory sharing, coordinated driving and autonomous driving. The connected autonomous vehicle scenarios offer many advantages in terms of safety, fuel consumption and $CO_2$ emissions reduction, but the increased connectivity, number of devices and automation, expose those systems to several crucial cyber and privacy threats, which must be addressed and mitigated.

Autonomous vehicles represent a truly disruptive innovation for travelling and transportation, and should be able to warrant confidentiality of the driver's and vehicle's information. Those vehicles should also avoid obstacles, identify failures (if any) and mitigate them, as well as prevent cyber-attacks while staying safely operational (at reduced functionality) either through human-initiated intervention, by automatic inside action or remotely by law enforcement in the case of any failure, security breach, sudden obstacle, crash, etc.

In the evoked scenario the main cybersecurity and privacy challenges deal with:

- Interoperable security and privacy management in heterogeneous systems including cyber-physical systems, IoT, virtual technologies, clouds, communication networks, autonomous systems.
- Real time monitoring and privacy and security risk assessment to manage the dynamicity and variability of systems.
- Developing novel privacy preserving identity management and secure cryptographic solutions.
- Novel approaches to hardware security vulnerabilities and other systemweaknesses as - for instance – Spectre and Meltdown or side channel attacks (c.f. appendix A).
- Developing new approaches, methodologies and tools empowered by AI in all its declinations (e.g. machine learning, deep learning, ontology).
- Investigating a deep verification approach towards also open-source hardware in synergy and implementing the security by-design paradigm (c.f. appendix A).

- Investigating the interworking among safety, cybersecurity, trustworthiness, privacy and legal compliance of systems.
- Evaluating the impact in term of sustainability and green deal of the adopted solutions.

## 2.4.4.3.2 Vision and expected outcome

The cornerstone of our vision rests on the following four pillars. First, a robust root of trust system, with unique identification enabling security without interruption from the hardware level right up to the applications, including AI, involved in the accomplishment of the system's mission in dynamic unknown environments. This aspect has a tremendous impact on mission critical systems with lots of reliability, quality and safety & security concerns. Second, protection of the EU citizen's privacy and security while at the same keeping usability levels and operation in a competitive market where also industrial Intellectual Protection should be considered. Third, the proposed technical solutions should contribute to the green deal ambition, for example by reducing their environmental impact. Finally, proof-of-concept demonstrators that are capable of simultaneously guaranteeing (a given level of) security and (a given level of) privacy, as well as potentially evolving in-reference designs that illustrate how practical solutions can be implemented (i.e. thereby providing guidelines to re-use or adapt).

End to end encryption of data, both in transit and at rest is kept to effectively protect privacy and security. The advent of quantum computing technology introduces new risks and threats, since attacks using quantum computing may affect traditional cryptographic mechanisms. New quantum safe cryptography is required, referring both to quantum cryptography and post quantum cryptography with standard crypto primitives.

Also, the roadmap for Open Source HW/SW & RISC-V IP blocks will open the path to domain-focused processors or domain-specific architectures (for instance, but not limited to the "chiplet-based approach"), which may lead to new approaches to cybersecurity and safety functions or implementation as well as new challenges and vulnerabilities that must be analysed (c.f. appendix A).

Putting together seamlessly security and privacy requirements is a difficult challenge that also involves some non-technical aspects. The human factor can often cause security and privacy concerns, despite of technologically advanced tools and solutions. Another aspect relates to security certification versus certification cost. A certification security that does not mitigate the risks and threats, increases costs with minimal benefits. Therefore, all techniques and methodology to reduce such a cost are in the scope of the challenge.

In light of this scenario, this Major Challenge aims at contributing to the European strategic autonomy plan in terms of cybersecurity, digital trustworthiness and the protection of personal data.

## 2.4.4.3.3 Key focus areas

**Trustworthiness**

Digital Trust is mandatory in a global scenario, based on ever-increasing connectivity, data and advanced technologies. Trustworthiness is a high-level concern including not only privacy and security issues, but also safety and resilience and reliability. The goal is a robust, secure, and privacy preserving system that operates in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be AI-enabled. This challenge calls for a multidisciplinary approach, spanning across technologies, regulations, compliance, legal and economic issues. To this end, the main expected outcomes can be defined as:

- Defining different methods and techniques of trust for a system, and proving compliance to a security standard via certification schemes.
- Defining methods and techniques to ensure trustworthiness of AI algorithms, included explainable (XAI) (cfr. Chapter 2.1 "Edge Computing and Embedded Artificial Intelligence")
- Developing methodologies and techniques from hardware trustworthy to software layers trustworthy (cfr. Chapter 1.3 "Embedded Software and Beyond" and Chapter 1.4 "System of Systems").
- Defining methods and tools to support the composition and validation of certified parts addressing multiple standards (cfr. Chapter 1.4 "System of Systems" and Chapter 2.3 "Achitecture and Design: Methods And Tools").
- Definition and future consolidation of a framework providing guidelines, good practices and standards oriented to trust.
- Enhancing current tools and procedures for safety and security verification and certification for Open-Source Hardware/Software (c.f. Appendix A).
- Architectures that provide mitigation, remediation and restoration against physical and software cyber threats ensuring integrity in Data, Software and Systems.

**Security and privacy-by-design**

The main expected outcome is a set of solutions to ensuring the protection of personal data in the embedded AI and data-driven digital economy against potential cyber-attacks:

- Ensuring cybersecurity and privacy of systems in the Edge to cloud continuum, via efficient automated verification and audits, as well as recovery mechanism (cfr. Chapter 1.4 "System of Systems" and Chapter 2.3 "Achitecture and Design: Method and Tools").

- Ensuring performance in AI-driven algorithms (which needs considerable data) while guaranteeing compliance with European privacy standards (e.g. general data protection regulation - GDPR).
- Establishing a cybersecurity and privacy-by-design European data strategy to promote data sovereignty.
- Establishing Quantum-Safe Cryptography Modules.
- Establishing a transparency security approach toward Open-Source Hardware/Software Architecture (c.f. Appendix A)

**Ensuring both safety and security properties**

The main expected outcome is to ensure compatibility, adequacy and coherence in the joint use of the promoted security solutions, and the safety levels required by the system or its components:

- Maintaining the nominal or degraded system safe level behaviour when the system's security is breached or there are accidental failures.
- Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc.).
- Ensuring safety, security and privacy of embedded intelligence (c.f. Chapter 1.3 "Embedded Software and beyond").
- Guaranteeing a system's coherence among different heterogeneous requirements (i.e. secure protocols, safety levels, computational level needed by the promoted mechanisms) and different applied solutions (i.e. solutions for integrity, confidentiality, security, safety) in different phases (i.e. design, operation, maintenance, repair and recovery).
- For safety-critical applications, the open-source software (for instance: Virtual Prototypes, compilers and linkers, debuggers, programmers, integrated development environments, operating systems, software development kits and board support packages) must be qualified regarding functional safety and security standards in order to offer a possibility to create transparent, auditable processes for ensuring safety and security (c.f. Appendix A).
- Assess complex System-on-Chip implementations and a Chiplet approach assembling functional circuit blocs with different functions (e.g.: processor, accelerator, memories, interfaces, etc.) regarding security functionalities, focusing on scalability, modularity as well as Edge paradigm (c.f. Appendix A).
- Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of transparency without compromising information and trustworthiness.
- Evaluating the environmental impact of the implemented safety and security solutions (the green chapter connection).

### 2.4.4.4 Major Challenge 4: Ensuring of safety and resilience

#### 2.4.4.4.1 State of the art

Safety has always been a key concept at the core of human civilisation. Throughout history, its definition, as well as techniques to provide it, has evolved significantly. In the medical application domain, for example, we have witnessed a transformation from safe protocols to automatic medication machines, such as insulin pumps and respiratory automation, which have integrated safety provisions. Today, we can build a range of different high-integrity systems, such as nuclear power plants, aircraft and autonomous metro lines. The safety of such systems is essentially based on a combination of key factors, including: (i) determinism (the system's nominal behaviour is always the same under the same conditions); (ii) expertise and continuous training of involved personnel; (iii) deep understanding of nominal and degraded behaviours of the system; (iv) certification/qualification; and (v) clear liability and responsibility chains in the case of accidents.

Nowadays, the digitalisation of ubiquitous systems, and the embedding of AI components (hardware or software) in them, highlights the limits of traditional safety techniques, which need to be extended and/or embedded in new overall safety-case arguments. These techniques for building safe systems include fault-tree analysis, failure modes and effect analysis, evidence-based development standards (such as ISO26262 and ISO 21448), redundancy, diversification and defence-in-depth (c.f. Chapter 1.3 "Embedded Software and beyond" for Major Challenge 1: Efficient engineering of embedded software to enable transition from embedded software engineering to embedded systems engineering.). As a result of the realities in modern systems and their usage, one promising approach is to move the safety paradigm from safety as traditionally studied in embedded systems, to resilience. Most of the methodical factors mentioned above are currently insufficient to cope with resilience in its full meaning.

At the same time, we have witnessed an increase of the interested in the open-source hardware and software, which drastically lowers the barrier to design innovative Systems-On-Chips (SoCs) (c.f. Appendix A, introduction).

As a result, new innovations are required to increase the resilience of systems by tackling challenges involving cross-cutting considerations such as legal concerns and user abilities, and to ensure safety-related properties under a chiplet-based approach (c.f. Appendix A, introduction).

#### 2.4.4.4.2 Vision & expected outcomes

The vision points to the development of safe and resilient autonomous cyber-physical systems in dynamic environments, with a continuous chain-of-trust from the hardware level up to the applications that is involved in the accomplishment of the system's mission, including AI. Our vision takes into account physical limitations (battery capacity, quality of sensors used in the system, hardware processing power needed for autonomous navigation features, etc.), interoperability (that could be brought e.g. open source hardware c.f. appendix A), and considers optimizing the energy usage and system resources of safety-related features to support sustainability of future cyber-physical systems. Civilian applications of (semi-) autonomous cyber-physical systems are increasing significantly. For example, drones can be deployed for monitoring social distancing and providing safety to the population (and also to deliver medicine in the UK). However, the use of drones is not accident-free. In 2015, at the Pride Parade in Seattle, a drone crashed and caused an accident that resulted in a woman being knocked out. Civilian applications thus inherently entail safety, and in the case of an accident or damage (for example, in uploading a piece of software in an AI system) liability should be clearly traceable, as well as the certification/qualification of AI systems.

The increasing trend towards the adoption of AI in civilian applications represents a great opportunity for European economic growth. However, unlike traditional high-integrity systems, the hypothesis that only expert operators can manipulate the final product undermines the large-scale adoption of the new generation of autonomous cyber-physical systems.

In addition to the key focus areas below, the challenges cited in Chapter 2.3 on Architecture and Design: Methods and Tools are also highly relevant for this topic, and on Chapter 1.3 on Embedded Software and beyond.

### 2.4.4.4.3 Key focus areas

**Dynamic adapdation and configuration, self-repair capabilities, (decentralized instrumentation and control for) resilience of complex and heterogeneous systems**

The expected outcome is systems that are resilient under physical constraints and are able to dynamically adapt their behaviour in dynamic environments:

- Responding to uncertain information based on digital twin technology, run-time adaption and redeployment based on simulations and sensor fusion.
- Automatic prompt self-adaptability at low latency to dynamic and heterogeneous environments.
- Architectures, including but not limited to the RISC-V ones (cfr. appendix A) that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification.
- Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimization.
- Develop explainable AI models for human interaction, systems interaction and certification.
- Resource management of all systems' components to accomplish the mission system in a safe and resilient way. Consider to minimize the energy usage and system resources of safety-related features to support sustainability of future cyber-physical systems.
- Identify and address transparency and safety-related issues introduced by AI applications.
- Support for dependable dynamic configuration and adaptation/maintenance to help cope with components that appear and disappear, as ECS devices to connect/disconnect, and communication links that are established/released depending on the actual availability of network connectivity (including, for example, patching) to adapt to security countermeasures.
- Concepts for SoS integration, including legacy system integration.

**Modular certification of trustable systems and liability**

The expected outcome is clear traceability of liability during integration and in the case of an accident:

- Having explicit workflows for automated and continuous layered certification/qualification, both when designing the system and for checking certification/qualification during run-time or dynamic safety contracts, to ensure continuing trust in dynamic adaptive systems under uncertain and/or dynamic environments.
- Concepts and principles, such as contract-based co-design methodologies, and consistency management techniques in multi-domain collaborations for trustable integration.
- Certificates of extensive testing, new code coverage metrics (e.g. derived from mutation testing), and formal methods providing guaranteed trustworthiness.
- Ensuring trustworthy electronics, including trustworthy design IPs (e.g. source code, documentation, verification suites) developed according to auditable and certifiable development processes, which give high verification and certification assurance (safety and/or security) for these IPs (cfr. appendix A).

**Safety aspects related to the human/system interaction**

The expected outcome is to ensure safety for the human and environment during the nominal and degraded operations in the working environment (cf. Major Challenge 5 below):

- Understanding the nominal and degraded behaviour of a system, with/without AI functionality.
- Minimising the risk of human or machine failures during the operating phases.
- Ensuring that the human can safely interface with machine in complex systems and SoS, and also that the machine can prevent unsafe operations.

- New self-learning safety methods to ensure safety system operations in complex systems.
- Ensuring safety in machine-to-machine interaction.

### 2.4.4.5 **Major Challenge 5: Human systems integration**

#### 2.4.4.5.1 State of the art

This ECS SRIA roadmap aligns societal needs and challenges to the R & D & I for electronic components. The societal benefits thereby motivate the foundational and cross-sectional technologies as well as the concrete applications in the research agenda. Thereby, many technological innovations occur on a subsystem level that are not directly linked to societal benefits themselves until assembled and arranged into larger systems. Such larger systems then most of the time require human users and beneficiary to utilize them and thereby achieve the intended societal benefits. Thereby, it is common that during the subsystem development human users and beneficiaries stay mostly invisible. Only once subsystems are assembled and put to an operational system, the interactions with a human user become apparent. At this point however, it is often too late to make substantial changes to the technological subsystems and partial or complete failure to reach market acceptance and intended societal benefits can result. To avoid such expensive and resource intensive failures, Human Systems Integration (HSI) efforts attempt to accompany technological maturation that is often measured as Technological Readiness Levels (TRL) with the maturation of Human Readiness Levels (HRL). Failures to achieve high HRL beside high TRLs have been demonstrated in various domains such as military, space travel, and aviation. Therefore, HSI efforts to achieve high HRLs need to be appropriately planned, prepared, and coordinated as part of technological innovation cycles. As this is currently only rarely done in most industrial R&D activities, this Chapter describes the HSI challenges and outlines a vision to address them.

There are three high-level HSI challenges along ECS-based products:

- The first challenge is to design products that are acceptable, trustworthy, and therefore highly likely to be used sustainably to achieve the expected individual, organizational, or societal benefits. Thereby, the overall vision for the practical use of a product by real users within their context is currently often unknown at the time of the technological specification of the product. Instead, the technological capabilities available in many current innovation environments are assembled to demonstrate merely technological capabilities but not operational use. This is often mistakenly called “use case” as it means “use to demonstrate the product” not “realistic use of the product by real users in realistic environments”. Thereby, sufficiently detailed operational knowledge of the environmental, organizational, and user characteristics is often not available and cannot be integrated into technology development. Therefore, the conception of accepted and trusted, and sustainably used technologies is often the result of trial-and-error, rather than strategically planned development efforts.
- The second challenge consists of currently prevalent silos of excellence where experts work within their established domain without much motivation, ability or interest to requirements that seem external to their domain. Instead, success is often seen as promoting the own area of expertise. This forms effective resistance against a holistic design of a system instead of subcomponent optimization and makes it difficult to design products for accepted, trusted, and sustained usage. For example, increasingly complex and smart products require often intricate user interactions and understanding that is beyond simpler “non-smart” products. Thereby, the developing engineers often do not know the concrete usage conditions of the to-be-developed system or constraints of their users and are therefore unable to make appropriate architecture decisions. For example, drivers and workers generally do not like to purely monitor or supervise automated functions, while losing active participation. This is especially critical when humans have to suddenly jump back into action and take control when unexpected conditions require them to do so. Therefore, aligning the automation capabilities with the human tasks that are feasible for users to perform and to match their knowledge and expectable responsibilities, are becoming paramount to bring a product successfully to the market. However, currently established silos of engineering excellence in organizations are difficult to penetrate and therefore resist such as external perceived requirements.

Thirdly, continuous product updates and maintenance are creating dynamically changing products that can be challenging for user acceptance, trust, and sustained usage. Frequent and increasingly automated software updates have become commonplace to achieve sufficiently high security levels and to enable the latest software capability sets as well as allow self-learning algorithms to adapt to user preferences, usage history, and environmental changes. However, such changes can be confusing to users if they come unannounced, or are difficult to understand. Also, the incorrect usage that may result from this may lead to additional security and acceptance risks. Therefore, the product maintenance and update cycles need to be appropriately designed within the whole product lifecycle to ensure maximum user acceptance and include sufficient information on the side of the users. Here HSI extends beyond initial design and fielding of products.

#### 2.4.4.5.2 Vision and expected outcome

The vision and expected outcome is that these three HSI challenges can be addressed by appropriately orchestrating the assessments of needs, constraints, and abilities of the human users, and use conditions with the design and engineering of products as well as their lifetime support phases. Specifically, this HSI vision can be formulated around three cornerstones:

- Vision cornerstone 1: conceiving systems and their missions, based on a detailed analysis of acceptance and usage criteria during the early assessment of the usage context. This specifically entails the assessment of user needs and constraints within their context of use and the translation of this information into functional and technical requirements to effectively inform system design and development. Such information is currently not readily available to system architects, as such knowledge is currently either hidden or not assessed at the time when it is needed to make an impact during system conception. Instead, such assessments require specific efforts using the expertise of social scientists such as sociologists, psychologists, and human factors researchers who have also familiarity or training in engineering processes. As part of this cornerstone, assessments are conducted that describe the user population and the usage situation including criticality, responsibilities, environment, required tasks and time constraints. Also, the organizational conditions and processes within which the users are expected to use the system play an important role that should impact design decisions, for example to determine appropriate explainability methods. This assembled information is shaping the system architecture decisions and is formulated as use cases, scenarios, and functional and technical requirements.

- Vision cornerstone 2: to translate the foundational requirements from cornerstone 1 into an orchestrated system mission and development plan using a holistic design process. Multifaceted developer communities thereby work together to achieve acceptable, safe, and trustworthy products. Thereby, the product is not designed and developed in isolation but within actively explored contextual infrastructures to bring the development and design communities close to the use environment and conditions of the product. Considering this larger contextual field in the design of products requires advanced R&D approaches and methodologies, to pull together the various fields of expertise and allow mutual fertilization. This requires sufficiently large, multi-disciplinary research environments for active collaboration and enablement of a sufficient intermixture between experts and innovation approaches. This also requires virtual tool sets for collaboration, data sharing, and solution generation.
- Vision cornerstone 3: detailed knowledge about the user and use conditions are also pertinent to appropriately plan and design the continuous adaptations and updates of products during the lifecycle. Converging user knowledge and expectations will allow more standardized update policies. This will be addressed by bringing the end-users, workers, and operators toward achieving the digital literacy with a chance to enable the intended societal benefits. The formation of appropriate national and international training and educational curricula will work toward shaping users with sufficiently converging understanding of new technology principles and expectations as well as knowledge about responsibilities and common failure modes to facilitate sustained and positively perceived interactions.

Within these cornerstones, the vision is to intermingle the multi-disciplinary areas of knowledge, expertise, and capabilities within sufficiently inter-disciplinary research and development environments where experts can interact with stakeholders to jointly design, implement, and test novel products. Sufficiently integrated simulation and modeling that includes human behavioral representations are established to link the various tasks. The intermingling starts with user needs and contextual assessments that are documented and formalized sufficiently to stay available during the development process. Specifically, the skills and competences are formally recorded and made available for requirements generation.

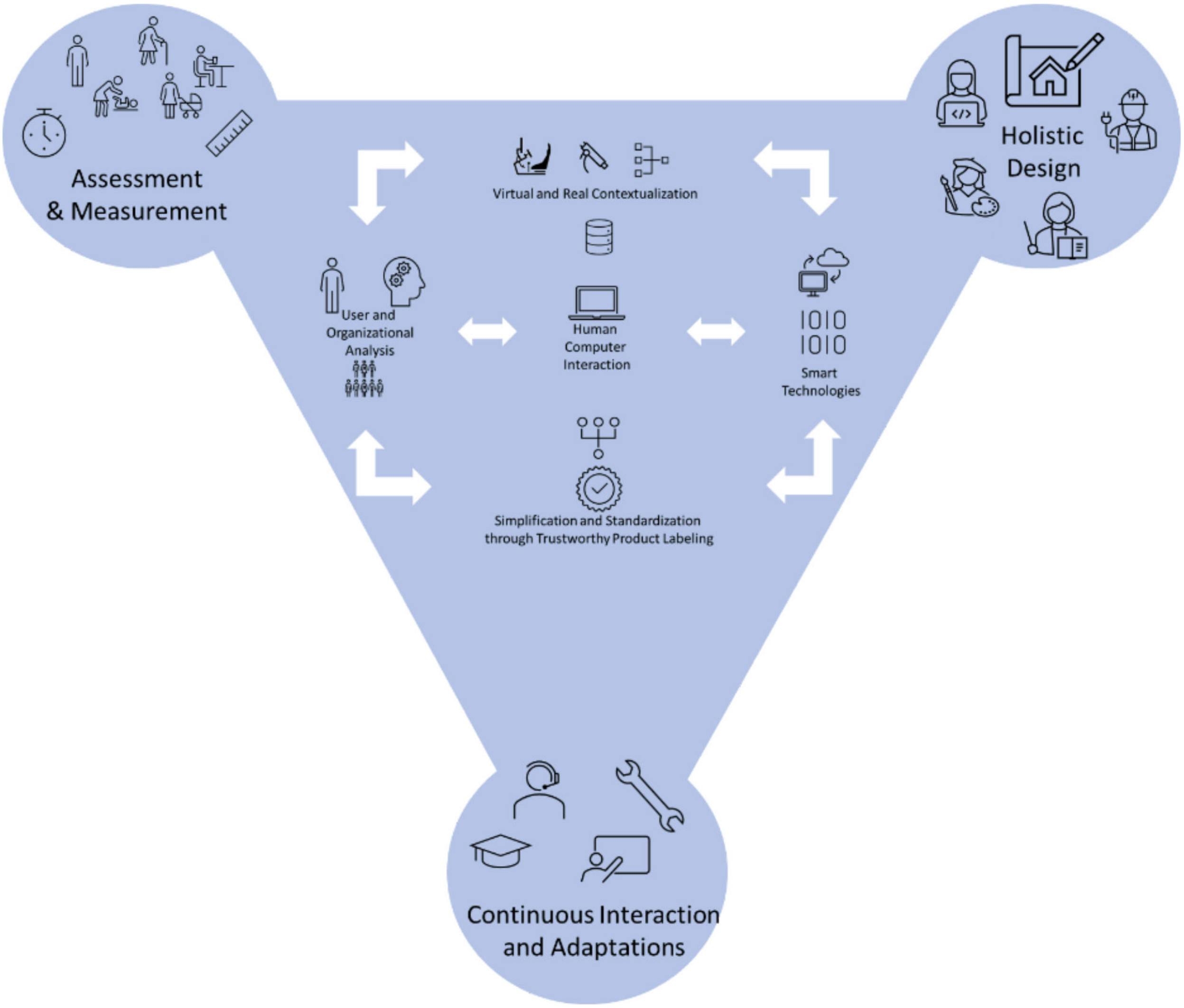


*Figure 2.4.3 - Human Systems Integration in the ECS SRIA*

## 2.4.4.5.3 Key focus areas

- Systematize methods for user, context, and environment assessments and sharing of information for user-requirement generation. Such methods are necessary to allow user centered methods to achieve an impact on overall product design.
- Develop simulation and modeling methods for the early integration of Humans and Technologies. The virtual methods link early assessments, holistic design activities, and lifelong product updates and bring facilitate convergence among researchers, developers, and stakeholders.
- Establish multi-disciplinary research and development centers and sandboxes. Interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support.

## 2.4.5 Timeline

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024-2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Ensuring HW quality and reliability** | **Topic 1.1:** quality: *in situ* and real-time assessments | • Create an environment to fully exploit the potential of data science to improve efficiency of production through smart monitoring to facilitate the quality of ECS and reduce early failure rates | • Establish a procedure to improve future generation of ECS based on products that are currently in the production and field → feedback loop from the field to design and development | • Provide a platform that allows for data exchange within the supply chain while maintaining IP rights |
| | **Topic 1.2:** reliability: tests and modelling | • Development of methods and tools to enable third generation of reliability – from device to SoS | • Implementation of a novel monitoring concept that will empower reliability monitoring of ECS | • Identification of the 80% of all field-relevant failure modes and mechanisms for the ECS used in autonomous systems |
| | **Topic 1.3:** design for (EoL) reliability: virtual reliability assessment prior to the fabrication of physical HW | • Continuous improvement of EDA tools, standardisation of data exchange formats and simulation procedures to enable transfer models and results along full supply chain | • Digital twin as a major enabler for monitoring of degradation of ECS | • AI/ML techniques will be a major driver of model-based engineering and the main contributor to shortening the development cycle of robust ECS |
| | **Topic 1.4:** PHM of ECS: increase in functional safety and system availability | • Condition monitoring will allow for identification of failure indicators for main failure modes | • Hybrid PHM approach, including data science as a new potential tool in reliability engineering, based on which we will know the state of ECS under field loading conditions | • Standardisation of PHM approach along all supply chains for distributed data collection and decision-making based on individual ECS |
| **Major Challenge 2:**<br>**Ensuring dependability in connected software** | **Topic 2.1:** dependable connected software architectures | • Development of necessary foundations for the implementation of dependable connected software to be extendable for common SW systems (open source, middleware, protocols) | • Set of defined and standardised protocols, mechanisms and user-feedback methods for dependable operation | • Widely applied in European industry |
| | **Topic 2.2:** dependable softwarisation and virtualisation technologies | • Create the basis for the increased use of commodity hardware in critical applications | • Definition of softwarisation and virtualisation standards, not only in networking but in other applications such as automation and transport | • Efficient test strategies for combined SW/HW performance of connected products |
| | **Topic 2.3:** combined SW/HW test strategies | • Establish SW design characteristics that consider HW failure modes | • Establish techniques that combine SW reliability metrics with HW reliability metrics | |
| **Major Challenge 3:**<br>**Ensuring privacy and cybersecurity** | **Topic 3.1:** trustworthiness | • Root of trust system, and unique identification enabling security without interruption from the hardware level up to applications, including AI | • Definition of a framework providing guidelines, good practices and standards oriented to trust | • Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of trustworthiness |
| | **Topic 3.2:** security and privacy- by-design | • Establishing a secure and privacy-by-design European data strategy and data sovereignty | • Ensuring the protection of personal data against potential cyber-attacks in the data-driven digital economy<br>• Ensuring performance and AI development (which needs considerable data) by guaranteeing GDPR compliance | • Provide a platform that allows for data exchange within the supply chain while maintaining IP rights |
| | **Topic 3.3:** ensuring both safety and security properties | • Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc.) independence, geographic distribution, emergent behaviour and evolutionary development | • Ensuring the nominal and degraded behaviour of a system when the underlying system security is breached or there are accidental failures<br>• Evaluating the impact of the contextualisation environment on the system's required levels of safety and security | • Identification of the 80% of all field-relevant failure modes and mechanisms for the ECS used in autonomous systems |
| **Major Challenge 4:**<br>**Ensuring safety and** | **Topic 4.1:** safety and resilience of (autonomous AI) systems in dynamic environments | • Resources' management of all system's components to accomplish the mission system in a safe and resilient way | • Apply methods for user context and environment assessments and sharing of information for stakeholder-requirement generation to prototypical use cases, | • Develop standard processes for stakeholder context and environment assessments and sharing of information |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024-2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **resilience** | | • Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimization | establish practices of use and generally applicable tools | • Develop standard processes for stakeholder knowledge, skills, and competence capturing techniques to inform requirements generation<br>• Develop educational programs to increase the levels of common stakeholder knowledge, skills and competences for sustainable product uptake across Europe |
| | **Topic 4.2:** modular certification of trustable systems and liability | • Contract-based co-design methodologies, consistency management techniques in multi-domain collaborations | • Definition of a strategy for (modular) certification under uncertain and dynamically changing environments<br>• Consolidation of a framework providing guidelines, good practices and standards oriented to trust<br>• Ensuring compliance with the AI standards | • Ensuring liability |
| | **Topic 4.3:** dynamic adaptation and configuration, self-repair capabilities (decentralised instrumentation and control for), resilience of complex systems | • Support for dependable dynamic configuration and adaptation/maintenance<br>• Concepts for SoS integration, including the issue of legacy system integration<br>• Using fault injection methods, models-of-the-physics and self-diagnostic architecture principles to understand the true nature of the world, and respond to uncertain information (included sensor's false positives) or attacks in a digital twin,<br>run-time adaptation and redeployment based on simulations and sensor fusion<br>• Architectures that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification | • Guaranteeing a system's coherence while considering different requirements, different applied solutions, in different phases | |
| | **Topic 4.4:** safety aspects related to HCI | • Minimising the risk of human or machine failures during the operating phases<br>• Ensuring that the human can safely interface with the machine, and also that the machine prevents unsafe operations<br>• Ensuring safety in machine-to-machine interaction | • Develop prototypical use cases where interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support. | |
| **Major Challenge 5:**<br>**Human–systems integration** | **Topic 5.1**: Establish skills and competences needed for engineering and management to jointly perform user, context, and environment assessments for user-requirement requirements generation | • Establish research lighthouses for HSI by establishing examples for effective HSI during product design, development and operation.<br>• Investigate through research the necessary individual knowledge, skills and common practices for effective HSI integration, on individual, process, and organizational level.<br>• Establish stakeholder knowledge, skills, and competence capturing techniques to inform requirements generation | • Bring the results of the short term activities on Topic 5.1 toward policy recommendations for education, development, and practice.<br>• Based on the short term activities on topic 5.1, develop recommendations for appropriate education to promote HSI for socio-technical developments and operations<br>• Based on the short term activities on topic 5.1, develop recommendations for appropriate tools and processes to promote HSI for socio-technical developments and operations | • Based on the medium term recommendations on topic 5.1, develop policies and standards, as well as sponsoring funding schemes for training and educational programs that facilitate HSI in socio-technical developments and operations.<br>• Based on the medium term recommendations on topic 5.1, develop policies and standards, as well as sponsoring excellence and standardization centers to establish common and standardized tools and virtual methods that facilitate HSI in socio-technical developments and operations. |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024-2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| | | | • Based on the short term activities on topic 5.1, develop recommendations on organizational prerequisites to promote HSI for socio-technical developments and operations | • Based on the medium term recommendations on topic 5.1, develop policies and standards for organization certifications of HSI in socio-technical developments and operations. |
| | **Topic 5.2:** Develop simulation and modeling methods for the early integration of Humans and Technologies | • Create tools that allow to link early assessments, holistic design activities, and lifelong product updates to facilitate convergence among researchers, developers, and stakeholders communities<br>• Establish tools to bring stakeholder knowledge, skills, and competence capturing techniques to inform design and development activities<br>• Establish tools to quantify risks of human acceptance and trust<br>• Establish tools to collect and share data bases on relevant human behavioral metrics (safety, acceptance, trust) | • To establish and promote the tools and methods identified during the short term activities for topic 5.2, establish centers of excellence for HSI for socio-technical systems, focusing on promoting early user need and constraint assessments, holistic design activities, and lifelong product updates. The centers of excellence should be harmonized internationally but reflect the idiosyncrasies of individual member states and situations. From the mid-term on, topic 5.2 and topic 5.3 are merged. | • Establish holistic design and systemic thinking education and training in technical and social-sciences academic and non-academic educational programs across Europe and individual member states to promote the knowledge and experience gained the centers of excellence. |
| | **Topic 5.3**: establish multi-disciplinary research and development centers and sandboxes | • Establish interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support.<br>• Establish tools and processes to update stakeholder knowledge, skills, and competence capturing techniques to inform design and development activities | • To establish and promote the tools and methods identified during the short term activities for topic 5.2, establish centers of excellence for HSI for socio-technical systems, focusing on promoting early user need and constraint assessments, holistic design activities, and lifelong product updates. The centers of excellence should be harmonized internationally but reflect the idiosyncrasies of individual member states and situations. From the mid-term on, topic 5.2 and topic 5.3 are merged. | • Establish holistic design and systemic thinking education and training in technical and social-sciences academic and non-academic educational programs across Europe and individual member states to promote the knowledge and experience gained the centers of excellence. |

## 2.4.6 Synergies with other themes

The **Major Challenge** “Ensuring HW quality and reliability” is a key element for any ECS, which is why it can be linked to any application area. It is directly linked to the technology Chapter: **Components, Modules and Systems Integration**. For quality, the novel design of reliability methodologies such as PHM requires direct connection to all cross-sectional technologies (**Edge Computing and Embedded Artificial Intelligence; and Architecture and Design: Methods and Tools**).

The **Major Challenge** “Ensuring dependability in connected software” is strongly linked to the Chapter **Embedded Software and Beyond** as implementations will cover embedded devices to a high degree. It is also linked to the **Connectivity** Chapter and the **Edge Computing and Embedded Artificial Intelligence** Chapter since software must reliably interact remotely, from a system to the edge and to the cloud. From a different perspective, it is also linked to the Chapter on **System of Systems** considering that software-based systems will be integrated over distances.

The **Major Challenges** “Cybersecurity and privacy” and “Safety and resilience” address robust and resilient systems in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be enabled by AI. The outcome of these challenges supports all application chapters, in particular **Health and Wellbeing, Mobility, Digital Industry, Digital Society** and **Agrifood and Natural Resources. Moreover**, they are also linked to the Chapters **Edge Computing and Embedded Artificial Intelligence, Architecture and Design: Methods and Tools, Embedded Software and Beyond and System of Systems**.

## 2.4.7 References

1. *Vital societal functions: services and functions for maintaining the functioning of a society. Societal functions in general: various services and functions, public and private, for the benefit of a population and the functioning of society.* ↩

**3.1**
MOBILITY

**3.2**
ENERGY

**3.3**
DIGITAL INDUSTRY

**3.4**
HEALTH AND WELLBEING

**3.5**
AGRIFOOD AND NATURAL RESOURCES

**3.6**
DIGITAL SOCIETY

# 3

*Strategic Research and Innovation Agenda 2024*

# ECS KEY APPLICATION AREAS

# 3.1

*ECS Key Application Areas*

# MOBILITY

# 3 ECS Key Application Areas

3.1

## Mobility

### 3.1.1 Scope

Mobility is a basic human need and Europe's mobility industry is a key contributor to it. The automotive sector alone provides employment, both direct and indirect, to 13.8 million Europeans, representing 6.1% of total EU employment. 2.6 million people work in the direct manufacturing of motor vehicles, representing 8.5% of EU employment in manufacturing[1]. The automotive sector is also the driver for innovation in many other mobility sectors in Europe, including aerospace, maritime and rail, but also in other sectors as e.g. farming and industry (advanced robotics).

The key enabling technologies of KDT (sensors, semiconductors, embedded AI enabled software in integrated intelligent systems) are essential building blocks for $CO_2$-neutral and energy efficient mobility solutions including the required energy transformation. But as the microelectronics-based computers, sensors, actuators and communication equipment use energy themselves, also more energy- and cost-efficient electronic and optoelectronic components, interconnected intelligent systems and (AI-based) embedded software, often connected to powerful AI-enabled backend cloud systems (e.g. traffic control systems), are necessary.

Therefore, the research scope encompasses the development of energy efficient mobility grade (for automotive, maritime, rail, aerospace, autonomous vehicle up to offroad and smart farming machinery applications) semiconductor. The have to support also AI based applications. The second important part is the development of the necessary middleware and embedded SW applications, which are often part of a cloud to edge continuum. The third equally important part is the development of the necessary development, verification, and validation tools.

### 3.1.2 Application trends and societal benefits

Our mobility is currently in a fundamental phase of change. Mobility is faced with great challenges and at the same time offers enormous potential to help solving essential problems of our world: global warming because of $CO_2$ created by our society (- Green Deal is coping with it -), an ageing society with special needs for easy and accident-free mobility. Therefore, our mobility is subject to a radical ecological (as well as political) change towards its contribution to the European Green Deal as well as towards automated and/or assisted mobility. The interaction with digitisation, urbanisation, connectivity, and individualisation increases the demand for innovative solutions that are based on people's needs like never before. It is important to accelerate the combination of these two developments in a meaningful way in the future.

During the COVID crisis individual transport was largely favoured due to a basic user need, a clean and safe personal environment. Only cars can offer such an environment today. On the other hand, the current energy crisis demands to reduce energy usage also in mobility. Shared and new mobility concepts are going to play an increasingly important role. A major challenge will be to combine this need for individual space in a public or shared mobility environment, which reduces the energy consumption of mobility by more than 20 % compared to today without setting $CO_2$ free or causing more accidents than experienced drivers.

This societal challenge, known as the European Green Deal, is at the forefront of the EU's priority list. As automotive traffic is currently contributing approximately 14% of global $CO_2$ emissions, $CO_2$-neutral mobility requires alternative mobility systems (battery or $H_2$ fuel cell based wherever possible, also synthetic $CO_2$-neutral fuels are necessary in some applications) for automotive vehicles, ships, and flying equipment. It also needs smart energy-production, intermediate energy storage, energy transmission and charging infrastructure. This is an important part of the energy transformation in Europe. Existing infrastructure must be optimised or replaced, wherever possible the use of existing mobility infrastructure is envisioned.

This ECS-SRIA chapter on mobility is aligned with the proposal for the partnership "Towards zero emission road transport" (2Zero) programme by Horizon Europe to achieve carbon-neutrality in road transport by 2050. There are plans to continue and strengthen this cooperation between 2Zero and the ECS community.

The second societal challenge relevant for the mobility domain focuses on the usage of smart perception, safety and automated mobility solutions and services to provide safe and comfortable inclusive mobility that is also suitable for the elderly, as well as people with special needs. Research, development, and innovation (R&D&I) of embedded AI-based software, sensors and electronic components and systems provide the core of automated on- and off-road vehicles, ships, trains, and airplanes. A special focus requires validation of the safety and reliability of the automated mobility systems in all traffic and environmental situations as there are currently no adequate methods and tools available. Digital twin technology will be crucial to evaluate, develop and update/maintain real-life vehicles. Therefore, the ECS-SRIA chapter on mobility is also closely aligned with the proposal for the partnership "Connected, Cooperative and Automated Mobility" (CCAM) under Horizon Europe.

Additional key aspects of the contribution by the ECS domain to the future of mobility are increasing user value, security, privacy protection features, affordability, and human interaction. Particularly in urban areas, intermodality and technologies supporting the shared principles will be crucial.

### 3.1.3 Strategic advantage for the EU

#### 3.1.3.1 Strong contribution to CO2-neutral Mobility

Mobility is at the heart of European lifestyle and its economy. Efficient transportation systems are more important than ever, and also help consolidate the European Union and make it more cohesive. However, the promise of freedom offered by road transport is viewed in sharp contrast to a range of concerns about its effect on safety, health, and the environment. Therefore, transport and mobility systems are in the process of a fundamental transformation towards a vision of sustainable, $CO_2$ emission neutrality that involves efficient, inclusive, and seamless solutions. $CO_2$-neutral mobility is mainly using electrical energy; therefore, mobility is also embedded in the European Energy Transformation. The key digital technologies (ECS) are essential for the transition to $CO_2$-neutral mobility.

### 3.1.3.2 Contribution to inclusive mobility

An additional societal aspect is an **inclusive mobility**: for decades, disabled people have promoted a universal approach to the design of transport systems to make them more accessible and useful for everybody. In view of the Covid-19 pandemic, this focus on human factors of transport innovation is expected to increase; it will particularly call for smart and intelligent and more and more automated mobility systems enabled by ECS.

### 3.1.3.3 Strong contribution to fatality-free mobility

Automation and advanced driver assistance system based on ECS have to contribute to a continuous reduction of fatalities of passengers, and improve transportation by different modalities.

### 3.1.3.4 Protect strong position of European automotive industry and ensure its sovereignty

Mobility is not only a visible expression of **Europe's economic and societal prosperity**, but also an important source of that prosperity. According to Europe's car manufacturers and transporters, the automotive sector employs around twelve million people (approximately 2.6 million directly and close to ten million indirectly), contributing 16% of the EU's GDP[2]. Currently, the transportation sector is undergoing a fundamental and complex transformation across all modes. This position is challenged by large US information technology giants and very aggressive and agile Chinese new automotive companies, which are very successful in fully electrical cars as well as new infotainment systems, advanced driver assistance systems and automated mobility.

### 3.1.3.5 Regain European sovereignty in semiconductors for mobility

Europe is ranked number one in automotive semiconductors. In the automotive value chain, Tier 1's and original equipment manufacturers (OEMs) are also top global players and intend to gain further market share through close collaboration with semiconductor and embedded software leaders in Europe.

The electronics components and systems (ECS) community will contribute substantially to these tasks by using new technologies, components and systems to target the following topics:

- Autonomous vehicles
- Electrified $CO_2$-neutral vehicles
- Over-the-air (OTA) updates
- New mobility concepts to reduce overall energy usage (e.g. mobility as a service)

Electrification of vehicles and development of powertrains for carbon-free energy carriers. Enabling technologies are coming from the European ECS industry – for instance, energy-efficient devices, power electronic components and systems, energy (e.g. battery) management systems, and embedded software solutions for power management.

Automated and autonomous vehicles and coordinated mobility to make traffic more efficient and thus reduce pollution by new electronics architectures, smart and connected sensor systems, AI-based real-time software, higher-performance in-vehicle controllers and networks, as well as connectivity devices and advanced embedded software solutions.

Rapid advances in AI and edge computing will ensure Europe can produce a step change in these areas. Automated and autonomous driving, mobility and logistics are high-profile applications where the use of AI technologies is growing very rapidly, affecting both society and industry directly. The European transport industry is being revolutionised by the introduction of AI (combined with electric vehicles). However, AI applications in transport are very challenging, as they typically involve highly complex environments, a large number of possible situations and real-time, safety- relevant decision-making. Leading IT companies in the US and China in particular are providing a challenge to European industry in these areas, and significant effort will be required to safeguard the leading position of the European automotive industry. Hence the development of digital twins is a crucial element to further develop and update all types of vehicles interacting with the environment, with each other and with the cloud.

Revenues related to automated and autonomous driving and connected cars are expected to boom (see Figure 3.1.1), with safety applications (e.g. automatic collision detection/prevention) expected to reach USD58 billion (up from USD18 billion in 2017), autonomous driving (e.g. distance/park/motorway assistant, pilot, traffic sign detection/ recognition) set to reach USD55 billion (up from USD14 billion in 2017) and connected services expected to reach USD43 billion in 2022 (up from USD21 billion in 2017).

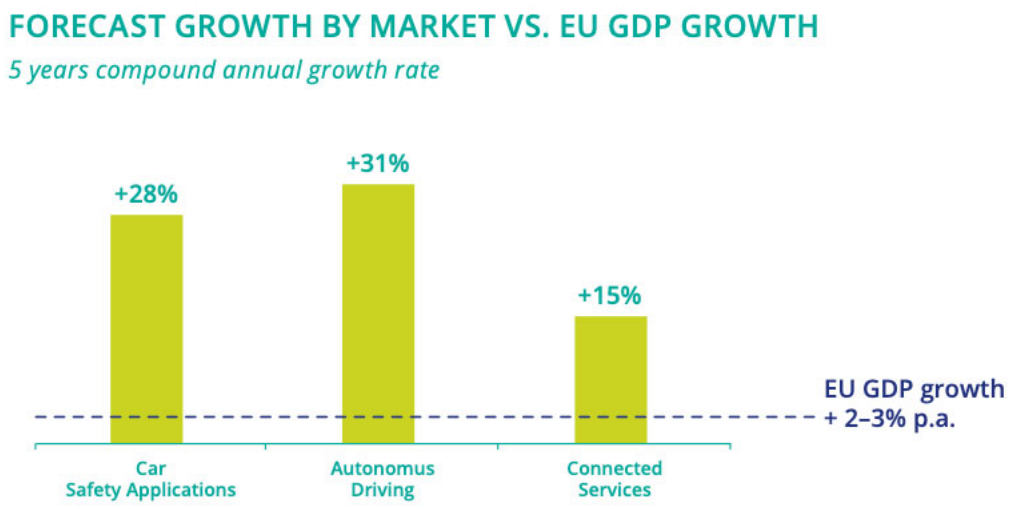


*Figure 3.1.1 - Forecast growth by market vs. EU GDP growth (Source: Goldstein Research)*[3]

There will be a need to more intensively monitor, interact with, and update the car remotely. Software upgrades need to be done over-the-air (OTA). Semiconductors have a shorter lifetime than cars and hence it is needed to predict their end-of-life and to replace them on-time before the car breaks down.

### 3.1.3.6 Regain European sovereignty in embedded software for mobility

All of the four mobility megatrends (electrification, autonomy, connectivity, shared mobility) highly rely on leading-edge software. Especially the car industry needs to face this new software-driven value chain. A typical modern vehicle likely has a software architecture composed of five or more domains (body, chassis, ADAS…), together comprising hundreds of functional components in the car and in the cloud. Currently, OEMs are constructing a complex software architecture with various software providers ending up in a complex scenario with a broad set of development languages, operating systems, and software structures/elements. Up to now no single software platform (middleware) on the market can meet the requirements of CCAM. The domain-based hardware architecture is rapidly evolving towards a zonal architecture, where the software architecture, implementation and the corresponding development environment needs to be compatible. A middleware layer has to separate the hardware layer from the software layer and allow faster time-to-market to standardised interfaces.

The work on the mobility challenges will help to protect the sovereignty in the digital heart of mobility devices (passenger cars, trucks, …). Currently Europe has a leadership in the embedded software in all kinds of vehicles. This is endangered by the push of the big global IT companies into the embedded IT systems of the vehicles. Europe has to protect its leadership in creating a next generation of middleware and operating systems prepared for the significantly increased complexity of CO2-neutral automated and assisted vehicles.

### 3.1.3.7 Convergence of automotive and energy eco-system

Electrified cars are becoming an integral part of the European energy eco-system. Vehicle batteries will be used as intermediate storage for electrical energy (bidirectional charging). Vehicles will even produce electrical energy (photovoltaic panels on car roofs or from heat-pumps), which will be partially send to the grid. This has severe consequences for the requirements of the electrical and software systems in the vehicles. Their operation hours over the intended lifetime of the vehicle are significantly increasing. Up to now, the lifetime for the components of vehicles is about 8000 h, which reflects the hours a typical vehicle is driving. As the vehicle will soon become an integral part of the grid, its total number of operating hours will be the total number of hours per year (both running and connected-to-the-grid time) multiplied by the expected lifetime of the vehicle in years. This means an increase of lifetime of the effected components (as in the bi-directional charging or the necessary embedded control software) by a factor of 5 to 15. This convergence of the automotive and energy eco-system creates also large challenges in the validation. It requires significant use of digital twins in the simulation, as it is not possible to do duration testing over 10 years prior release of a component.

### 3.1.3.8 Digitalisation in maritime industry

The EU’s maritime industry is characterised by high value-added expertise, rapid innovation, rigorous safety standards and a leading position in green technologies. A strategy to further build on these strengths will ensure that the EU retains its competitive position in the global maritime industry and reaps the rewards in terms of jobs and wealth creation.

### 3.1.3.9 Digitalisation in aerospace and rail industry

The current leading position of the European aerospace and rail industry will require a further shift to the greater autonomy of planes, trains and infrastructure, and increased trustworthiness of radio and other communication technologies. Therefore, this shift is also strongly dependent on progress in key digital components and AI-based real-time software.

An important priority of the European Commission, in its Communication on the European Green Deal, is ‘’accelerating the shift to sustainable and smart mobility’’. This will require a strong boost to multimodal transport, automated and connected multimodal mobility, a ramp-up of the deployment of sustainable alternative transport fuels and less polluting transportation, especially in cities.

### 3.1.3.10 New resource optimised mobility modes

New means of transport systems and interaction among different providers (public/private), including other transport modes (multimodal transport for passengers and goods), will be enabled through further development of new and harmonised vehicle-to-everything (V2X), logistics operation software, traffic management devices and guidance systems to enable mobility-as-a-service (MaaS). Easy access to these systems for users will guarantee the highest standards of privacy, to avoid potential impacts caused by the general data protection regulation (GDPR), since information (about origin, destination, financial data, etc) needs to be shared. Software drives tomorrow's mobility and transport innovations.

## 3.1.4 Major Challenges

The Green Deal and digitalisation are significantly influencing the ECS-SRIA in the mobility domain because of one overall objective: the reduction of $CO_2$ and other emissions, and ensuring inclusive, safe and secure mobility for an ageing global society. This leads to five challenges in R&D&I for mobility.

Five Major Challenges have been identified in the mobility domain:

- **Major challenge 1** (climate and energy): Enable $CO_2$-neutral (electrified or sustainable alternative fuels based) mobility (passenger cars, trucks, airplanes, ships, bicycles, tricycles, wheelchairs, drones, and mobile off-road machinery (e.g. for smart farming or mining)) and required energy transformation.
- **Major challenge 2** (digitalisation): Enable affordable, automated, and connected mobility for passengers and freight on road, rail, air, and water.
- **Major challenge 3**: Provide modular, scalable, re-usable, flexible, cloud-based, safe&secure end-to-end **software platforms** (operating system and middleware) able to manage software-defined mobility of the future, sometimes labelled as "**CAR-OS**".
- **Major challenge 4** (validation): Provide tools and methods for validation and certification of safety, security, and comfort of embedded intelligence in mobility (using also digital twins).
- **Major challenge 5** (real-time data handling): Achieve real-time data handling for multimodal mobility and related services.

The results of R&D&I from challenge 1 will be used in green $CO_2$-neutral vehicles of all kinds, some of them integrated into the 2Zero EU partnership, and therefore roadmaps and research programmes are (and will be) aligned. The SRIA of the private public partnership CCAM activities working on "Connected, Cooperative & Automated Mobility" is well aligned with this SRIA in the major challenges 2 to 5 as the key digital components, tools and systems described in this SRIA are essential building blocks in the challenges in CCAM. The outcome of the research on the challenges described here will be used in partial or fully automated vehicles for the CCAM EU programme. Therefore, roadmaps and research programmes are of 2ZERO, CCAM, KDT and BDVA are (and will be) aligned.

### 3.1.4.1 Major Challenge 1: Enable $CO_2$-neutral (electrified or sustainable alternative fuels based) mobility and required energy transformation

#### 3.1.4.1.1 Status, vision and expected outcome

Status, vision, and selected outcome

Worldwide efforts on the regulation of pollution and $CO_2$ emissions are leading to a strong increase in the electrification of vehicles, either with batteries ("battery electric vehicles", BEVs), "hybrid electric vehicles" (HEVs) with petrol or diesel engines or using fuel cells. Possible scenarios developed by BIPE[4] in France are shown in Figure 3.1.2. Depending on the evolution of regulations in particular, the split between the various energy sources could be significantly different between the scenarios in figure 2. However, the most probable scenario is that of the "Green Constraint". But currently there are discussions about bans of fossil fuel engines even as soon as 2035, therefore the data are expected to change.

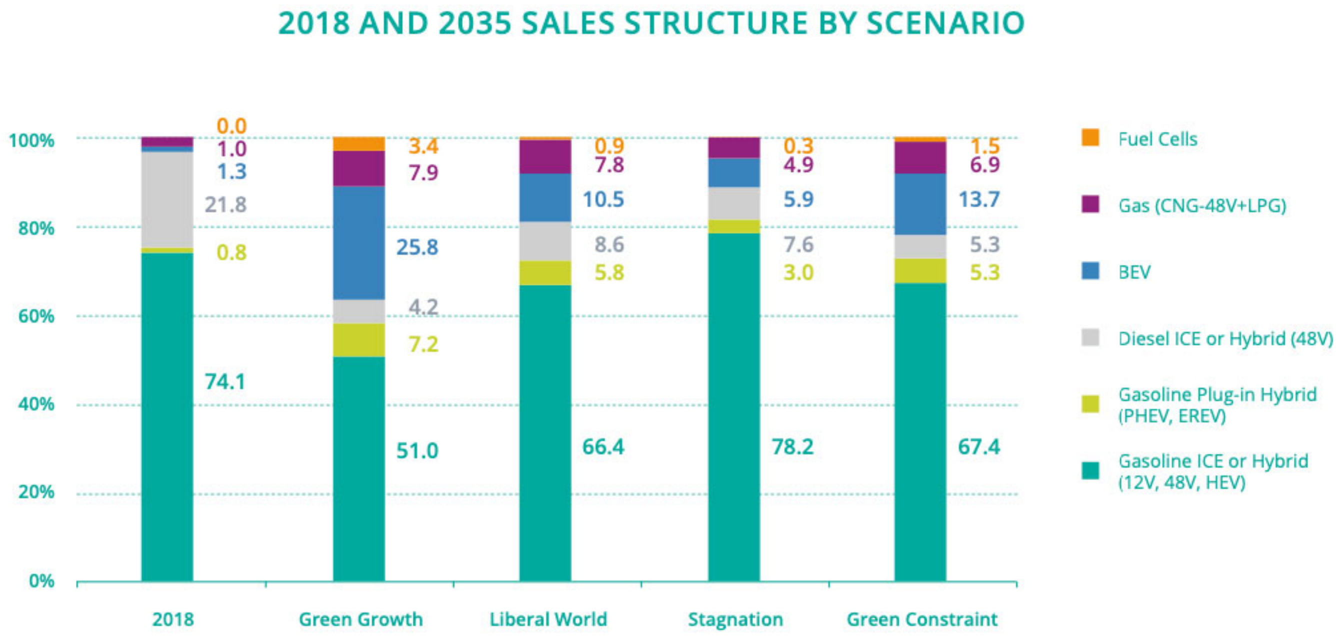


*Figure 3.1.2 - Sales structure of cars 2018 and 2035 (4 scenarios) (Source: PFA France 2018)*

Looking in more detail at the difference between low voltage systems (particularly 48V) and high voltage systems, there are six important observations that can be made:

- All new cars in Europe will be electrified by 2035.
- The proportion of electrified cars in the world will reach about 70%.
- Low-voltage systems will take about 60% of the market, high-voltage will take the rest.
- Around one-third of the market will require on-board chargers for high voltage in the range 400–1000V.
- Fuel cell electric vehicles will still play a significant role in long-haul trucks and trains, as well as in airplanes, ships, and drones by 2035.

The expectation is that the overall electrification scenario will lead to massive changes in the supply chains and the distribution of competences. In the field of power electronics, Europe is now in an excellent position and its industry needs to organise itself to ensure it benefits from the opportunity.

An important aspect in the $CO_2$ reduction is the speed of reduction. Selling new cars with best performance characteristics will only show an effect in the medium and long term. Any solution that improves the existing parc of 250 million cars in the world would have a much higher impact.

FISITA has explained in a recent study how, for example, car sharing, more efficient tires, teleworking and better lubrification could add-up to significant and instantaneous $CO_2$ reductions. In this respect, the electronics industry should regard solutions that support rapid deployment of $CO_2$ reduction initiatives.

### 3.1.4.1.2 Key focus areas

The focus area has the following topics to address:

- Modular, flexible, and scalable platforms and electrical/electronic (E/E) architectures.
- Hardware upgradability.
- Exchange of existing components and systems by higher efficient modules.
- Reconfigurable and adaptable software architectures.
- Software updateability (including over-the-air, OTA).
- On-board technologies (devices, actuators and sensors, virtual sensors).
- Embedded intelligence (AI-powered and AI-enabled intelligence):
    - Control software, real-time capable algorithms.

  - Fault-tolerance, fail-operational concepts.
  - Cognitive vision.
- New control software is required to take full advantage of new solid-state batteries so that they have an extended lifetime, as well as a higher driving range in vehicles. As lifetime is key for batteries used in mobility systems, tools for accelerated lifetime testing, diagnostic systems as well as control systems that can extend the lifetime and limit degradation, are essential for the success of electrified green mobility. New power electronics based on silicon carbide (SiC) and gallium nitride (GaN) devices are needed to ensure energy-efficient operation. AI and model-predictive control algorithms, supported by high-performance, multi-core, real-time operating systems, has to offer the necessary intelligence based on ultra-low power/high-performance control units.
- Similarly, advanced control methods for fuel cell-based vehicles (mainly in trucks and buses) that both minimise degradation and maximise efficiency are crucial. For example, predictive control schemes that take into account forecasts on e.g. route, traffic, weather, etc. are necessary. State-of-health monitoring systems (virtual sensors) as well as adequate new sensors to measure the operating conditions within fuel cells without negatively influencing their operation, are required.
- For both electric battery and fuel cell-based mobility, new safety concepts using (AI-based) IoT diagnostics must ensure the safety of these systems, especially in accident situations.
- Low environment impact of new technologies in terms of energy consumption at production, deployment, use and end of life treatment.
- Reduction of sensible materials such as rare earth materials.
- Recyclability.
- Efficient and fast charging and filling of alternative energy into green vehicles is another critical research topic.
- The conversion of renewable energy into green energy, as electricity stored in vehicles or $H_2$ or alternative fuels, also needs efficient electronics with real-time embedded software communication with the power grid to minimise the need of new charging/filling infrastructure, which is one of the cost drivers limiting the speedy success of green mobility.
- Smart Battery: with the batteries in electric vehicles being the most expensive and life-time critical parts, future battery systems will be equipped with sensing technology, intelligence, and communication systems to monitor their own health and record their lifetime dataset. This enables better usage of the batteries as well as optimised second life concepts.
- Power electronics (fast-switching elements, wide bandgap materials, low power, etc.).
- Predictive diagnosis and maintenance (including recovery strategies, fault detection and localisation, surveillance sensors, etc.).
- Cloud/edge/fog processing approaches.
- Distributed logistics systems for smart farming, movers and shuttles.
- Standards, including communication and interoperability standards, electromagnetic spectrum, and bandwidth management, charging units, car access systems, etc.
- Reliable and human-like perception systems.
- Tailored ECS-enabled solutions for disabled people (supporting robots, smart wheelchairs, etc).
- Proof of robustness and trustworthiness of architectures and quantification of the operational risks.
- Collaborative and self-organised multi-agent systems, e.g. in logistics applications also covering cooperation between land and air vehicles.
- Bio-inspired transport solutions and systems.

Digital innovation is key to ensuring inclusive mobility for persons and goods by providing mobility access to all, with a focus on special needs, by reaching 90% of the EU population compared to the current 60%. As targeted by CCAM, this can be achieved through assisted vehicles by 2050.

By 2050, 67% of the population is expected to live in urban areas. As cities become bigger and smarter, this trend will lead to new opportunities for tailored and specialised vehicle design specific to urban users, including the needs and operations of commuters, as well as ride-hailing and last-mile delivery.

New vehicle concepts and ECS-enabled architectures should lead to flexibility, scalability, and modularity - while featuring safety, security, and reliability - to ensure urban-readiness (appropriate range, compatibility with charging infrastructures, ease of parking and operations, etc) in all kinds of urban and suburban areas, most likely with different implementation levels of infrastructure and smart technologies. Additionally, it is assumed that these vehicles will not have to be designed for high-speed operation and long range and can easily be charged sufficiently fast and comfortably to meet the daily needs of urban and suburban mobility usage scenarios. This aspect may also include sharing concepts, and consideration should also be given to use by the elderly and disabled.

Another important aspect is the need for reliable and efficient wireless communication technology combined with different types of sensing systems to achieve efficient traffic, and increase safety as well as reduce fatalities. This further sets requirements on components and systems for wireless communication to achieve ultra-high reliability and resilience as well as to meet challenging performance and latency demands.

The challenge targets the following vehicle categories:

- Passenger cars (including light four- wheelers, M1/M2 category).
- Trucks (including power-driven vehicles having at least four wheels used for the carriage of goods (N1), agricultural and forestry tractors, and non-road mobile machinery (T)).
- Ships.
- Airplanes.
- Motor vehicles with less than four wheels (L category).
- Off-road vehicles (G).
- All kind of unmanned air vehicles (such as drones).
- All kind of manned light air vehicles.
- Special-purpose light vehicles (air, land, water).

The developments described above ask for innovative mobility solutions in the years to come, affecting European society::

- Urban personal, light personal and freight mobility (including innovative micro-vehicle designs suitable for urban/suburban commuters' needs, with the option for usage within shared mobility schemes. Such micro-vehicles would also be capable of interfacing with urban collective transport systems (i.e. easy access to buses, trams, and trains for last-mile transfers to achieve full intramodality)).
- Light and flexible multi-passenger vehicles (e.g. collective, or individual, owned or shared up to M1 category) with robust safety measures for passengers and vulnerable road users, and including specific features to facilitate shared use such as autonomous-capable vehicles with automated relocation to charging points or areas with insufficient vehicle density.
- Log-haul and right-sized vehicles and tailored ECS for commercial uses, such as for long distance, last-/first-mile delivery, construction and maintenance support, which are suitable for urban scenarios.
- Connected and automated mobile machinery to optimise harvesting and reduce accidents.

### 3.1.4.2 Major Challenge 2: Enable affordable, automated, and connected mobility for passengers and freight on or off road, rail, air and water

#### 3.1.4.2.1 Status, vision, and selected outcome

Europe envisions fatality-free transportation as well as seamless mobility choices for its citizens, particularly in view of the aging society. Moreover, the transport industry in Europe in general aims to maintain its leading position by offering sustainable solutions for safe and green mobility across all transportation domains – automotive, avionics, aerospace, maritime (over water as well as under water transport) and rail. Europe's strength lies in its established expertise in developing complex electronic components, cyber-physical systems, and embedded intelligence. However, hurdles related to autonomy, complexity, safety, availability, controllability, economy, and comfort need tackling as automation increases.

The overall vision is to achieve always-connected, safe and secure, cooperative and automated transportation systems using highly reliable and affordable European-made electronic components and systems. These systems will also incorporate new human-machine interaction technologies.

For the road sector, the key objectives are (a) to reduce the number of road fatalities and accidents caused by human error to zero by 2050, (b) to ensure automated transport introduces no additional road fatalities, and (c) to decrease validation costs down to 50% of development costs from the current 70–80%. Key Digital Technologies are crucial for achieving these goals and supporting the ambitions of the Horizon Europe Partnership on Connected, Cooperative and Automated Mobility (CCAM). Collaborations in and across industrial domains, learning from operational field data, and joint strategic actions are essential. No single entity can singlehandedly manage these significant R&D efforts.

For waterborne transport, as automation progresses ships will become fully connected, globally. Remote vessel monitoring is already possible, allowing for condition-based maintenance. Building on increasing onboard automation, the remote operation of vessels will become possible, eventually moving towards full autonomy for vessels. The wider use of unmanned autonomous vessels (UAVs) – either aerial, underwater or on the surface – will increase the flexibility and energy efficiency of operations.

For avionics and aeronautics, automation is paving the way for more efficient flight management, reducing pilot workload, and enhancing predictive maintenance, which collectively promises safer and more efficient air travel. Additionally, Urban Air Mobility (UAM) is revolutionizing cityscapes, with automation enabling flying taxis and drone deliveries, presenting a transformative solution to urban congestion, and offering a new dimension to urban transport.

For the rail sector, automation is driving the development of driverless trains, optimizing track usage, enhancing scheduling accuracy, and ensuring safer and more punctual journeys for passengers.

Connected, cooperative and ultimately automated mobility will play a central role in shaping our future lives. ECS will enable different levels of partial, conditional, highly and fully automated transportation, posing new challenges for traffic safety and security in mixed scenarios where vehicles with different automation levels coexist with non-automated vehicles. Both stepwise automation ("conversion design") and full automation (Society of Automotive Engineers, SAE, level 5: "purpose design", e.g. a people mover in a structured environment), have been developed to the prototype level and are being deployed in field-operation tests right now. Nonetheless, these solutions need to be further explored and improved towards safe and reliable capabilities in extended operational design domains. Additionally, cross-fertilisation with other industrial domains such as Industry 4.0 and evolving communication technologies (5G/6G) is essential.

As the proportion of electronics and software, considered as a percentage of the total construction cost of a vehicle, increases, so does the demand for the safe, secure, reliable, and unhackable operation of these systems. In addition, privacy protection is paramount for car owners and drivers/operators. This demands robust and fail-operational technologies that deliver intrinsically safe operation and dependable fall-back position from component to subsystem, and provides a solution for problems in interaction with the cloud. Also, multi-core-based platforms and sensing devices, combining advanced sensing in harsh conditions, novel micro- and nano-electronics sensors, advanced sensor fusion and innovative in-vehicle network technologie are neededs.

Key elements of ECS for cars that need to be developed are shown in Figure 3.1.3.

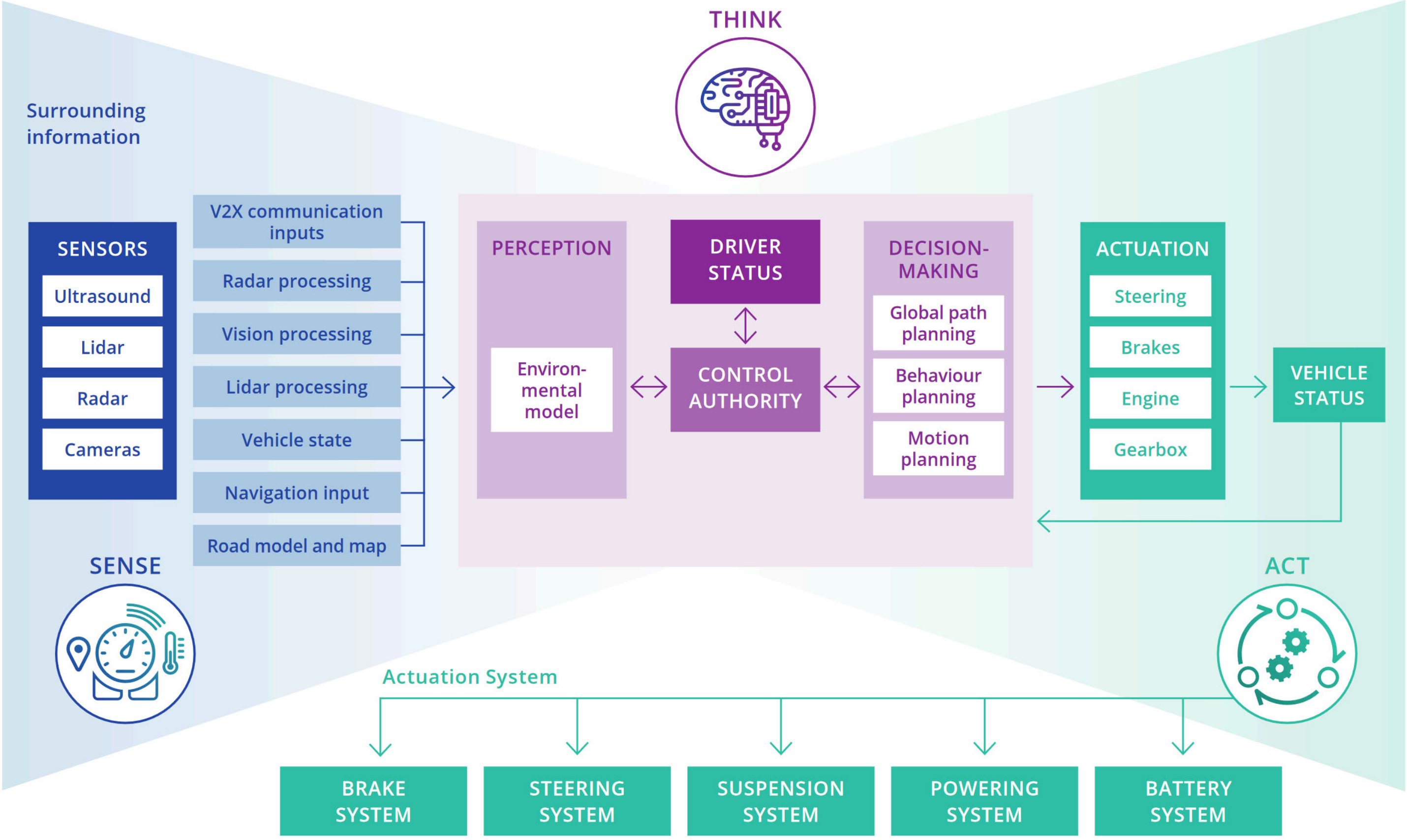


*Figure 3.1.3 - ECS-based components of automated vehicle*

### 3.1.4.2.2 Key focus areas

The following research, development and innovations areas and their subtopics have been identified:

- Dependable and affordable environment perception and localisation sensors, and V2X communication. Attention should be paid to sensor interference, more in particular the robustness of sensors to environmental conditions, to interference by other sensors and to malicious interference.
- Integrated sensing and communication systems to further evolve towards fully automated transport and safeguarding VRU's (Vulnerable Road Users) in all type of traffic situations.
- Centralised service/function-oriented hardware/software architectures, including open APIs, for road vehicles, ships, trains that are supported by the cloud and edge computing via 5/6G.
- Dependable and reconfigurable hardware and software, including remote access and Over-The-Air (OTA) software upgrades.
- Hardware and software platforms for control and higher performance in-vehicle networking (up to 25Gbit/s) units for automated mobility and transportation (including support for AI), for example the usage and adaptation of IoT integration platforms, also for automated and connected

environmentally friendly vehicles.

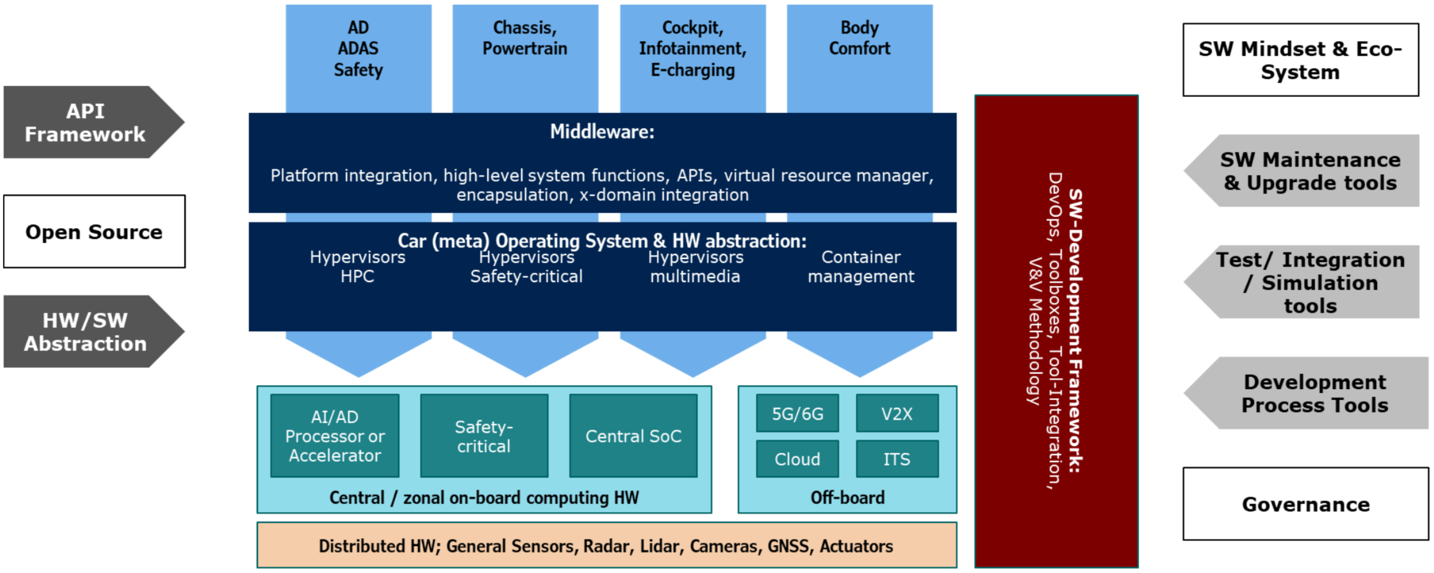
- New developments towards higher performance and efficiency: These are also required to ensure the reliability and safety of the power electronic components and systems for the drivetrain and charging systems, as well as for steering, breaking/suspension/air condition control in automobiles, trains, ships, and flying equipment.
- Trustworthiness of vehicles' data.
- Interaction between humans and vehicles.
- Active safety systems.
- Advanced AI-based and predictive control methods to create new active safety paradigms for the next generation of automated vehicles, e.g. to operate beyond the boundaries typical for the current generation of stability controllers and chassis control systems, when this is needed to prevent road accidents. This also implies a redefinition of the software architecture to integrate the chassis control and driving automation functions. The current generation of chassis control systems – which will be used in the first generation of automated vehicles – is designed to keep the vehicles within limits that are desirable for human drivers, but further research is required to assess the new active safety options (e.g. race driving techniques to prevent crashes in emergency conditions) enabled by driving automation.
- V2X-based chassis control systems, e.g. vehicle stability controllers using the road curvature profile ahead, and other infrastructure-related information, e.g. tire-road friction information from preceding vehicles.
- Multi-functional cross-domain and preview-based control software implementations, e.g. powertrain and brake-by-wire controllers concurrently managing energy efficiency, active safety, and comfort aspects (e.g. powertrain torque distribution to induce desirable pitch in braking, compensation of the longitudinal acceleration oscillations caused by road irregularities through road preview-based control of the powertrain torque).
- Vehicle hardware/software and robotics to improve comfort in parallel with safety.
- (Predictive) health monitoring and lifetime analysis for the perception and control systems (including all required sensors, V2X systems and localisation systems) and AI components of (highly) automated vehicles used in the operational phase.
- Connected maritime systems and automated transport.
- Smart and autonomous ships.
- Driverless trains.

These requirements result in completely new hardware and software architectures for the control systems due to exploding sensor data volumes, as well as new power saving hardware and software components. This requires a new decoupling from hardware with drivers and operating system, from the application components, adaptive AI-based routing and control algorithms, multimedia components and many more, and at the same time a co-designed process of interface developments. Therefore, the Major Challenge 4 was introduced to create a common middleware architecture and implementation.

### 3.1.4.3 Major Challenge 3: Modular, scalable, re-usable, flexible, cloud-based, safe&secure end-to-end software and hardware platform for the software-defined vehicle of the future

#### 3.1.4.3.1 Status, vision and expected outcome

Today's mainly hardware-defined cars are rapidly transforming into software-defined transportation platforms. Currently, OEMs and their suppliers are developing automotive software modules in isolation, ending up in a complex software architecture which does not scale at all. The following figure (McKinsey and Company) illustrates the state-of-the-art in how proprietary platforms are built at present. Even though integration among different domains and vehicle systems is essential to unlock new use cases, companies are currently missing an end-to-end platform to easily connect everything together.



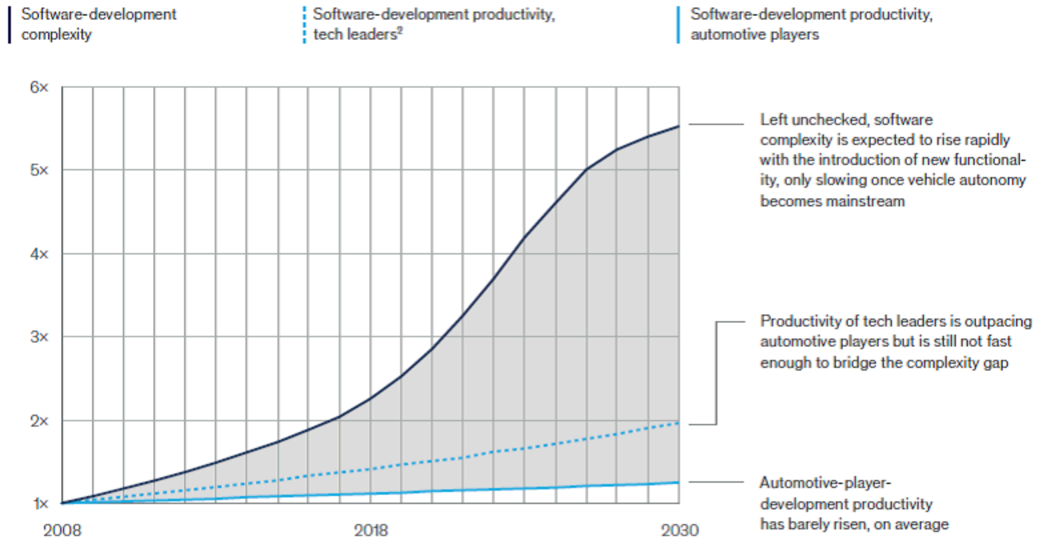
*Source: European Commission DG Connect, Unit E.4, SDV Sherpa Governance Group 2023-07-17)*

*Figure 3.1.4 - Layer structure of Software Defined Vehicle building blocks.*

Currently, automotive software developers working on different software stacks across a vehicle do not coordinate their activities on a regular basis. Furthermore, it is difficult to align software updates and patches across modules. Because of the rapid transformation to software-defined vehicles (driven by new vehicle functions, features, properties), the automotive industry is facing a widening and unsustainable gap between software complexity and productivity (see figure 3.1.5 below). To succeed in this dynamically changing environment and to be globally competitive, companies need to minimise (or at least limit) the complexity by reducing the effort required to develop and maintain software. Consequently, the current software operating model needs to be revisited in terms of:

- Architecture, design, requirements.
- Development methodologies (e.g. agile-at-scale, or fundamental changes in development and software testing).
- Software performance management, toolchain infrastructure.
- Where software is developed within the organisation, including locations, and partnerships involved.

**Relative growth over time, for automotive features,**[1] indexed, 1 = 2008



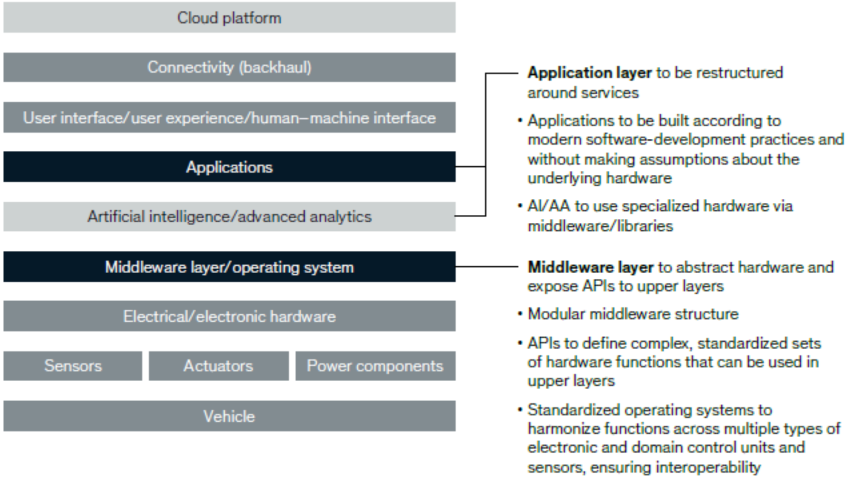
[1] Analysis of >200 software-development projects from OEMs and from tier-1 and tier-2 suppliers.
[2] Top-performing quartile of technology companies.

Source: Numetrics by McKinsey

*Figure 3.1.5 - Gap between software complexity and productivity.*

Ultimately, an end-to-end software platform, consisting of virtualisation, operating system and a middleware layer with standardised interfaces abstracting the hardware layer for the application and function software layer is strongly needed to be able to manage the rising software complexity and to develop future vehicles in an effective and efficient manner. Software should be truly integrated end to end, software modules should be developed on a common code base, and a primary robust operating system should be able to cover all major systems throughout the vehicle.

### 3.1.4.3.2 Key focus areas



**Application layer** to be restructured around services

- Applications to be built according to modern software-development practices and without making assumptions about the underlying hardware
- AI/AA to use specialized hardware via middleware/libraries

**Middleware layer** to abstract hardware and expose APIs to upper layers

- Modular middleware structure
- APIs to define complex, standardized sets of hardware functions that can be used in upper layers
- Standardized operating systems to harmonize functions across multiple types of electronic and domain control units and sensors, ensuring interoperability

*Figure 3.1.6 - Example of architecture decoupling HW and SW and supporting the vehicle middleware layer.*

The following topics have been identified for essential research:

- Development of a scalable, cloud-capable, and modular target architecture that supports decoupling of hardware and software and features a strong middleware layer (see illustrative example, figure 3.1.6). The target platform (middleware) to be developed needs to support current and future operating systems (proprietary, open-source) and also different E/E architectures (domain-oriented, zone-oriented etc.).
- Development of a neutral SDK (cf., the smartphone world before and after the iPhone of 2007) which allows any software application developer to develop and test independently of hardware and operating system.
- Abstraction of the complexity of underlying hardware, middleware, kernel, interfaces, and drivers into simple to use and to re-use, robust, safe&secure APIs.
- Support of safety and security according to automotive standards (safety-criticality is the main difference to the smartphone and consumer electronics market).
- New software development methodologies (e.g. agile-at-scale).
- Eventually, the targeted software platform should basically fulfil and feature:
  - ROS1 and ROS2 compatibility.
  - Hardware SOC abstraction, runs on x86 and ARM.
  - freedom of choice of SOC.
  - Middleware abstraction simplifies the use of complex middleware interfaces.
  - Hard real-time execution and real-time logging of data.
  - Fully deterministic software execution.
  - System safety enabled through managed nodes with lifecycle management.
  - System security through process-level security, encryption, authentication.
  - Support for automotive hardware, i.e., ECUs and automotive sensors.
  - Functional safety certification (ISO 26262, SEooC, up to ASIL D).
  - Appropriate testing methods, e.g. condition coverage or integration tests.

- Development environment, tools, toolchains.
- Complete and integrated solution for both intra- and inter-ECU communication.
- Integration of common frameworks such as AUTOSAR, Apex.OS and others.
- Simple to integrate into custom frameworks.
- Support for today's most relevant protocols for automotive ethernet.
- Capable to handle large amounts of data efficiently.
- High-performance communication with low runtime consumption
- Ensuring compatibility to SIMPL[5] (cloud-to-edge federations and data spaces made simple). SIMPL is the smart middleware that will enable cloud-to-edge federations and support all major data initiatives funded by the European Commission, such as common European data spaces.

### 3.1.4.4 **Major Challenge 4: Provide tools and methods for validation and certification of safety, security, and comfort of embedded intelligence in mobility**

#### 3.1.4.4.1 Status, vision and expected outcome

To achieve the EU-wide goal of zero fatalities by 2050, active safety systems and automated vehicles are necessary (the term “vehicle” here covers mobility systems on land, water and in the air: cars, trains, ships, airplanes, smart farming and other off-road vehicles). Although several technology demonstrators for highly automated vehicles already exist, there is a severe lack of cost-effective, commonly accepted verification & validation (V&V) methods and tools. Winner et al. predict that more than 400 million km of road driving would be required to statistically prove that an automated vehicle is as safe as a manually driven one, implying that a proven-in-use certification by performing physical tests on the road is no longer feasible.

This lack of effectively applicable V&V methods has created a major barrier for the market introduction of these systems. The development and use of Digital Twins is becoming a cornerstone for future development and updates of this type of complex automated systems, interacting with the cloud. Meanwhile many experts in Europe, as well as in many other countries of the world, work together under the guidance of UN/ECE to create standards for the approval of ADAS and AD functions in mobility. The draft of the Regulation (EU) 2019/2144 for ADAS functions is approved and contains definitions for the expected functionality of many ADAS functions, as well as first indications of how to prove them. The associated ADAS and AD functions are Lane Departure Warning System, Advanced Emergency Braking on Heavy Duty Vehicles, Speed Limitation Devices, Reversing Detection, Pedestrian and Cyclist Collision Warning, Blind Spot Information System, Emergency Lane Keeping System, Advanced Emergency Braking on Light Duty Vehicles, Protection of Vehicles against Cyber Attack, Intelligent Speed Assistance, Emergency Stop Signal, Alcohol Interlock Installation Facilitation, Driver Drowsiness and Attention Warning, Driver Availability Monitoring System, Event Data Recorder, Systems to replace driver's control; systems to provide the vehicle with information on state of the vehicle’s surrounding area and Platooning.

The main challenge is the tight interaction of these safety-critical automated systems with their environment. These interactions get more complex the higher the automation level gets. This means that not only the correct functioning of the automated cyber-physical mobility system itself needs to be tested, but also its correct reaction to the behaviour and specifics of its surroundings. This leads to a huge number of potential scenarios that every automated mobility solution will have to handle in a safe way. It is important to take not only the commonly occurring scenarios encountered by the mobility systems as vehicles, trucks, airplanes, ships etc. in account, but also the occurrence of safety-critical events during these scenarios. Many of these safety-critical events fortunately do occur only seldom, but that makes it even more difficult to test the correct reactions of the automation systems in these situations.

Many highly automated cyber-physical systems have adopted machine learning (ML) and AI to enable autonomous decision-making and render applications smart. While the use of ML and AI components offers great promise for improving our everyday lives in many, sometimes unimaginable, ways, it also brings a host of very difficult verification, validation and certification challenges in the context of safety- critical applications. The opacity of ML/AI components requires the development of completely new V&V techniques, and to accordingly extend existing V&V methodologies. It is important to not only secure stable solutions based on ML, but also determine how to exploit increased learning based on new data, and to update existing vehicles with updated algorithms using the additional learning from new data, while guaranteeing no side-effects.

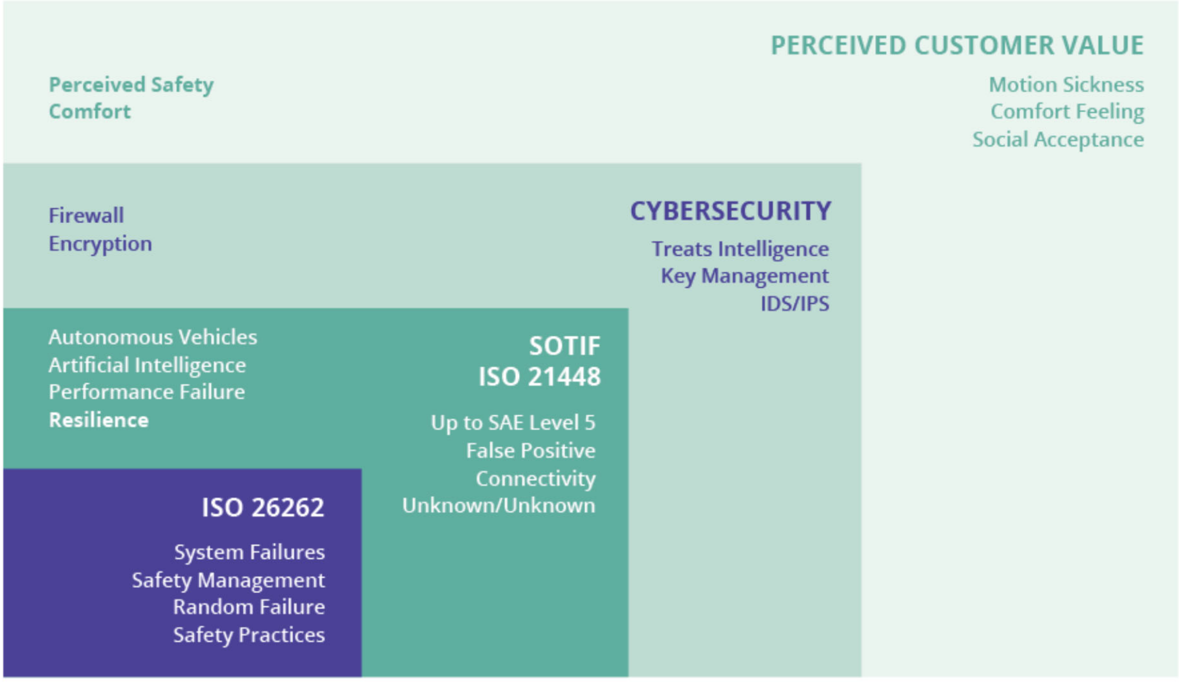


*Figure 3.1.7 - Validation framework for automated vehicles (Source: AVL List GmbH)*

Modern highly automated cyber-physical systems increasingly dynamically evolve after their deployment, and OTA updates and upgrades are becoming necessary in such systems. This requires a tight integration of the analysis of data from the field and fast software changes with subsequent over-the-air updates of the vehicle in the field, and ensure that any safety and/or security relevant problems identified in vehicles in the field are solved as soon as possible at all vehicles in the field. This requires new methods and trustable tools for these updates and upgrades, together with the respective re-verification and re-certification approaches, necessary to avoid negative impacts on both safety and security. These verification and validation tests must be integrated in fully automated CI/CD pipelines.

Automation functions of vehicles rely on environment sensors, such as cameras, lidar, radar and ultrasonic sensors, as well as communication to other vehicles or infrastructures. As these safety- relevant components may degrade over time or be exposed to cyber-threats, accelerated reliability and cybersecurity test methods are required. This will need further diagnostic devices to check the reliability of hardware, sensors, and their software.

The role of the driver and any additional passengers in an automated vehicle is completely changing, and therefore new test methods and tools are necessary to ensure comfort and perceived safety (societal acceptance). These are already in the early development phases in terms of new functionality and their safety.

Many of the above issues are mentioned in existing or upcoming automotive standards for cyber-physical systems – for example, Safety of Intended Functionality (SOTIF), ISO 26262 and UL4600 (see Fig. 7). As none of these standards are mature enough to certify fully automated vehicles with reasonable effort, close cooperation between the standardisation committees and the research consortia will be necessary.

The expected outcome is twofold:

- Digital innovation to increase road safety as specified in the CCAM programme: reduce the number of road fatalities and accidents caused by human errors to zero by 2050, as well as ensuring that no additional road fatalities are introduced by automated transport.
- Reduce validation costs down from the current two-to-five times of the implementation of automation functions in mobility by 60–80%.

### 3.1.4.4.2 Key focus areas

To ensure the safety, security and comfort of automated mobility systems consisting of embedded AI-based software, sensors, and actuators, as well as processing platforms in vehicles, ships, trains, airplanes and off- road vehicles, several verification, validation, and certification toolchains are necessary. These should ensure the safety, reliability, security and comfort for passengers and the surrounding traffic participants based on costs that do not exceed those of the design and implementation of the following functions:

- Verification of components of automated mobility systems as environment sensors/ communication systems, perception systems, environment awareness, route planning and actuator systems, diagnostics devices and black box monitoring systems. A special case here is the use of consumer-grade components in vehicle automation. Test concepts and tools have to be developed on several levels:
  - Perception system tests focusing on an adequate functionality of sensors and the fusion of several sensor inputs.

    - Manouver planning route decision and track control systems testing.
    - Complete automated vehicle, airplane, ship etc., in the defined operating environments (ODDs).
    - Correct and secure communication with other traffic participants and/or traffic operators.
- Validation of complete automated vehicles to perform safely and securely, and to provide comfort for passengers as well as other traffic participants in the specified operation design domain (geolocation area, weather conditions, road/sea/air conditions, etc.).
- Validation of the reliability of all components as well as their interaction as a complete automated cyber-physical system in the specified operation period.
- Validation of the safety, security, reliability, and comfort for the deployment of OTA update packages for automated on-road or off-road vehicles, trains, ships, and airplanes.
- Verification of the completeness and reliability of training datasets for machine-learning and AI algorithms used in automated cyber-physical systems.
- Validation of the accuracy of simulation models in the specified operational design domain (ODD) used in virtual validation toolchains.
- Development of Digital Twins (for example for vehicles, trucks, drones, ships, airplanes, sensors, pedestrians, environment etc.) for validation of new concepts, verification of Car-2-Cloud interactions and preparation of updates of automated vehicles.

Validation toolchains, their components and underlying methods should lead to safe, reliable, and secure argumentation, describing why the performed tests resulted in the estimated residual risk for automated cyber-physical systems for on-road or off-road vehicles, ships, trains, and airplanes. Optimisation methods can be used to balance multiple design objectives – e.g. ensure that the residual risk remains below a certain limit (such as stipulated by regulatory bodies) while meeting financial design targets. The verification, validation and certification tools and methods may be used for cyber-physical systems with different levels of automation.

A special focus is on the verification, validation and certification of embedded AI-based systems, and the required training data for the respective machine-learning algorithms. Ecosystems for the creation and maintenance of reliable labelled data are envisioned. To integrate with different legacy systems, eco-systems supporting open platforms are required.

Virtual validation, or more concretely scenario-based virtual validation, is considered a cornerstone for the verification, validation, and certification of vehicles. Two aspects are essential here: (i) scenarios representing the most relevant situations; and (ii) reliable simulation models.

Scenarios may be derived from requirements of safety analyses, extracted from naturalistic driving, or synthetically created using gaming theory-based methods with a defined relevance. Statistical safety evidence from scenario-based verification and validation derived from naturalistic driving is needed. Also, here the establishment for open platforms and ecosystems for the creation and maintenance of reliable scenarios is encouraged. The definition of performance (safety, security, reliability, and comfort) indicators for different automation functions and SAE levels (in the case of road vehicles) is necessary. Again, ecosystems to share these data are useful.

Reliable simulation models for environmental sensors, vehicles, drivers and traffic participants, as well as traffic, are vital. The development of these models, and the corresponding test systems, are essential. To test safety-critical scenarios using real vehicles in a safe environment requires the creation of stimulators for the different environmental sensors under different weather, traffic and road conditions. The verification, validation and certification of vehicles will be carried out with a combination of virtual test environments using model-in-the-loop (MIL) and software-in-the-loop (SIL) in the cloud with massive parallel processing in order to allow for testing of very high numbers of scenarios in combination with different critical events and varying ODD conditions as sun, rain, fog, snow etc., mixed virtual/real environments (vehicle-in-the-loop (VIL), and hardware-in-the-loop (HIL)), as well as a proving ground for real-world public road testing. Road testing will result in amounts of data larger than 20 TB per hour per vehicle, and therefore adequate data acquisition, management and (cloud or on-premises) evaluation systems capable of handling the specific data types of the sensors are critical (although these do not exist yet). Additionally, OTA data collection from in-use operations is required to continuously collect unknown scenarios that can be fed back into development to improve the quality of the systems.

Additional challenges covering this topic can also be found in Chapter 2.3 (Architecture and Design: Methods and Tools) and Chapter 2.4 (Quality, Reliability, Safety and Cybersecurity) of this SRIA.

### 3.1.4.5 Major Challenge 5: Achieve real-time data handling for multimodal mobility and related services

#### 3.1.4.5.1 Status, vision and expected outcome

To enhance citizens' health and quality of life, European municipalities are progressively restricting cars with conventional powertrains from city centres in favor of sustainable urban land use. At the same time, in view of the rising demand for individual accessibility, flexible transit and fast delivery, the EU emphasises the importance of multimodality in its transport strategy. This approach combines collective and individual solutions, ranging from micro-mobility, such as e-scooters via car-sharing and ride-pooling, right up to long-haul transport systems through common hubs, platforms and systems for booking, customer services and payment. In the future, Europe will aim for diversity beyond road transport, exploring high-speed rail or electric aircraft. However, challenges persist, including limited peak capacities, missing last-mile connections and isolated mobility-as-a-service system. These bottlenecks impede efforts to decrease travel times, streamline supply chains, and reduce single occupancy trips. Sharing services will play a pivotal role in enhancing public transport flexibility, complemented by innovative solutions like taxi and delivery drones or guided transport systems such as hyperloop solutions that can be expected to fill the gaps in the time, cost, and green environment map.

Recent global events such as natural disasters have spotlighted potential vulnerabilities in this vision. Highly connected and infrastructure-based mobility solutions show limited resilience against flooding and wildfires. It is a pressing priority for mobility service providers to develop and deploy transportation that is both flexible and safe, merging the convenience of multimodality with stringent health and environmental standards while being $CO_2$- and emission-neutral at the same time. The same applies to making autarkic heavy vehicles and machinery for rescue and clean-up operations zero-emission. In another sense, multimodal mobility could also mean putting services and deliveries on wheels, which so far would have required people to travel to places, even if they are elderly or disabled. Having robotic functionality, ad-hoc networking capabilities and a battery as mobile electricity source on a tractor might provide just the right level of resilience that will be needed for future emergencies, and make full use of the opportunities of automation, connectivity, and electrification in a new way.

As pointed out by the EU-funded Coordination and Support Action "Action Plan for the Future of Mobility in Europe"[6], the vision of a truly integrated and seamless transport system for people and freight must be developed and implemented, and the full potential of transformative technologies has to be exploited. This can only be achieved if user-centredness, cross-modality and technology transfer become the focus of efforts for all stakeholders in transport.

## 3.1.4.5.2 Key focus areas

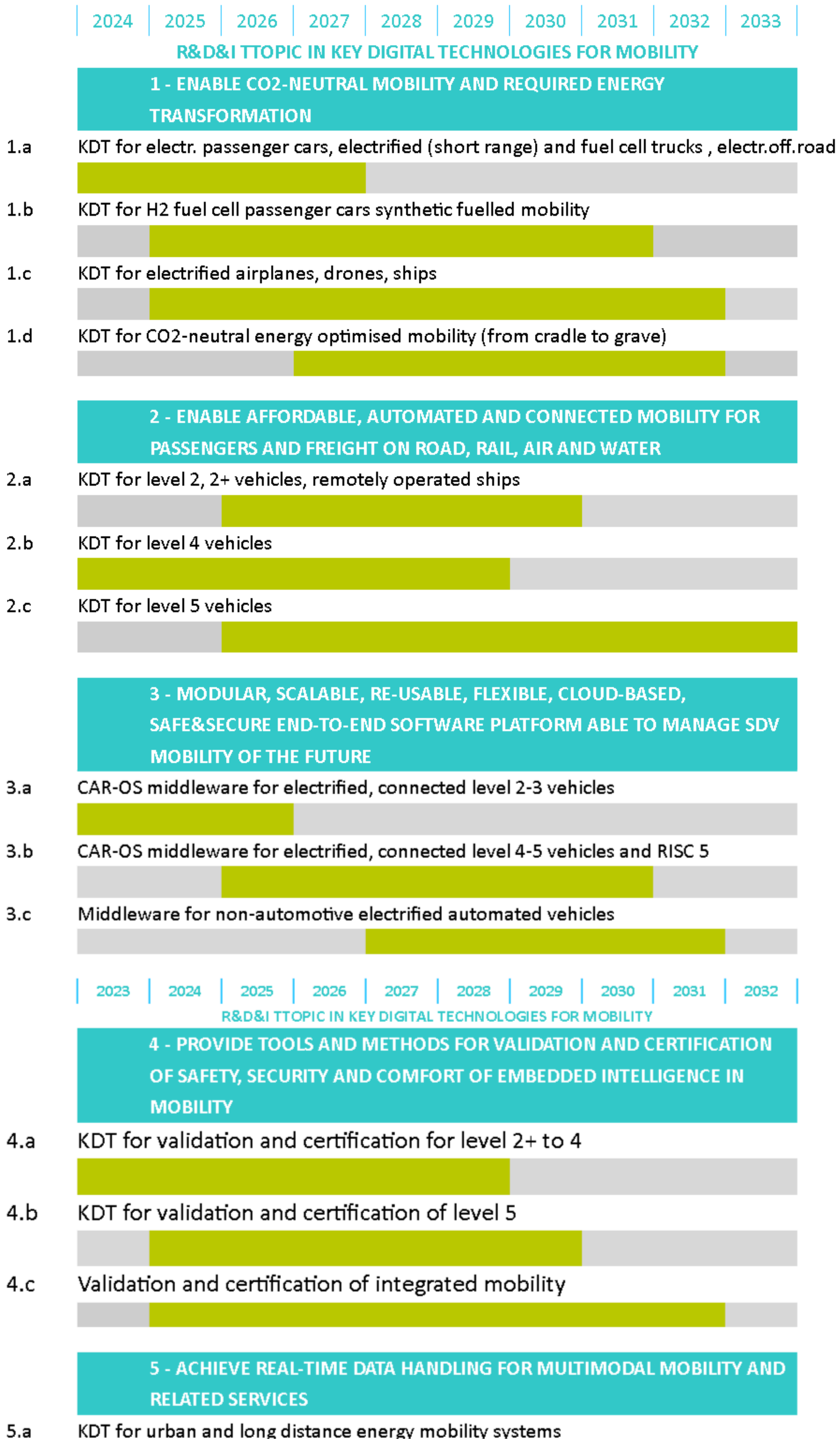
- Design a low/zero-emission, safe and accessible transport system tailored to user needs expectations, defining user profiles and mobility patterns, and identifying technology options.
- Enable mobility everywhere for everyone through the technological development of, for example, sensors, AI, machine learning, predictive maintenance, safe and secure vehicle software, and electronics.
- Enhance efficiency and capacity in rail projects for automated maintenance and transfer of goods between modes.
- Create intelligent decision-support systems for passengers and transport operators that enable smart travel demand management.
- Achieve real-time data handling for multimodal mobility and related services.
- Develop convenient sharing concepts through automated maintenance of vehicles and define approaches for implementation.
- Develop a framework for cybersecurity in passenger and goods transport across all modes and provide IT connectivity that allows plug-and-play data sharing.
- Increase data security and privacy in authentication and payment processes for mobility services (through the concepts of trustee roles, blockchain, etc.), and support the respective initiatives.
- Employ robots, drones, and shared public transport services or logistics.
- Multimodal navigation systems providing travellers with efficient, safe, and healthy transfer options.
- Development of modular mobility platforms for the on-site provision of services and goods delivery.
- Integrate cross-modal hubs and interfaces into the urban structure and connect them by harmonised infrastructure to smart sustainable corridors.
- Provide open application programming interfaces (APIs) and user data and statistics for all modes and providers, enabling demand-oriented and demand-responsive cross-modal means of transportation.
- Ensure accessibility of shared services and incentivise shared fleets of personal mobility devices at hubs to facilitate mode change for those with disabilities and reduced mobility.
- Individualised mobility shells for demand-responsive transportation means.
- Make vehicles and transportation systems more resilient by smart application of automation, connectivity, and electrification.

## 3.1.5 Timeline

The roadmap for the key digital technologies in mobility are aligned with European roadmaps for terrestrial, water and aerospace transport:

- A new European Road Transport Research Advisory Council (ERTRAC) roadmap entitled "Sustainable Energies and Powertrains for Road Transport – Towards Electrification and other Renewable Energy Carriers".
- Urban mobility roadmap.
- Long-distance freight transport roadmap.
- Towards zero logistics emissions by 2050.
- The joint European Technology Platform (ETP) common paper published in 2019.

- The European roadmap on connected and automated driving published in 2019.
- The Joint Strategic Research Innovation and Deployment Agenda (SRIDA) for the AI, Data and Robotics Partnership (euROBOTICS), September 2020.

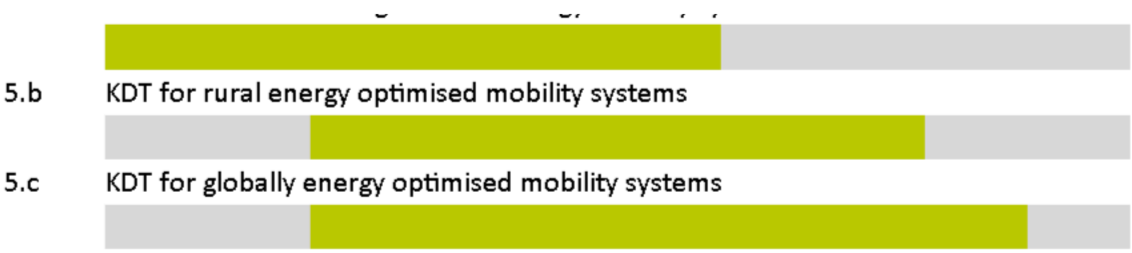


R&D&I TTOPIC IN KEY DIGITAL TECHNOLOGIES FOR MOBILITY

| | | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1 - ENABLE CO2-NEUTRAL MOBILITY AND REQUIRED ENERGY TRANSFORMATION** | | | | | | | | | | |
| 1.a | KDT for electr. passenger cars, electrified (short range) and fuel cell trucks , electr.off.road | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | |
| 1.b | KDT for H2 fuel cell passenger cars synthetic fuelled mobility | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | |
| 1.c | KDT for electrified airplanes, drones, ships | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |
| 1.d | KDT for CO2-neutral energy optimised mobility (from cradle to grave) | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |
| | **2 - ENABLE AFFORDABLE, AUTOMATED AND CONNECTED MOBILITY FOR PASSENGERS AND FREIGHT ON ROAD, RAIL, AIR AND WATER** | | | | | | | | | | |
| 2.a | KDT for level 2, 2+ vehicles, remotely operated ships | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | |
| 2.b | KDT for level 4 vehicles | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | |
| 2.c | KDT for level 5 vehicles | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | **3 - MODULAR, SCALABLE, RE-USABLE, FLEXIBLE, CLOUD-BASED, SAFE&SECURE END-TO-END SOFTWARE PLATFORM ABLE TO MANAGE SDV MOBILITY OF THE FUTURE** | | | | | | | | | | |
| 3.a | CAR-OS middleware for electrified, connected level 2-3 vehicles | 🟩 | 🟩 | 🟩 | | | | | | | |
| 3.b | CAR-OS middleware for electrified, connected level 4-5 vehicles and RISC 5 | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | |
| 3.c | Middleware for non-automotive electrified automated vehicles | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |

R&D&I TTOPIC IN KEY DIGITAL TECHNOLOGIES FOR MOBILITY

| | | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **4 - PROVIDE TOOLS AND METHODS FOR VALIDATION AND CERTIFICATION OF SAFETY, SECURITY AND COMFORT OF EMBEDDED INTELLIGENCE IN MOBILITY** | | | | | | | | | | |
| 4.a | KDT for validation and certification for level 2+ to 4 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | |
| 4.b | KDT for validation and certification of level 5 | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | |
| 4.c | Validation and certification of integrated mobility | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |
| | **5 - ACHIEVE REAL-TIME DATA HANDLING FOR MULTIMODAL MOBILITY AND RELATED SERVICES** | | | | | | | | | | |
| 5.a | KDT for urban and long distance energy mobility systems | | | | | | | | | | |



The roadmap combines the objectives in the application research programmes 2Zero and CCAM with the derived ECS mobility challenges. The following roadmap indicates when R&D&I activities are required to ensure the key digital technologies are available for use in the different mobility domains. In areas that already include ongoing electric mobility, the focus is more on improvements to existing concepts (for example, optimisation of costs), while for others (such as electric aircrafts) it is more about focusing on lower technology readiness levels (TRLs). These are both going on in parallel and are also influencing each other.

This roadmap is a preliminary estimate in regard to when the ECS will need to be ready for the various technology fields. It will be continuously updated as new domain roadmaps become available.

## 3.1.6 Synergy with other themes

Mobility is a domain that needs multiple key enablers, as described in other chapters of this document. It is transversal to almost all chapters, from components to systems.

For instance, semiconductor technologies are evolving rapidly. In the past, silicon was the dominant material, but its performance is now being outpaced by wideband materials such as SiC and GaN. These materials allow reduced packaging, increased operation temperatures, higher switching frequencies and therefore new concepts of compact power electronics modules. This is a major disruption that changes the market for electric mobility.

Closely linked to these semiconductor technology updates are packaging technologies. Moving from standard industrial modules to full heterogeneous integration is the second major disruption. Only adapted packaging can permit the full exploitation of the benefits of such new semiconductor technologies.

Other components that are of strategic importance are passives, such as capacitors and coils that can withstand higher temperatures and switching frequencies. For these, it is necessary to look at innovative materials that bring improved performance at a lower cost and a high rate of recyclability for the whole system.

The convergence of the automotive and energy eco-system for bi-directional charging, and also the future usage of cars as producers of electrical energy for the grid, requires a close cooperation of the activities in Chapter 3.2.

A further aspect of mobility is the increasing level of automation, which is also having a huge influence on other in-vehicle components in the area of digital technologies for embedded software, AI, sensors, actuators and trustworthy communication. In this respect, there is a strong need for cybersecurity to protect cars, drivers, and the environment. Remote access and OTA updates of rapidly improving complex software for the upgrade of car systems are therefore obligatory. This requires a safe, secure, and available infrastructure in cities as well as rural areas.

This infrastructure includes 5G/6G communication to allow massive transfer of data to and from cars, which can be considered as “datacentres on wheels”. In the background of such operations, a performant (and GDPR-compliant) cloud data system needs to support the mobility of each individual. The overall management of such an infrastructure should include smart grid operations to minimise energy waste and losses through inefficiencies, as is further elaborated upon in the Energy chapter. It is clear that this requires system developments, from small sensor systems to micro and large grid control, including all aspects of cohabitation of modules and sub-systems (electro-magnetic compatibility, EMC, and thermal considerations).

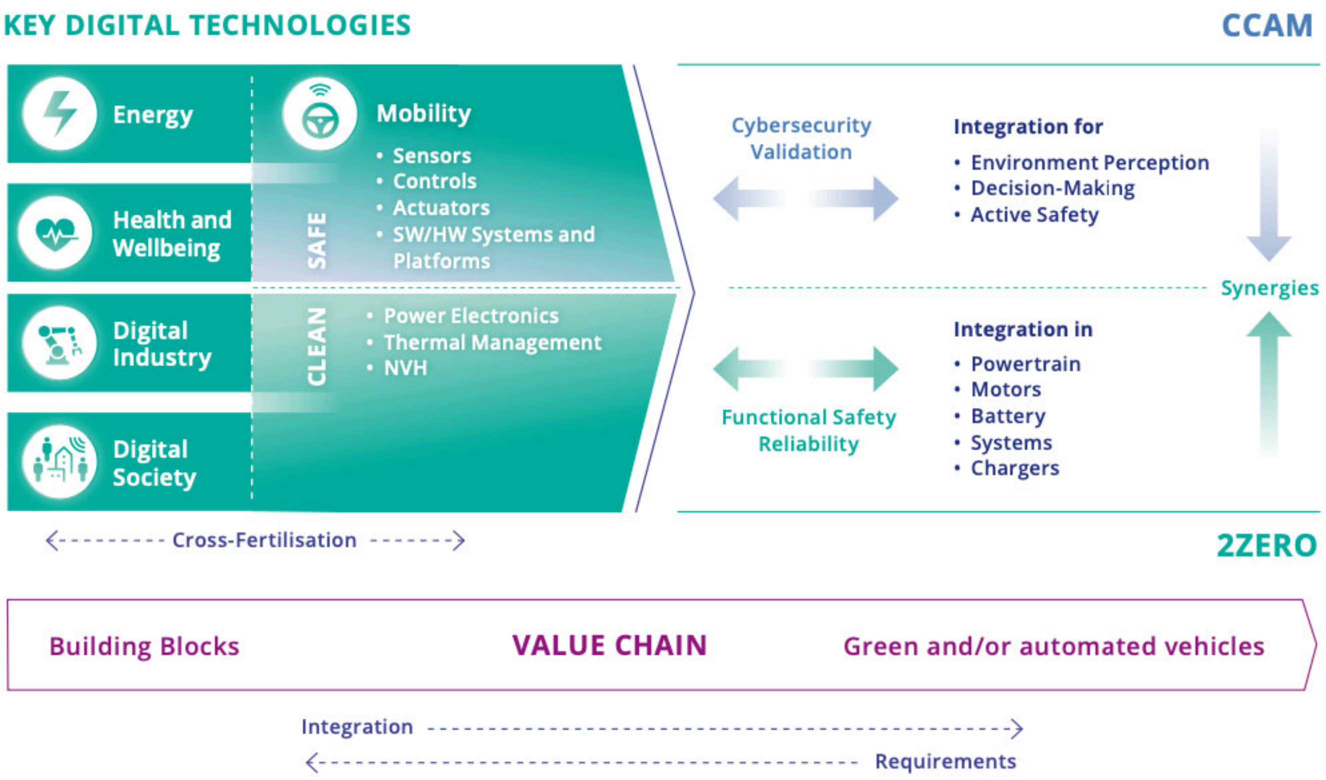


*Figure 3.1.8 - Synergies with European partnerships*

It should also be noted that synergy potentials exist between the domains of safe and clean mobility, not just at the level of the application in a multimodal urban mobility system but also at the level of the enabling technologies. Examples include electronic architectures for fail-safe power distribution and control within the vehicle, functional safety and reliability of systems and cybersecurity, and control in power systems. Additional alignment is already in progress with existing or planned programmes for rail (Transforming Europe's Rail System), maritime (Zero Emission Waterborne Transport) and aerospace (Clean Aviation).

## 3.1.7 References

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2. *"Internal Market, Industry, Entrepreneurship and SMEs" (available at https://ec.europa.eu/growth/ sectors/automotive_en)* ↩
3. *Sources Goldstein Research "Smart Healthcare", 2018; International Energy Agency "Energy Efficiency", 2017; Frost & Sullivan "European Smart Grid", 2016; Bloomberg New Energy Finance "Global storage market", 2017, IHS "Smart Grid Sensors", 2015; BIS Research "Global augmented and virtual reality", 2016; Gartner (IoT) 2017; MGI "The Internet of Things: mapping the value beyond the hype", 2015.* ↩
4. *https://lebipe.com/* ↩
5. *https://digital-strategy.ec.europa.eu/en/news/simpl-cloud-edge-federations-and-data-spaces-made-simple* ↩
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# 3.2

*ECS Key Application Areas*

# ENERGY

3.2

# Energy

## 3.2.1 Scope

### 3.2.1.1 Change towards the carbon neutral society and challenges for ECS

Energy systems *supplying clean, affordable and secure energy* are the focus of *The European Green Deal*. To achieve this goal, the European Union set targets for a renewable energy share of 32 percent and a Greenhouse gas emission reduction of 55 percent by 2030. Renewable energies bring several benefits such as mitigating climate change, emission reduction as well as improvements in the European energy security[1]. Although the EU even surpassed its' 2020 target of 20 percent, sustained action with an accelerated pace is necessary to prepare the economy and society for the upcoming climate challenges. The drop in $CO_2$ emissions was overcome rapidly by the uneven recovery from the Covid-induced recession (Figure 3.2.1), which put a major strain on the European energy system with a rebound in coal and oil use[2].The power sector must be further transformed from fossil fuel-based to renewable generation and, at the same time, needs to grow in order to enable decarbonisation of mobility, industry, and thermal energy supply, and reach the climate targets. The recent change in the supply strategy in Europe to be independent of strategically critical gas or oil suppliers is a further boost for renewable energies and efficiency measures. The shortage of materials (e.g. batteries and other electronic equipment) has already had a serious effect on the R&D and direction of developments. Some materials are getting rarer or can contribute to conflicts. Furthermore, there is a growing shortage of skilled workers, which is a huge societal challenge and needs to be compensated by fast technological progress and innovation. Therefore, smarter components are needed to compensate the growing shortage of technical knowledge and skills.

Because of the increasing residual load, resulting from the local mismatch between decentralised renewable generation and load, a digitally controlled transmission and distribution infrastructure is required. Thus, electronic components and systems (ECS) are key to future energy systems being optimised in both design and operation, for high efficiency, low $CO_2$-emissions, cost, and security of supply. The development of energy systems is driven by action against climate change, booming decentralised renewable generation (solar, wind), digitalisation and AI technologies, as well as cyber security issues. The Energy Chapter highlights the Major Challenges in the changing energy landscape based on electrical energy generation, supply, conversion, and use. Highest efficiencies and highly reliable, secure solutions are required to achieve the change towards a carbon neutral society in 2050.

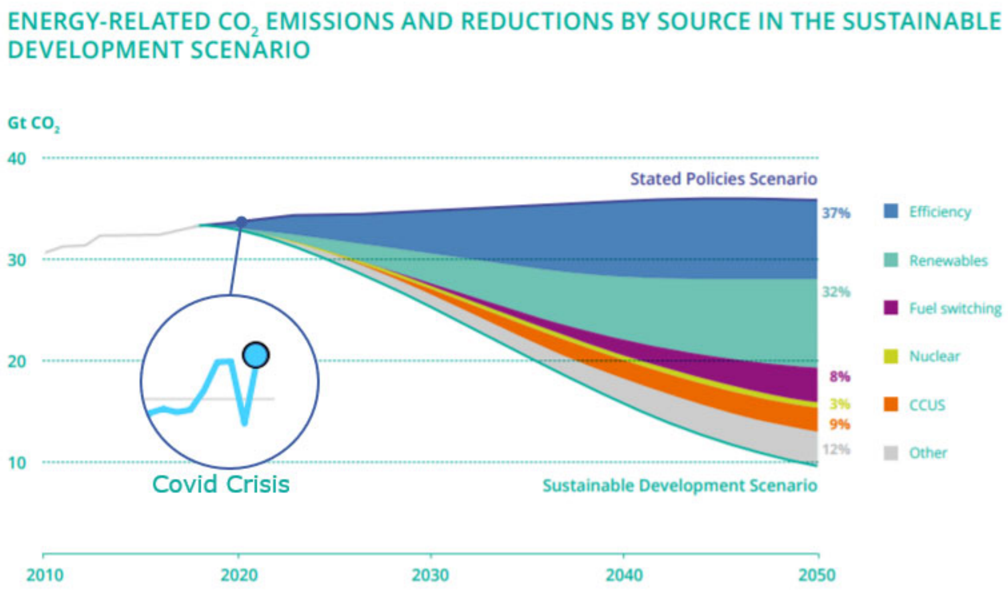
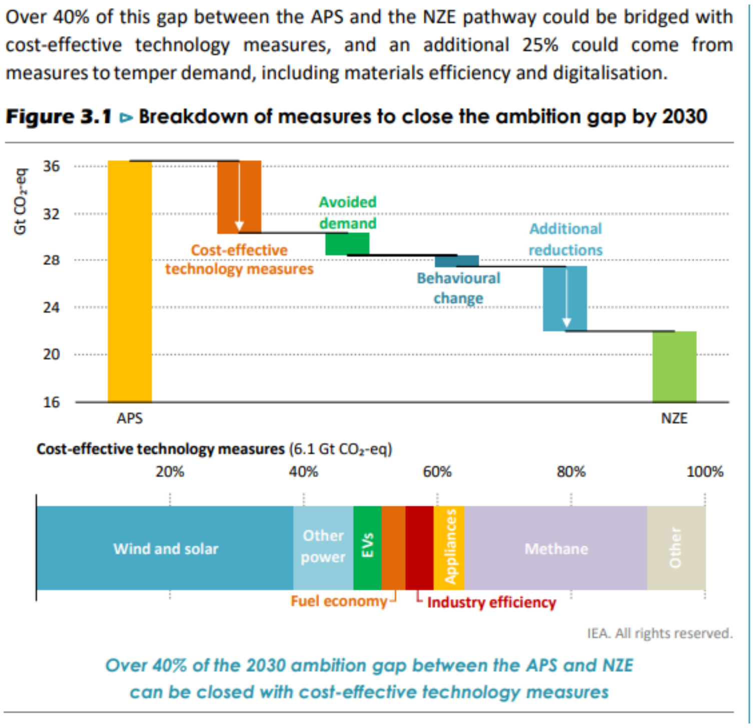


*Figure 3.2.1 - Efficiency and renewables provide most potential for $CO_2$ emissions reductions. Source: IEA World Energy Outlook 2019. In the graph the impact of Covid in 2020 & 2021 is indicated, emission level is back on the levels from before the Covid crisis. Source: IEA Global Energy Review: $CO_2$ Emissions in 2021.*

## 3.2.2 Application trends and societal benefits

### 3.2.2.1 Application trends

At present, 75 percent of total greenhouse gas emissions in the EU come from the energy sector. The energy world is undergoing a radical transformation: promoted e.g. by EU and national roadmaps, the globally installed capacity of renewable generation has doubled within the past 10 years. Europe alone expanded its renewable generation capacity by 6.4% in 2021. This increase is dominated by wind and solar energy being characterised by strongly intermittent, distributed generation. Altogether wind and solar energy made up one fifth of Europe's electricity generation in 2021 with plant capacities ranging from domestic solar (≤ 10 kW) via commercial solar and wind (≤ 500 kW) to power stations at utility scale (≥ 1 MW). At the same time, the levelised cost of electricity (LCOE) from photovoltaic (PV) sources dropped by 13 to 15%. However, the rise of renewables is still too slow - wind and solar generation growth must nearly triple to reach Europe's 2030 green deal target. In the long term, it enables the substitution of fossil fuel-based transportation, domestic heating, and commercial & industrial processes as well as address the strong economic growth of non-OECD countries. Since the pursuit of all economically viable opportunities for efficiency improvement can reduce global energy intensity by more than 3% each year, increasing energy efficiency may be accountable for 30 percent $CO_2$ emission-reduction by 2050 with current policy settings, but can be even increased up to 40 percent if worldwide announced climate pledges are met. Energy supply to all sectors affordably and reliably needs to match the demand and availability as efficient as possible (Figure 3.2.2).



Over 40% of this gap between the APS and the NZE pathway could be bridged with cost-effective technology measures, and an additional 25% could come from measures to temper demand, including materials efficiency and digitalisation.

**Figure 3.1 ▷ Breakdown of measures to close the ambition gap by 2030**

IEA. All rights reserved.

*Over 40% of the 2030 ambition gap between the APS and NZE can be closed with cost-effective technology measures*

*Figure 3.2.2 - Measures to reach the Net Zero pledge announced for 2050. Source: IEA World Energy Outlook 2021.*

Thus, the power grid architecture developed for centralised, unidirectional, demand driven power generation will be transformed into a multi-modal energy system (MM-ENS) architecture (Figure 3). It will comprise distributed renewable generation, energy conversion units for sector coupling, transmission and distribution grids allowing bi-directional power flow, and energy storage for all modes of energy (electric, thermal, chemical). Energy management systems (EMS) will optimise ENS-operation. It will match load and demand at all levels ranging from the nanogrid (behind the meter, building level) and the microgrid (district or community level) to the regional distribution grid, which is connected to the cross-regional transmission infrastructure. Fossil-fuelled power plants, which used to operate on schedules orienting at the demand, will turn into back-up power supply facilities.

The overall reduction of energy consumption in addition to efficiency measures will be always a target, since all energy usage that can be avoided also implies reduction of emissions. This can be achieved by control elements for switching off energy use and zero power stand-by functionality or by transformation to new technologies as in the last decade the transfer to LED illumination had a high impact. Upcoming threats are energy consuming ICT technology related applications like blockchain, AI, data traffic, or digital currencies. The challenge will be to develop highly efficient algorithms and methodologies to decrease energy consumption despite the increased use of these new technologies.

Key to these new energy applications will be smart sensors, networks of sensors, and smart actuators that enable status monitoring on each grid level as well as smart converters (for all voltage levels). The converters need to use highly efficient and fast semiconductor power devices and modules that enable real-time control of energy system components and grids for optimised operation based on forecasts of generation and demand but also in case of any critical event. The future grid operation requires a sophisticated information and communication infrastructure including cloud services, IT security, and AI technologies. Altogether, they will contribute to significant reduction of energy consumption and, consequently, $CO_2$ emission.

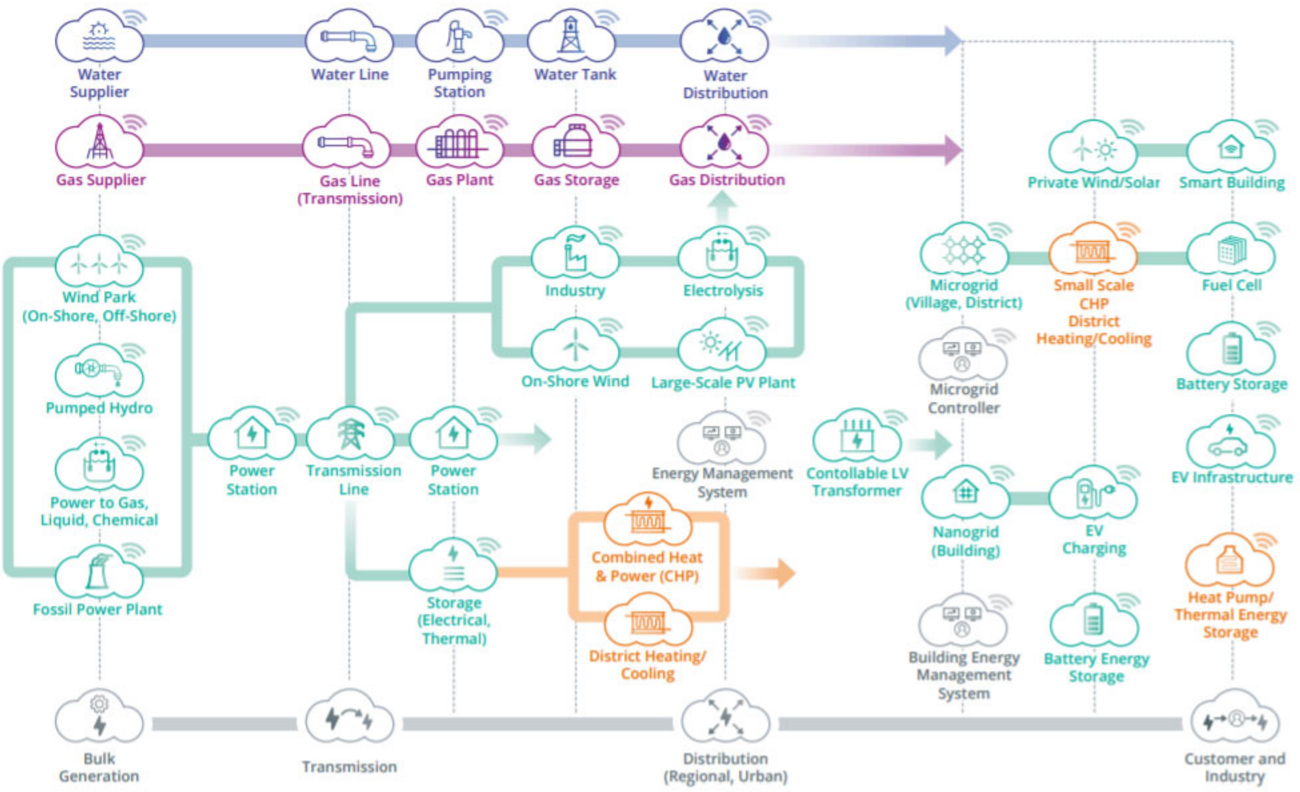


*Figure 3.2.3 - Interconnected Energy Infrastructure; Source: Siemens Corporate Technology*

**To achieve the targets of the Green Deal and to have competitive advantages for European based technologies and solutions, research has to be performed in the following areas:**

1. Significant reduction and recovery of losses (application and SoA-related).
2. Increase of power density and reduction of losses (e.g. through exploitation of new materials) and a decrease of system size by miniaturisation and integration, on the system and power electronics level.
3. Increased functionality, reliability, and lifetime (incl. sensors & actuators, ECS HW/SW, semiconductor power devices, artificial intelligence, machine learning, monitoring systems, etc.).
4. Manufacturing and supply of energy relevant components, modules, and systems.
5. Management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility. Grid stabilisation through e-vehicle charging.
6. Energy supply infrastructure for e-mobility, digital live, and industry 4.0.
7. “Plug and play integration” of ECS into self-organised grids and multi-modal systems, real- time digital twin capability in component and complete system design (to simulate system behaviour).
8. Safety and security issues of self-organised grids and multi-modal systems through smart edge devices and high-level IT security (resilient communications and trustworthy AI).
9. ECS for energy storage technologies: production, transportation, storage, distribution, combustion and energy conversion systems.
10. Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.
11. Energy technologies in the circular economy approach: predictive and condition-based maintenance with repair and recycle capabilities.
12. Aligning with standardisation of our energy systems.
13. Manufacturing and world-leading technologies for energy relevant applications in Europe.
14. Scheduling for cost-efficient energy consumption.
15. Involvement of the consumer: traceable eco-footprint and incentives towards environmentally-friendly behavioural change.

### 3.2.2.1 External requirements and Societal Benefits

In alignment with the **Parisian Agreements**, the EU committed to substantial reductions of $CO_2$ emission. In particular, the EU aims to make Europe the first climate-neutral continent by 2050 (EU long-term strategy) while boosting the competitiveness of the European industry. Carbon pricing throughout the EU economy is going to be implemented more strictly. Further climate laws will be introduced and continuing policies will be clarified by the European Commission in 2022. The new policy regarding **"Clean energy for all Europeans package"** was completed by the EU in 2019 as a comprehensive update of its energy policy framework and updated with the new Green Deal in July 2021. It emphasises renewable energy, energy performance of buildings, energy efficiency, governance regulation, and electricity market design. Smarter buildings with more automation and control systems for effective operation shall be promoted. E-mobility infrastructure is going to be supported further. Energy efficiency targets and energy labels were tightened to encourage the industry to innovate.

*Figure 3.2.4 - Energy from renewable sources: Wind turbines and photovoltaic (Source: © Mariana Proenca/Karsten Wurth – Unsplash)*

To achieve the **Green Deal** goal of "clean, affordable and secure energy" in all sectors, new laws and regulations will be required. While subsidies and regulations will promote sustainable developments in all application domain of ECS (energy, industry, mobility, communication, consumer goods, and cities), the energy domain with targeted 40% renewables in the energy mix until 2030 is the foundation to all of them. Additional perspectives are given by the United Nation's "**Roadmap 2050**" addressing sustainable development solutions and implementations towards a carbon-neutral global population.

*Figure 3.2.5 - Electrification of the transport sector.*

All these factors are considered for the roadmaps on research, development, and innovation of ECS for the applications in the energy sector. Potential targets comprise the implementation of electricity storage solutions (e.g. vehicle2grid, battery grid storage), the further increase in efficiency and the reduction in life cycle costs of energy generation from renewable sources (Figure 3.2.6), the electrification of transportation (Figure 3.2.5), and the thermal processes in industry as well as the development of secure, self-learning energy management systems for buildings and industrial sites. ECS as enablers support the EU and national energy targets to achieve sustainability (Figure 3.2.6) and are essential for a highly developed energy landscape towards a fair, democratic, healthy and prosperous society.

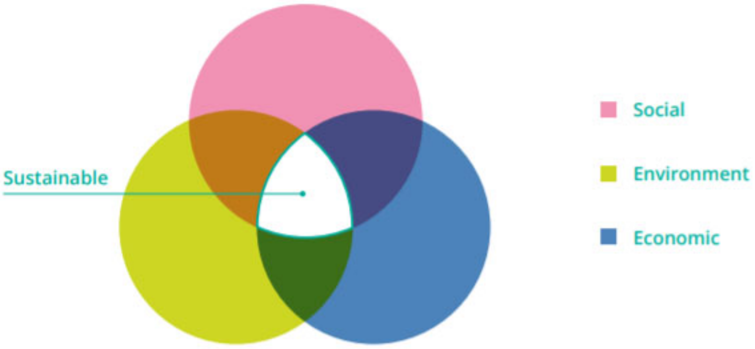


*Figure 3.2.6 - Three pillars of sustainability (Source: Purvis, Mao, Robinson 2018: Three pillars of sustainability: in search of conceptual origins).*

Energy efficiency through ECS fosters economic development towards a circular economy and new employment opportunities. They will have a huge impact on job generation and education if based on the complete supply chain and fully developed in Europe. With more than 11 million jobs in the field of renewable energies[3] and indirectly involved technologies, this is a visible and significant factor for economic and societal stability. The capability of maintaining the understanding of the complete systems as well as the competence from small-scale solutions up to balanced regional energy supply solutions are key to the European competitiveness and success in the global market of energy solutions. Also the consumer itself can contribute its share, thus consumer empowerment to energy savings and efficiency should be taken into account for the development of energy systems.Societal benefits include access to knowledge, development of modern lifestyle and the availability of energy all the time and everywhere – with a minimum of wasted energy and a minimum of greenhouse gas emissions. Therefore, ECS and its application domains enable Europe to meet the needs of the present without compromising the ability of future generations to meet their own needs.

### 3.2.3 Strategic Advantage for the EU

European ECS companies are among the leaders in smart energy related markets, e.g. for electrical drives, grid technologies, and decentralised renewable energy sources. Four European-based power semiconductor suppliers are among the top 20 in the world, having a combined market share of over 22% in 2021. Two of them amongst the top 5 including the market leader. The major growth driver there includes growth in renewable energy sectors such as solar power generation. Three power modules suppliers are found among the top 10 with one worldwide leader in the automotive, in the discrete power device and in the security-IC sectors, respectively, while the combined market share is more than 35%. Overall, the share of European suppliers in this growing market is increasing, which underlines their competitiveness. The companies invest in Europe and expand fab capacity or even build up new semiconductor fabs in Europe. This position will be strengthened so that further employment is secured by innovative research within Europe. The technological progress will have a multiplying effect by creating a convergence between semiconductor and other promising future technologies like 6G, IoT, AI, and cloud-edge computing. As a result, EU ECS market prospects are seen very strong. A seamless line from ECS R&D&I to production covering future energy businesses from generation over conversion to distribution and transmission ensures Europe's technological non-dependence. Since the beginning of the Covid19-crisis, the ECS industry moved to protect employees, and secured supply chains. Despite the crisis, the ECS industry recorded on average a double-digit growth in 2020, with the fourth quarter marking the best quarterly result to date. In contrast to other industries, which had to contend with declining demand, the ECS industry experienced the opposite development and consequently suffered supply bottlenecks for electronic components. In the future, the focus on a strong R&D strategy is essential to emerge stronger from the crisis. Targeted investments in innovation can create a long-term competitive advantage and fill knowledge gaps. Especially the investments in new technologies rather than simply focusing on product variation or optimisation to extend the product life cycle leads to the achievement of a pioneering role and should therefore be pushed. ECS enable affordable energy conversion efficiencies of 93% – 99%, which improve the use of renewable energy resources. Involving new materials such as wide band-gap semiconductors, new device architectures, innovative new circuit topologies, architectures, and algorithms, the total system cost can be lowered. The focus on ECS development secures a smooth implementation of renewable energy power plants into the EU grid, a step towards the long-term goal for 2050. To further ensure a competitive, self-sufficient and efficient energy transmission and consumption in the EU, the energy highway through Europe, decentralised intermittent energy sources, bi-directional grid and storage systems, and distributed AC/DC network and grid technologies need to be implemented. These measures will support the EU by reaching its goals of a connected, breakdown and blackout protected, market-based, and yet more consumer-oriented energy market. Consequently, EU's energy system will serve as blueprint for global application. The scenery was already set in the recent years – with the change in the supply strategy to be independent of strategically critical gas and oil the conversion has to be faster and the change heat pumps and battery electric vehicles in combination with the Green Deal targets will even need a faster development for the conversion to a highly dynamic energy grid for the provision of renewable energies.

### 3.2.4 Major Challenges

Five Major Challenges have been identified for the energy domain:

- **Major Challenge 1**: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems.
- **Major Challenge 2**: Energy Management from On-Site to Distribution Systems.
- **Major Challenge 3**: Future Transmission Grids.
- **Major Challenge 4**: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply.
- **Major Challenge 5**: Cross-Sectional Tasks for Energy System Monitoring & Control.

### 3.2.4.1 Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems

#### 3.2.4.1.1 Status, vision and expected outcome

According to the IEA's Efficient World Strategy, digitalisation enhances energy efficiency gains in the transportation and industry sectors[4]. Smart and efficient energy systems are drivers of energy savings. Therefore, they are in full alignment with the Green Deal. Alternative ways of energy generation (hydro, photovoltaic, and wind) and the electrification within the industry, the transport / mobility, and the construction / building sectors result in the challenge of creating smart, efficient, and reliable energy generation, conversion, and storage components.

**Smart Energy Systems**

For operating smart energy systems, all the energy conversion and storage components need to be equipped with smart actuators and sensors for status and health monitoring as well as optimisation of grid operation. The integration of sensor, connectivity and edge processing in supplementary/additional parts will enable the creation of intelligent facilities by retrofitting. The creation of secure electronic control units requires development of specific hardware and software.

Consequently, smart control units need to be developed for all types of energy production, conversion, and storage components comprising smart electronic converters, actuators, sensors, security systems and reference communication interfaces. They shall have plug-and-play functionality and real-time digital twin capabilities in component and complete system design to simulate system behavior for evaluation of its' health status.

For offshore energy generation, such as windfarms and tidal energy generators, fibre optical sensors is an emerging technology beneficial for online monitoring of metal fatigue and excessive turbulences. This technology is currently being developed for such monitoring in aircraft wings and ship masts.

**Conversion**

Electrification of industry is one of the main implications to reach the 2050 decarbonisation targets, mainly via the conversion from fuel-based heating processes to electro-heating solutions. In addition, direct electrification of industrial production processes (such as electro-synthesis of chemicals or electrolysis) is also crucial for replacing present $CO_2$ emitting solutions. In the case of Heating, Ventilation, and Air Conditioning (HVAC) systems, significant reductions in consumption can be obtained by optimizing the system that handles all the processes of energy management or by changing the use of the Machine-to-Machine (M2M) technologies. For both strategies, efficient ECS are required to obtain optimal control functionality based on sensing, collecting, processing, and evaluating device related data. DC power supply requirements based on advanced semiconductor power devices will provide lower power consumption and thus, feature higher efficiency of the increasing ICT energy consumption (i.e. through data centres) . Investments in the next-generation computing, storage, and heat removal technologies will be required to avoid a steep increase on energy demands and to minimise the implications of unavoidable data centre energy use on the global climate. In data centres and 5G/6G networks, photonic ICs can route information streams from fibre to fibre without conversions into electronics in between. This will be highly efficient and save energy. The advanced features of 5G/6G will innovate the use of the technology (Figure 3.2.7), but as consequence of larger data rates and through-puts, cost and energy demand will increase substantially. Therefore, energy harvesting capability of sensors and devices in the 6G environment will be one of the crucial aspects towards a green and cost-efficient technology landscape[5].

*Figure 3.2.7 - 5G as enabler of an interconnected smart network. Source: European Commission, Towards 5G.*

Power electronics circuits based on semiconductor power devices are used in all conversion processes. Silicon based power devices are approaching their ultimate limits in terms of breakdown voltage, current, switching frequency and temperature capabilities. Next generation power semiconductor devices will rely on Wide Band Gap (SiC, GaN) and Ultra WBG (diamond, $Ga_2O_3$) technologies. Due to this unstoppable trend, research on device reliability, packaging and assembling methods suitable for very high electric fields and high temperature, is strongly required. A focus also needs to be set on the medium voltage grid (< 45 kV).

**Storage**

Energy storage deployment provides energy system flexibility. Looking at further storage possibilities, different options for various capabilities need further efficiency improvements. As an example, optimised converters, sensor solutions for monitoring, and battery management systems need to be developed for storage options, all including ECS. In power generation, hydrogen with its many uses (Figure 3.2.8) is one of the leading options for storing renewable energy. Hydrogen can be used in gas turbines to increase power system flexibility. In combination with fuel cells, it is also a great vector of clean energy since it allows to produce electricity directly onboard of EV or in areas, which are cut off from the power grid. With declining costs for renewable electricity, interest is growing in electrolytic hydrogen. ECS will be employed in electronics for electrolyzers, fuel cells, as well as power management and health monitoring.

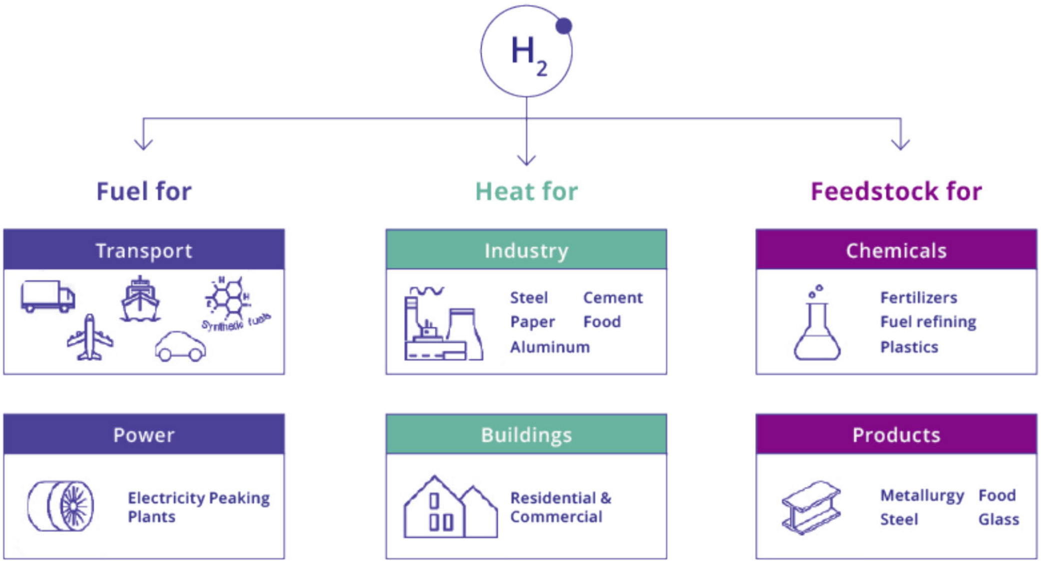


*Figure 3.2.8 - The many uses of Hydrogen, source: Bloomberg NEF.*

### 3.2.4.1.2 Key focus areas for increased efficiency and smart energy generation, conversion and storage components

- Increased efficiency at all levels:
    - Power conversion and wide-bandgap semiconductor power devices.
    - Power supply.
    - Energy harvesting.
    - Energy management.
- Residential, commercial, and industrial demand side management (scheduling and load adaption):
    - Sensors, actuators, drives, controls and innovative components.
    - Full monitoring in adaptive and controlled systems.
    - High efficiency electric drives, heat pumps, cooling, HVAC, data centres and other consumers of electricity for variable load operation.
    - Solutions for increasing power demand of 5G/6G systems.
- Development of Energy Management Systems including:
    - Optimisation module.
    - Demand and generation forecast.
    - Customer preferences.
    - Weather forecasts.
    - Price/tariff information/forecast for scheduling controllable loads and generators.
    - Smart sensor network: internal and external physical parameters that influence energy conversion efficiency.
    - Resilient and smart communication and edge devices.
    - Deployment of Trustworthy AI.
    - Fiberoptic sensors for fatigue detection.
    - Converters for power quality improvement (e.g. electronics filters to manage resonances).
    - Sensors and controls for the management of decompression and compression and leakage detectors for methane, hydrogen, and other gases.
    - ECS for the coupling of processes in the chemical and electrical industry.
    - Traceability and labelling of green energy.
- Conversion of industrial processes:
    - “Industrial electrification” (Replacement of $CO_2$-emitting processes by others based on “clean” electricity).
    - Electric drives for commercial & industry applications.
    - Industry 4.0 with combination of Cyber-Physical Systems (CPS), Internet of Things (IoT), Artificial Intelligence (AI).
    - DC subsystems for industrial production / data centre applications and DC distribution grids.
    - Photonic routing in data centres from fibre to fibre without conversion to electronics.
    - Carbon capture technologies compensating production emissions (up to negative emissions).
- Development and application of storage optimised for residential, commercial, industrial utilisation:
    - Control, interfaces to batteries, fuel cells, hydrogen storage electrolysers.
    - Integrated battery driven applications (e-car charging, PV – system local storage).

  - Power Storage to "buffer" net fluctuations and to avoid long distance transmission.
  - Smart storage technologies from low to medium voltage.

### 3.2.4.2 **Major Challenge 2: Energy Management from On-Site to Distribution Systems**

#### 3.2.4.2.1 Status, vision and expected outcome

The distribution grid comprises commercial scale renewable generation as well as private smaller renewable power generation units, conversion between different energy modes, storage, control and protection systems for the grid infrastructure together with all kind of consumption.

**Autonomous Control Systems**

In the future distribution grid, generation and consumption by power electronics systems will surpass the share of synchronous generation. This leads to potential grid instabilities due to lack of inertia. Therefore, autonomous control systems need to be implemented to control the high demand loads. These control systems should be organised hierarchically to adjust the heavy loads according to the actual local production and storage capabilities so that import or export of power is minimised. Price control systems such as TOU (Time of use) can help to prevent grid violations. Storage devices, such as local community storages or e-Vehicles, can be charged when the price is low and discharged when the price is high, to provide flexibility as well as to ensure stability and reliability in the grids.

For industry or larger groups of buildings, control methods increase the flexibility of the total system and can be set up using hierarchical and intelligent control methods to minimise costs and to provide peak-shaving (Figure 9). For larger power production facilities, hybrid generation and storage solutions are also discussed, which integrate the power production facilities with storage devices to have the best arbitrage cost. Novel grid architectures for manufacturing strive to increase topological and energy flexibility within production cells to enable adaptive production optimisation. Also, blackouts and their consequences need to be prevented, since for example for large industrial electrolyzers they result in serious safety and cost issues.

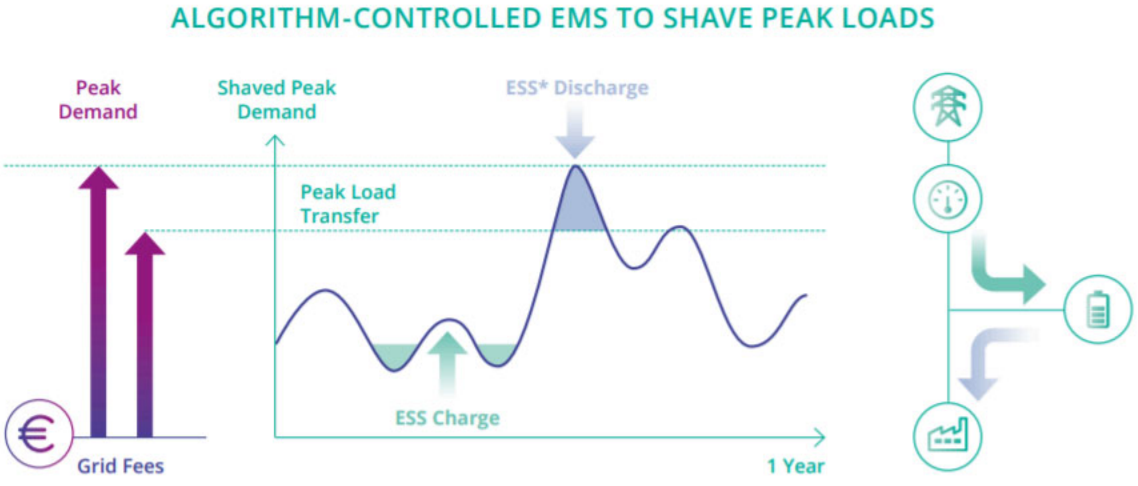


*Figure 3.2.9 - Visualisation of an algorithm-controlled energy management system to shave peak loads. An energy storage system predicts load peaks and charges/discharges a battery accordingly. Source: EDF Renewables.*

**Security, Reliability and Stability of Energy Systems**

For stable, resilient on-site energy systems, multi-modal energy management systems allowing integration of electricity, heating & cooling, molecules, and transport (e-vehicle charging incl. Vehicle-2-Grid) will be developed. Their features comprise high level IT security, energy trading via local energy market platforms, renewable energy certification, development of solutions for low voltage electronic systems that are easy to setup, as well as support for self-learning against evolving needs.

Energy Management Systems for industrial and residential customers include optimisation module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast. They require beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles. Furthermore, the interface to the grid might be used for additional power quality services based on power electronics converter technologies beyond state-of-the-art reactive power compensation (e.g. virtual inertia and balancing).

#### 3.2.4.2.2 Key focus areas for on-site or behind the meter systems

- Security, reliability and stability of total energy system:
  - Automation of grids.
  - Storage of data.

  - Trustful AI and ML for optimised operation of the grid.
  - Machine-learning based forecasting algorithms for generating accurate generation profiles of expected power production and consumption.
  - Deployment of sensors and edge computing devices to health-check grid assets to increase lifetime and optimise operation.
  - Converters for power quality improvement (e.g. electronics filters to manage resonances).
- Stable and Resilient On-Site Energy Systems:
  - Integration of electricity, heating & cooling, molecules, and transport (e.g. Vehicle2X).
  - Coupling with energy trading systems, e.g. local energy market platforms.
  - High level IT security.
  - Renewable energy certification.
- Hybrid solutions:
  - Integrating power production facilities with storage devices.
  - Arbitrage cost, keeping level of production according to market bid.
- Virtual markets:
  - Flexibility in demand & supply.
  - Aggregation of Energy consumption and production.
- Electric energy supply for manufacturing:
  - Higher uptime using novel industry grids and UPS.
  - Stable power supply using novel electronics converter technologies.
  - Blackout prevention.
- Plug-and-play capability for components, self-learning:
  - Integration of low voltage systems using flexible planning rules.
  - Cost effective solutions to minimise set up-time and manual parametrisation.
  - Reduced physical size and weight of individual transformer stations with equivalent power ratings.
  - Development of solid-state transformers with:
    - New functions for the operation of power systems.
    - Avoidance of infrastructure extensions caused by increasing share of distributed generation.

### 3.2.4.3 Major Challenge 3: Future Transmission Grids

#### 3.2.4.3.1 Status, vision and expected outcome

**New grid challenges**

Future transmission and distribution grids will remain an integral backbone of energy systems. Coupling of different domains like electricity, thermal, gas etc. will enable new business opportunities which require new technological solutions for high power electronics, combined with sensors and ICT for monitoring, intensive control and prediction.

The energy generation and energy consumption pattern will drastically change as the industry and society at large will be highly electrified. Base industries such as the chemical industry, steel and cement production will completely change production technology to enable fossil free production and will require extreme amounts of electric energy. New industries such as giga volume battery production factories are planned in several places in Europe[6]. This together with a massive expansion of supercharger station for private passenger cars and heavy trucks with individual charge capacity of more than 1 MW will put severe challenges on the grid capacity in both networking and electronic components to manage highest possible efficiency. Therefore, further ECS R&D needs to work towards improvements of the grid capacity with the highest possible efficiency (Figure 10). Thus, continued development of components for HV transmission for 1.2 MV or even higher voltages are needed to roll out an efficient energy transmission over Europe. In addition, new business models must be developed for the electric energy market enabled by the smart grid technology.

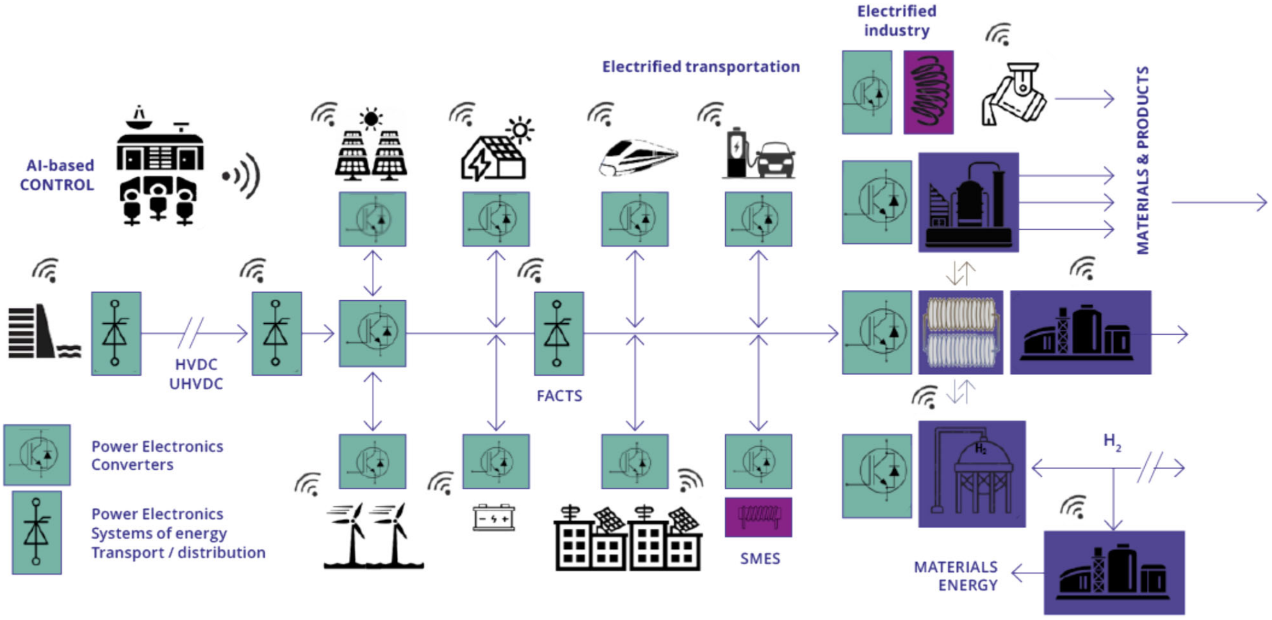


*Figure 3.2.10 - Power ECS at each point of the future transport and distribution grid. Source: CSIC Scientific Challenges: Towards 2030, Volume 8.*

**Resilience**

To account for adverse conditions caused by climate change, the new national and transnational grids must include autonomous electricity generators based on fuel cells or local storage systems for communications and network information management as well as water-resistant components or modules. Also, sensors need to be placed at critical points to immediately alert authorities in case of unexpected incidents. To be able to quickly react to an electricity line fault, the system will benefit from powerful switches and AI to successfully reroute the systems. Additionally, predictive maintenance (e.g. with digital twins) of the energy supply sensors provides further safety and resilience. Due to the weak tectonic movement in most of the parts in Europe, transmission grids could become much more resilient and loss-less when buried in the ground. Thus, extra isolation technology needs to be considered and critical points equipped with smart ECS for monitoring, control, and prediction.

## 3.2.4.3.2 Key focus areas

- Grid stability during the industrial transition:
  - Efficiency increases.
  - Development of smart medium voltage grid.
  - Development of components for HV transmission for 1-2 MV or even higher voltages.
  - New solutions for high power electronics, combined with sensors and ICT for monitoring, control and prediction.
  - Development of new simulation and business models to foster innovations regarding grid stability.
- Development of a Trans-European energy infrastructure:
  - Secure, cross-regional transmission infrastructure.
  - Multi-terminal HVDC systems connecting remote energy generation sites.
  - Interaction between distribution systems on community and district level.
  - Development of components for HV transmission for > 1.2 MV.
  - Minimise Losses.
- Requirements on ECS by disruptive changes in transmission and use:
  - Flexibility in system design and operation.
  - Water-resistant components/modules.
  - Autonomous electricity generators based on fuel cells.

- Modelling, sensing and forecasting weather conditions and thus, supply and demand.
- Intelligent power devices, systems, and switches.
- Status-/health-monitoring (e.g. ice sensor/detection) for transmission lines.
- ECS for multi-modal energy systems.

### 3.2.4.4 Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/Regional Energy Supply

#### 3.2.4.4.1 Status, vision and expected outcome

A 40% renewable energy share in the electricity sector in Europe by 2030 needs additional decentralised, intermittent energy sources, bi-directional grid and storage for energy supply in transport, industrial and smart cities applications.

**Multi-energy Systems (MES)**

MES help to achieve optimised energy management. All sectors are integrated to maximise overall system efficiency. Energy flows between sectors and their storages ensure the highest use of renewable energy while balancing fluctuations.

Heating supply uses district heating, supported by heat-pumps and boilers, using thermal storage in the district heating system (Figure 11). Integration with industry makes use of waste process energy using heat pumps to boost from low (40-50 deg) to high temperatures in the pipe (80-90 deg). Electrolyzers add to the gas system or transport. Water treatment uses excess power from renewables adding further flexibility.

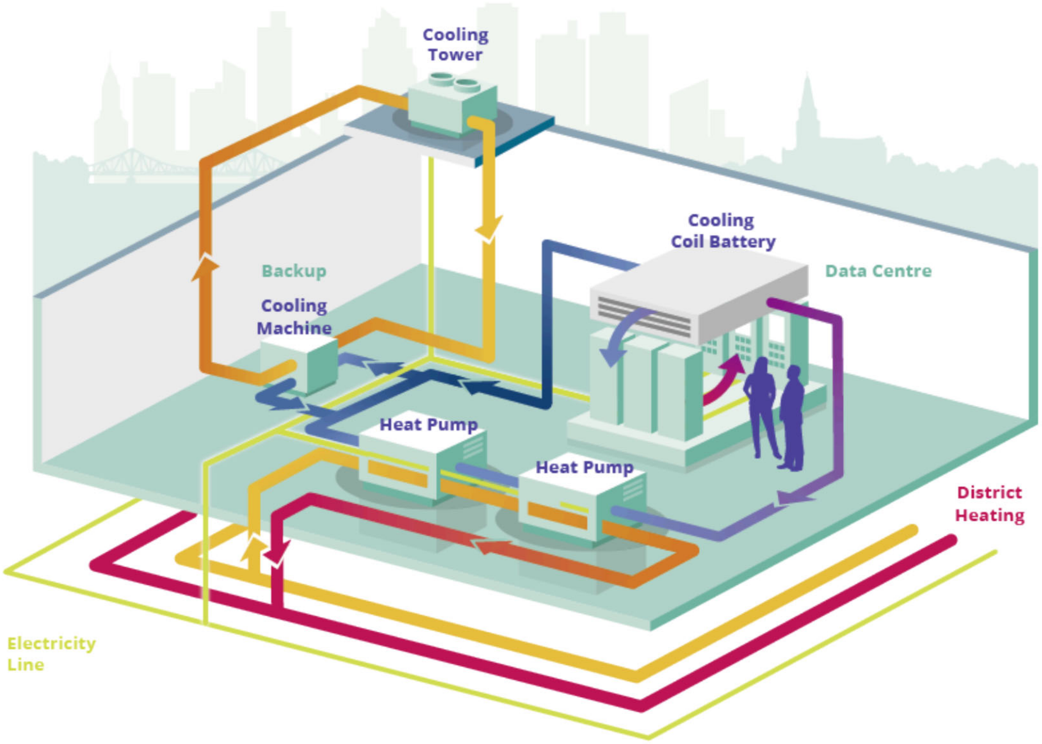


*Figure 3.2.11 - A Combination of heat pumps and district heating. Source: IEA HPT.*

Local communities use MES concepts on regional level. Different local inputs are gathered for an overall aggregated control for the larger regions as well. Autonomous controllers are used behind the meters to support overall control. A clear hierarchical set up, control structure and knowledge of market interactions are necessary.

Complex integrated control systems use AI, machine learning and comprehensive communication grid/IoT platforms (including edge computing) to get all data for control and optimisation. Risk and security analysis provide resilience and ensure stability of MES.

**Urban Transformation**

Emission free cities use electrification and decentralised storages to improve efficiency and reliability. ECS as indispensable components ensure efficient management of data and data storage. AI approaches and the ECS supply chain for integrated applications in energy are key enablers for smart power grids. Electrification of urban mobility supports individual and public transport (incl. utility EV) and furthermore, contributes to the stabilisation of the grid. The first needs household and public charging, the latter uses well defined charging points on (bus) lines or at terminals. Powers vary from 10 kW (LV) to 600 kW (MV). Reservation and optimisation are based on ICT.

Other, crucial aspects of emission free cities are an efficient urban energy infrastructure, low carbon and smart residential and service buildings, low carbon mobility, smart water systems and smart waste management. Even the shift to LEDs without any smart functions can result in energy savings of ~50% in an industrial setting[7]. Carbon capture technologies will add another dimension to the energy systems.

**Storage Solutions**

In households, battery energy storage devices can used to increase self-consumption. Some regions will use heat/cooling storage. Algorithms/models for optimal use of storage (community/private/ industrial) are based on technical parameters, demand and generation forecasts, customer preferences, in order to reduce power peaks and to support integration of RES into existing infrastructure.

MES in larger communities with different kinds of storage possibilities (electrical, thermal, gas, water etc.) play an important role. V2X is used as huge distributed electrical energy storage. Systems with electrolyzers might use storage tanks for gas production. Thus, development of grid-supporting control algorithms and supporting regional energy management for communities (e.g. P2P trading via storage systems, self-consumption optimisation) are needed.

#### 3.2.4.4.2 Key focus areas for achieving efficient community and regional energy management

- Electric Energy Supply for urban mobility:
  - Development of household and public charging infrastructure.
  - Creation of HV (wireless) charging points along the (bus) line or at fleet terminals, for public transport.
  - Reservation and optimisation services implemented with ICT solutions.
- Electric Energy Supply for urban life:
  - Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimisation.
  - Local DC-coupling of various technologies for fast charging at home.
- Regional Energy Distribution infrastructure:
  - communication infrastructure to support self-organised local energy communities.
  - sustainable off-grid supply with power electronics-based grid forming capabilities.
  - Virtual power plant functionality optimizing match between generation and demand.
- Operation of connected energy systems:
  - Connectivity, Security, Integrity, Resilience, Variability.
  - Interoperable platform for energy management
- Storage systems:
  - Development of grid-supporting and peak-shaving control algorithms.
  - Support for regional energy management for communities.
  - Peer-to-peer trading by using storage systems.
  - Self-powering systems for small IoT nodes.
  - Local energy harvesting to substitute battery powered devices and eliminate the high demand of energy for the battery manufacturing and distribution logistics.

### 3.2.4.5 Major Challenge 5: Cross-Sectional Tasks for Energy System Monitoring & Control

#### 3.2.4.5.1 Status, vision and expected outcome

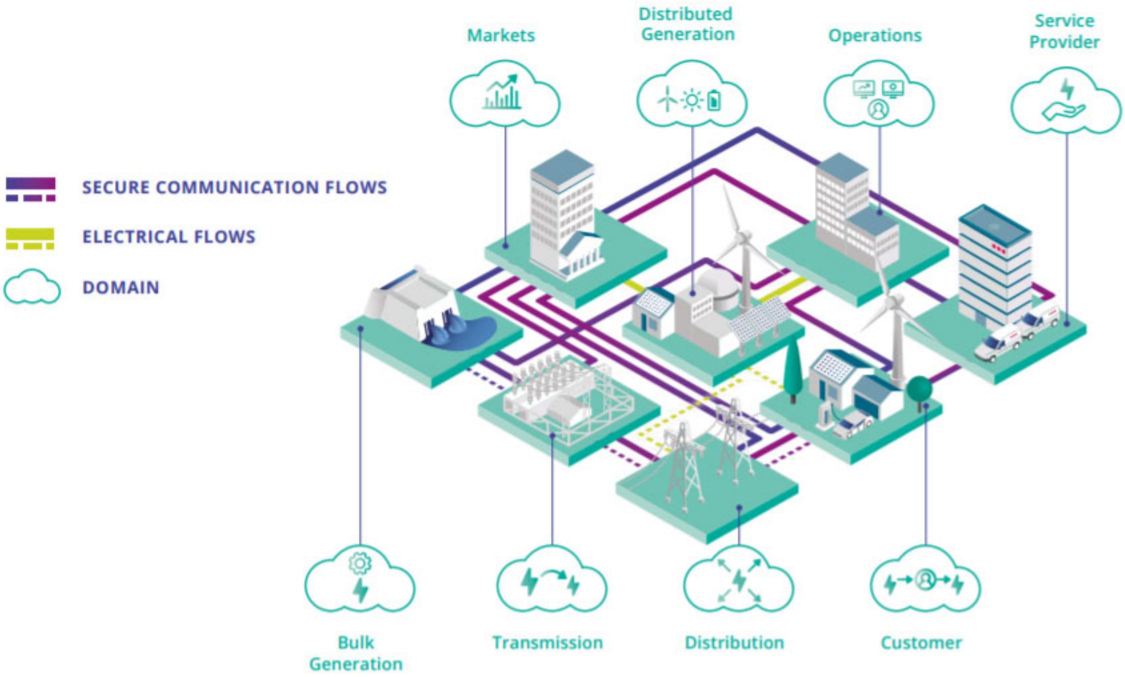


*Figure 3.2.12 - Interaction of actors in different Smart Grid Domains through secure communication flows and electrical flows. Source: NIST Framework and Roadmap for Smart Grid Interoperability Standards.*

Focusing on current energy management platforms, they still have shortcomings in terms of automation, interaction and intelligence. Thus, when the traditional energy grid is evolving into a smart grid, it needs to integrate ICT and power electronics massively. The ECS empower the electrical utilities providers and consumers, improve efficiency and availability while constantly monitoring, controlling, and managing the demands. The huge complex networks need cross-sectional approaches for monitoring and control to achieve efficiency, security and reliability of the communication and electrical flows (Figure 12) - all based on new ECS technologies.

To ensure security, reliability and stability of the total energy system, it is important to know the current state of the system at all times. Therefore, observability and state estimation together with forecast of expected production and consumption play an important role. This requires automation of the grids, use of sensors at different levels, storage of data, AI and machine learning to operate the grids in an optimised way and at the same time obeying data security and GPDR. Data collection within the grid needs to be limited on chosen parameters to avoid unnecessary costs and complexity.

The IoT technology as application in the smart power grid can help to achieve sustainable energy, low latency, and reliability.[8]
Machine-learning used for forecasting energy demand in smart grid environment contributes to medium-term and long-term prediction of consumption and production and is able to solve energy management issues through improved accuracy of prediction[9]. It allows administrators to optimise and plan their resources and manage energy inconstancies and variations.
Nevertheless, security concerns and vulnerabilities need to be identified in today's electricity grid and sufficient solutions implemented to reduce the risks to an acceptable secure level.[10]

**Energy Management Platforms for integrated energy systems**

The European electrical power system is undertaking a transformation process driven by targets towards renewable energy sources. A challenge will be that all different energy infrastructures (electric, thermal, molecules) will be interconnected on high, mid and low power/voltage scale but all have completely different time scales of response. Different energy sources from different operators can be managed through ML, algorithmic trading, agile transformation, etc. In this way, challenges of current and future applications like the energy transition and the digital revolution can be faced appropriately.[11] Energy Management Systems (EMS) are required to enable efficient and combined operation of multiple energy systems and components. Within a study that quantitatively examined 98 scientific papers dedicated to EMS in buildings and households, the identified focus areas were mostly the reduction of energy costs or peaks, as well as the increase of comfort. Results show that high computation time is a significant weakness of current EMS. A possible solution to that could be heuristic algorithms. Furthermore, the study suggests that stronger focus on high uncertainties and robustness is needed in order to transfer EMS with operational management and scheduling into practice. The integration of forecast methods also needs further attention. Regarding sector coupling (e.g. heat and electricity), major challenges exist due to great complexity and uncertainties over longer optimisation horizons. Moreover, multi-level EMS in combination with cloud computing offer exciting approaches for new research questions.[12]

**Hardware**

Electrical grids aim to become more distributed, smart, and flexible to meet the increasing electricity demand. For new grids, the trend is to design energy generation and consumption areas together, in distributed form. Therefore, especially power electronic devices play a crucial role to regulate distributed generation and dispersed energy-storage devices together and into the grid. Future power converters also act as edge devices actively contributing to a stable grid either in grid forming devices, virtual inertia and other functions. Hence, the intensive use of power electronic converters in the microgrid brings their control methods to the forefront, which should meet good dynamic response and high reference tracking characteristics[13]. The domain of combining low power and high-power components does require fundamentally new HW solutions. It necessitates heterogeneous integration at the highest and most diverse levels, which leads to unprecedented EMC and thermo-mechanical concerns. It may open the door to developments possible in no other application field. Exemplary, while sensors (e.g. for self-monitoring) placed directly into power switches controlling the energy flow to an entire city, two heterogeneous worlds meet (e.g. kV and pW, MA and nA). The sensors must be able to withstand strong magnetic field changes and temperature fluctuations (300 degrees +), thus requiring research and innovation.

## 3.2.4.5.2 Key focus areas in the cross-sectional tasks

- Self-adaptive control based on Artificial Intelligence / Machine Learning:
    - Data driven analytics (descriptive, diagnostic, predictive, and prescriptive) in smart grid.
    - Fraud detection.
    - Design, development, and application of deep learning in smart grid.
    - Artificial intelligence in advanced metering infrastructure.
    - Predictive and condition-based maintenance concepts resulting in reduced maintenance costs and increased lifetime for equipment and infrastructure.
- Algorithms for status, prediction & demand:
    - Multiobjective optimisation algorithms in smart grid; e.g. forecasting of generation and consumption.
    - state-estimation based on measurement values, simulation values, trained models (machine learning).
    - optimal utilisation of storage systems (community storage, private storage, industrial storage systems) based on technical parameters, demand and generation forecasts, customer preferences.
    - Short/long-term demand and generation forecast algorithms for different energy domains (electricity, warm water consumption, etc.) and integration into overall systems.
    - New theories and applications of machine learning algorithms in smart grid.
    - Data management, weather forecast, energy use forecast with a time horizon of 24 hours and with resolutions of at least 15 minutes (prevalent use of renewable solar, wind, hydroelectric sources according to demand profiles and use cases).
- Flexibility in management of energy supply and price offers to control the demand and avoid grid congestion:
- IT security, connectivity, integrity:
    - Artificial intelligence techniques for security.
    - Smart, secure edge devices for secure data management and control.
    - Energy management systems for low-power/low-cost devices.
    - Smart edge computing and AI for autonomous energy control.
- Hardware Innovation:
    - H-bridge quasi-impedance source inverter (qZSI) for PV Systems.
    - Three-phase back-to-back inverter for Wind Energy Conversion Systems.
    - Ultra-capacitor with high efficiency (95%) and high-power density.
    - New generation of Smart Meter.

## 3.2.5 Timeline

| Major Challenge | Topic | short term | medium term | Long term |
|---|---|---|---|---|
| | | 2024–2028 | 2029–2033 | 2034 and beyond |
| **Major Challenge 1:**<br>**Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems** | **Topic 1.1:** smart electronic control systems for energy conversion and storage | High efficiency converters, smart actuators & sensors, Plug- and Play Functionality, Real Time Digital Twin, Integrated Security System, Status & Health Monitoring, Integrated reference communication interface, self-powering systems for off-grid operation | Further development of intelligent power devices and electronic control towards higher system energy efficiency, lower system costs and integration or newly developed device technologies<br>- 55% GHG emissions | Getting closer to zero emissions (due in 2050) |
| | **Topic 1.2:** ptimised storage possibilities | Control interfaces to batteries, fuel cells, electrolizers;<br>Optimised converters<br>Sensor solutions for cell and module monitoring<br>Battery management systems<br>Self-powered electrochemical energy storage systems (SEESs) | Grid Integration<br>Further development based on the needs and opportunities by larger volumes | Development of excellent storage possibilities to balance energy generation volatility; efficient energy distribution and usage |
| | **Topic 1.3** electric drives for domestic, commercial & industry application | Heat pumps, cooling devices, HVAC development, innovation and installation | Supplying clean, affordable, and secure (made in Europe) energy to these applications | "In all cases, the 2050 target is to electrify these [...] processes with technical solutions based on renewable ("clean") sources." (Green Deal) |
| **Major Challenge 2:**<br>**Energy Management from On-Site to Distribution Systems** | **Topic 2.1:** stable and resilient multi-modal energy management systems | Distributed Generation, Interconnectivity: Renewable energy sources and grid connection | Integration of electricity, heating, cooling, and transport<br>Virtual power plant functionality optimzing match between generation and demand;<br>Secure gateways allowing energy trading,<br>Coupling with energy trading systems (e.g. local energy market platforms)<br>Renewable energy certification (labeling through ECS) | Efficient energy distribution and usage; cost efficiency; high level IT-security |
| | **Topic 2.2:** energy management systems for industrial and residential customers | Development of beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles<br>Handle uncertaintnies at industrial sites through ECS | optimisation module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast;<br>Demand side management for buildings<br>Virtual Energy Market | Energy Management Systems optimizing operation of components for lifetime &revenue |
| | **Topic 2.3:** autonomous control systems | Control of high demand loads for efficient energy distribution | Price-control systems<br>Storage devices provide flexibility, stability and reliability in the grids | Minimise costs, provide peak-shaving; hybrid solutions; novel grid architectures for manufacturing to enable adaptive production optimisation |

| Major Challenge | Topic | short term | medium term | Long term |
|---|---|---|---|---|
| | | 2024–2028 | 2029–2033 | 2034 and beyond |
| **Major Challenge 3:**<br>**Future transmission grid** | **Topic 3.1:** Grid stability during the industrial transition | Development of components for HV transmission for 1-2 MV or even higher voltages<br>New solutions for high power electronics, combined with sensors and ICT for monitoring, control and protection | Further improvements on grid capacity with highest possible efficiency<br>Development of business models that encourage new technological solutions | European Energy transition to zero-carbon emissions |
| | **Topic 3.2:** Resilient systems for the European transmission grids | Water-resistant components/modules<br>Autonomous electricity generators based on fuels cells<br>Modelling<br>Intelligent power devices, systems, and switches | Modelling, weather forecast, sensing data<br>Digital twin<br>ECS for multi-modal energy systems (cooling with excessive energy, use thermal capacities) | Multi-Modality across Europe |
| **Major Challenge 4:**<br>**Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply** | **Topic 4.1:** Regional energy distribution infrastructure | Secure Cross Regional Transmission Infrastructure<br>communication infrastructure to support self-organised local energy communities | Sustainable off-grid supply with power electronics based grid forming capabilities | Energy flows between sectors and their storages ensure the highest use of renewable energy while balancing fluctuations |
| | **Topic 4.2:** Electric energy supply for urban life and mobility | Development of household and public charging infrastructure; charging points on bus lines or terminals<br>Reservation and optimisation services implemented with ICT solutions. | Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimisation<br>Local DC-coupling of various technologies for fast charging at home | Emission free cities with electrification and decentralised storages to improve efficiency and reliability |
| | **Topic 4.3** Storage systems for urban communities | Development of grid-supporting and peak-shaving control algorithms<br>Battery energy/ heat/ cooling storage devices for households | Peer-to-peer trading by using storage systems;<br>Self-consumption optimisation | Support for regional energy management for communities |
| **Major Challenge 5:**<br>**Cross-sectional Tasks for Energy System Monitoring & Control** | **Topic 5.1:** AI, machine learning and algorithms for status, prediction and demand | Data driven analytics and deep learning in smart grid; AI in advanced metering structure; smart sensors with improved data processing; stream processing for real time application | Innovative approaches ensuring clean, secure and affordable energy for EU citizens; multiobjective optimisation algorithms in smart grid; optimal utilisation of storage systems; short-/long-term demand and generation forecast algorithms for different energy domains | Safe and interconnected smart grid netword; cross-sectional approaches for energy monitoring and control; integrated energy systems; optimal match between generation and demand; energy flexibility |
| | **Topic 5.2:** IT security, connectivity, integrity | Smart, secure edge devices for secure data management and control | Artificial intelligence techniques for security | Eliminate security vulnerabilities as best as possible |
| | **Topic 5.3:** Hardware | Improvements in robustness of HW devices to withstand strong magnetic field changes and temperature fluctuations | Good dynamic response and high reference tracking characteristics of power electronic converters; new HW solutions to combine low power and high power components | Optimal regulation of distributed generation and dispersed energy-storage devices; robust devices able to control high energy flows |

## 3.2.6 Synergy with other themes

Energy supply and energy efficiency are fundamental for all other applications from mobility and industry to societal sectors. The requirements on the ECS for the energy applications strongly spark the technology developments in (high-) power electronics but also for sensors, photonics, signal processing, and communication electronics along the full supply chain, i.e., from design to processing to integration.

Hence, the “Energy” Chapter has close links to the "Embedded Software and Beyond", to the "Process Technological Equipment and Manufacturing" and to the "Components, Module, and System Integration" Chapters. Energy applications have specific and often particularly high requirements in terms of reliability, safety, and security, so that they are instrumental for the definition of the research work in the transversal Chapter on "Quality, Reliability, Safety and (Cyber-) Security".

Also, the new communication infrastructure with a huge amount of new application results in an increased energy demand, giving rise to new challenges for the sustainable energy supply.

Due to recent progress in automotive propulsion concepts based on batteries, fuel cells, and hybrid engines, the synergies to the “Mobility” Chapter are particularly high. The new technologies requested for those applications require higher efficiency and reliability, which shows a strong connection to the high priority R&D&I areas listed in Chapter 3.2 “Energy”. The strongest interface is seen in the subjects of charging and storage infrastructure.

Finally, the Power Supply scenario with the availability and integration of several renewable sources with variable power generation profile, can be considered as an example of “System of Systems” (SoS), enabling the synergy with the related transversal SoS chapter. Power management is fundamental for modern and future factories driven by Industry 4.0 concept, where digitalisation plays a key role. Industrial IoT (IIoT), big data, artificial intelligence (AI) are enabling factors for energy-aware systems with full exploitation potential of synergy across several chapters. Furthermore, a synergy with the “Connectivity” Chapter is fruitful to discuss future energy needs for 5G and 6G infrastructures.

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# 3.3

*ECS Key Application Areas*

# DIGITAL INDUSTRY

## 3.3
# Digital Industry

### 3.3.1 Scope

To be able to manage everything in a machine, factory or company network, industries have divided the necessary technologies into levels or technology stacks. In these levels or stacks, sensors and actuators are closest to processing materials or handling items, and therefore seen as the lowest in the hierarchy in the Edge-to-Cloud Continuum. Moving up the levels, you find super-sets and/or System of Systems and/or interconnected IoTs like devices, unit processes, production or manufacturing lines, operations control, company or enterprise business processes, and an increasing number of machines, lines, company boarders, as manufacturing has become more networked, complex, dynamic and global.

The Industry 4.0 changes to the mode of operation have a profound impact on how are managed and operated the factories, supply chains, construction zones and processes. Powerful networked digital tools are needed to achieve the necessary Situational Awareness and control of autonomous vehicles, robots and processes at various autonomy levels. The technological tools that are part of the Web 5.0 concept can encompass such complex non-hierarchical environments.

The European Industry 4.0 movement needs an open-source-based, stable and extensible semantic Internet to overcome user interface, networking and communication challenges. The Internet with smart agents is an overarching concept containing multiple technologies, such as Industrial Internet of Things, Artificial Intelligence (AI), Advanced Data Analytics, Augmented and Virtual Reality (AR /VR). The Internet with Industrial Metaverse (Digital Twins) can be seen as an expanding set of interconnected virtual and augmented worlds, accessible from AR/VR head mounted displays, desktop computers and even mobile phones. The entities that are present in the Industrial Metaverse may be humans, devices and autonomous physical and virtual machines such as Digital Twins and AI agents.

This SRIA addresses the digitalisation of the major European industrial sectors promoting the European sovereignty in the internal manufacturing ecosystem together with future sustainability and greener industrial processes and artefacts. These include discrete manufacturing (e.g. manufacturing of automobiles, trains, airplanes, satellites, white goods, furniture, toys and smartphones), process industries (e.g. chemical, petrochemical, food, pharmaceuticals, pulp and paper, and steel), provisioning, production services, connected machines, UAVs and robots. Emphasis is also given to any type of factories, productive plants and operating sites, value chains, supply chains and lifecycles, new materials for structures and electronic components.

Digitalisation is as a key enabler for the future success of European industry. This Chapter will address the potential for the development of topics such as responsive, smart and sustainable production, Artificial Intelligence (AI) in digital industry, industrial services, digital twins and autonomous systems. As discussed at the end of the Chapter, nearly all of the topics in the Technology chapters of the SRIA are of vital importance to industrial applications. These include standardisation, engineering tools, cybersecurity and digital platforms. To digitise European industry, potentially all enabling technologies will need to be employed to realise the required competitive edge, and of course a focus on digital industry would not be complete without the enabling technologies.

Today, the digital landscape remains fractured, with significant challenges in areas such as standardisation, interoperability, and translating research to real commercial impact. These challenges must be met effectively if we are to achieve a strong, greener, resilient, responsive European economy, where sustainable, human-centric solutions help Europe achieve strategic autonomy into the future.

### 3.3.2 Application trends and societal benefits

As stated in the new industrial strategy for Europe (“Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: A New Industrial Strategy for Europe”, Brussels):

Europe needs an industry that becomes greener and more digital while remaining competitive on the global stage. The twin ecological and digital transitions will affect every part of our economy, society and industry. They will require new technologies, with investment and innovation to match. They will create new products, services, markets and business models. They will shape new types of jobs that do not yet exist which need skills that we do not yet have. And they will entail a shift from linear production to a circular economy.

The digital sector will also contribute to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint. Scalability is key in a digitalised economy, so strengthening the digital single market will underpin Europe’s transition. Europe must also speed up investment in research and the deployment of technology in areas such as AI, 5G, data and metadata management. 5G private networks will become into the industry and at the same time hybrid clouds will enable networks that are sharing content and resources seamlessly. This will be required by Web 4.0 smart services and things: goal oriented intelligent connection of semantic resources. Connectivity will expand between systems and people. Personnel at the mill level will be more aware and artificial knowledge from the cloud will be nearby all the devices, sensors and processes to the human. This can be made more accurate, for example, with precision time protocol (PTP) support on hardware level (industrial devices at least) to get better indoor location (time of flight).

European factories and machines already have a high level of automation and digitisation. Many of the leading end-user companies are European based, and Europe also has a number of significant system and machine building, engineering and contracting companies that have a competitive edge in automation and digitisation. The business environment is changing. Through specialisation in new or niche end products, production is becoming more demand-driven and agile, while production is increasingly geographically distributed. In addition, the outsourcing of auxiliary business functions such as condition monitoring and maintenance is gaining in popularity, leading to highly networked businesses. There are many opportunities for energy, waste, material, recycling optimisation, etc., over the value chains and across company boundaries. Such advantages can only be realised by having a significant increase in digitisation.

This transition should include the adoption of applications that do not require to be kept internal or confidential, as solutions based on web/cloud services allows for the mediation of key factors such as their use by non-AI professionals, and off-line development of advanced criteria models and inferential engines through the expertise of specialised centres.

The exploitation of AI for core business functions generally requires a complete rethinking of data management and their use and tracking inside the supply chain. Instead, the implementation of a System of System (SoS) framework enables the data to be to capitalised on through appropriate actions, in which analysis and analytical tools usually reach their limits. Interaction between systems will be more direct (knowing neural nets). This will require more interfaces that will enable adaptive connectivity with access rights (part of information will remain always hidden). This enabled finally real predictions.

Industrial Metaverse will speed up training of employees. It will enable simulations before actual building physical system. It can be used to help field workers with AR/VR. Even product design collaboration around the world will come possible. Virtual designs will enable building physical products and vice versa: adding digital assets from physical items.

The actual value chain will come from existing installations, as it is unusual for new factories to be built. As new, fast and secure communication protocols will provide easy connectivity and interoperability across systems; this will enable the potential for extensive integration. Easy access to a secure internal network will provide all existing information to users at anytime and anywhere within the plant. Moreover, new interesting features could be accessed through cloud or edge-based computing systems. However, this will require new hardware infrastructure to be added to the plant, along with greater processing power to handle larger amounts of data.

Digital infrastructure and micro services will help evolve business models towards selling added value as a service. Investment in projects will create networks between vendors and providers. In modern business- to-business (B2B) relationships, ongoing R&D and industrial pilots will aim to deliver a range of after-sales services to end customers. Typically, such services will include condition monitoring, operations support, spare parts and maintenance services, help desks, troubleshooting and operator guidance, performance reporting, as well as the increasingly required advanced big data analytics, prognostics-based decision support, and management information systems.

Industrial services often represent 50% or more of industrial business volume, and this share is steadily growing. The share of services is generally higher in high-income countries than in low-income countries. The importance of service businesses in the future is obvious, since they also enable sustained revenue after the traditional product sales, with the service business being typically many times more profitable than the actual product sale itself.

### 3.3.3 Strategic Advantage for the EU

It is important here to note the view of manufacturing from the recent Science Europe report, "Guidance Document Presenting a Framework for Discipline-specific Research Data Management":[1]

Europe is home to a competitive, wealth-generating manufacturing industry and of extremely comprehensive manufacturing ecosystems which accommodate complete manufacturing supply chains. Europe's manufacturing industry is the backbone of the European economy, bringing prosperity and employment to citizens in all regions of Europe.

The EU is a global market leader for high-quality products, and European Industry is the world's biggest exporter of manufactured goods, which represent 83% of EU exports. Thanks to the strengths of its manufacturing industry, the EU annually achieves a considerable trade surplus in the trade of manufacturing goods as depicted in the below diagram. This healthy surplus generated by the manufacturing industry allows the EU to finance the purchase of other, non-manufactured goods and services, such as raw materials, energy (oil and gas), and services. The surplus in manufactured goods thus compensates the deficits which are generated by purchasing non-manufactured goods. However, the surplus generated by EU's manufacturing sector cannot fully compensate these deficits anymore: in the first three quarters of 2022 there was a significant increase in extra-EU trade, driven by rising commodity prices, in particular for energy and food, as the Russian invasion of Ukraine put additional upward pressure on these products. However, in the fourth quarter, exports only increased by 0.9% compared with the previous quarter while imports fell by 8.2% due to falling prices of energy products. In the first quarter of 2023 both imports and exports fell and this continued in the second quarter of 2023 when exports fell by 2.0% and imports by 3.5%. The trade balance improved from a deficit of €155 **billion** in the third quarter of 2022 to a trade surplus of €1 billion in the second quarter of 2023. From Q1 2019 to Q2 2022, as depicted in Figure 3.3.1, there has been a recovery in respect to the strong decline due to the COVID-19 pandemic and implications of the Russian invasion of Ukraine, both affecting the international situation. Nevertheless, even if imports increased a lot in 2021 and 2022, and even if exports are still decreasing, the balance is changed actually at the end of 2023 toward a potentially positive value next year..

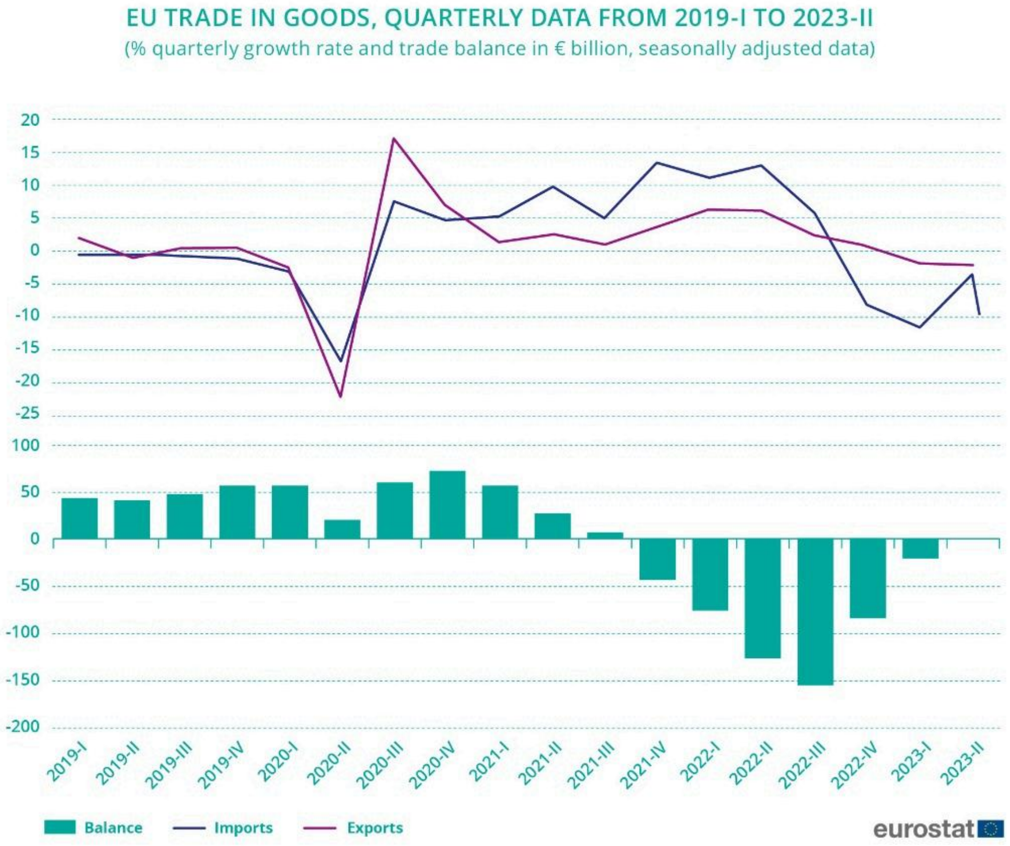


*Figure 3.3.1 - Trends according to Eurostat in International trade in goods for the EU – Extra-EU trade in goods in the period from Q1 2019 to Q2 2023*[2]

The decrease of extra-EU imports in the second quarter of 2023 was mainly due to the energy sector (-15.6 % compared with the first quarter of 2023) and raw materials (-10.9 %), as shown in Figure 3.3.2. With the exception of machinery & vehicles, exports also decreased in this exports report. The largest decreases were for energy (-22.5 %) and raw materials (-9.3 %)

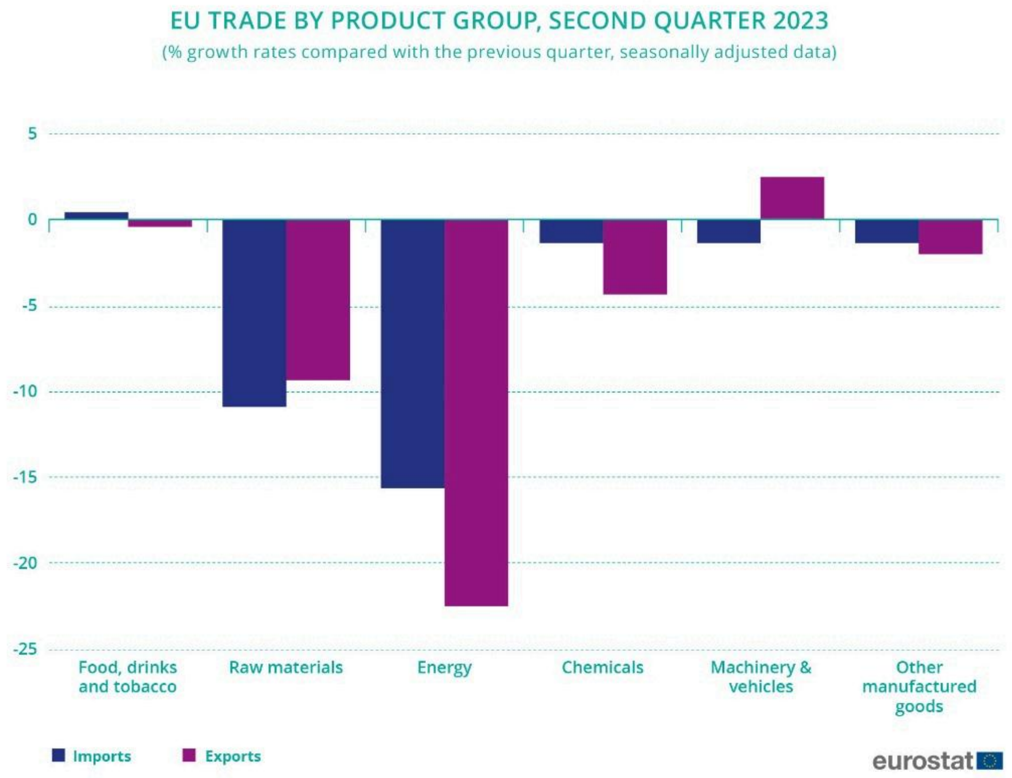


*Figure 3.3.2 - Trends according to Eurostat in International trade in goods for the EU –EU trade by product group second quarter 2023*[3]

Although Europe's industry is a worldwide technology leader in most manufacturing market segments, this position is constantly being challenged by international competitors. While being highly competitive, statistics show that EU manufacturing industries constantly need to keep up with worldwide competition. Competitors, especially from Asian economies, have reached advanced levels, often supported by state-supported programmes and plans. Furthermore, industrial structures are changing with significant foreign investments, including those by emerging economies, in Europe and in the US. And finally, large-scale digitalisation, changes in trade rules, and global environmental concerns create new challenges, demanding EU industries to strongly invest in new technologies and reinforcing synergies internally to the EU rich supply chain.

In addition, it is worth noting the perspective of the recent P4Planet 2050 Roadmap of SPIRE, "Transforming the European Process Industry for a Sustainable Society":[4]

Process industries are an essential part of the European economy. Process industries are crucial components of numerous value chains that deliver goods and services to our society and to European citizens. The materials produced by the process industries ultimately aid in providing shelter and housing to families, transporting passengers or freight, offering comfortable working spaces, producing and preserving food and beverages, and producing the sophisticated devices needed in modern healthcare and high-tech digital world. In other words, process industries enable the life we are living. Currently the process industry provides about 6.3 million jobs directly and 19 million indirectly. Process industries continuously attract talent and incite academia to train the next generation of experts. Process industries contribute about €565 billion/year to GDP, drive innovation, and develop solutions for societal problems.

Focused innovation efforts will transform the European process industries. The process industries will adapt existing processes and develop disruptive new mainly digital processes to fulfil the needs of this society in transition, both in the short and the longer term. New solutions (both technical and non-technical) are crucial. As major technological challenges are similar across process industries, increased collaboration is needed inside EU industrial supply chain in a empowered Edge-to-Cloud Continuum landscape. Europe and its process industries can only succeed in solving the puzzles of climate change and circularity if they jointly define and implement ambitious research, innovation, industrial and financing policies enabling fast and smooth transitions.

As many process industries compete on a global playing field, the competitiveness of these industries needs to be safeguarded throughout the transition. The transformation of EU process industries requires unprecedented levels of investments. If new technologies come at higher cost without a predominant EU ownership, there is a risk that European process industries lose their competitiveness. This needs to be avoided through an effective policy framework, but competitiveness can also be boosted by innovation and scale (e.g. driving down cost of process technologies or of inputs).

### 3.3.4 Major Challenges

Six Major Challenges have been identified for the Digital Industry domain:

- **Major Challenge 1**: Responsive and smart production.

- **Major Challenge 2**: Sustainable production.
- **Major Challenge 3**: Artificial Intelligence in digital industry.
- **Major Challenge 4**: Industrial service business, lifecycles, remote operations and teleoperation.
- **Major Challenge 5**: Digital twins, mixed or augmented reality, telepresence.
- **Major Challenge 6**: Autonomous systems, robotics.

### 3.3.4.1 Major Challenge 1: Responsive and smart production

#### 3.3.4.1.1 Status, vision and expected outcome

Responsiveness, flexibility and smartness is currently considered inside the European productive landscape based on pre-Industry 4.0 automation technology. At the same time, in addition to the critical situations to be handled, European Industry must be much more responsive to any changes that may occur, not only from a scientific and technological point of view.

Today's automation solutions are not inherently flexible by design.

Adaptive and self-learning systems principles must be applied to automation solutions, enabling the automation system and solution flexibility, responsiveness and smartness.

Many European initiatives and reports cover this topic:

- MADE IN EUROPE INITIATIVE with its SRIA[5] prepared by European Factories of the Future Research Association (EFFRA[6]) name as a key priority: the Agile and robust optimal manufacturing towards "… sustainable manufacturing in Europe based on joined expertise and resources. It will boost European manufacturing ecosystems towards global leadership in technology, circular industries and flexibility. The Partnership will contribute to a competitive, green, digital, resilient and human-centric manufacturing industry in Europe. It will be at the centre of a twin ecological and digital transition, being both a driver of, and subject to, change.

- SMART-EUREKA[7] envisions enhancing "the current strengths of the EU discrete manufacturing sector with its leading capabilities and technologies in simulation, modelling, automation, processing and servitising.

- ManuFuture[8] claims that "the European manufacturing system in 2030 must be resilient and adaptive to cope with a rapidly changing and unpredictable environment, overcome disruptions and adapt to meet the changing market needs". In their 2023 report [9], the World Manufacturing Foundation calls to "Digital, Data Driven, AI Based, Mass Customization, Servitised and Circular Business Models

The main benefits of a more responsive and resilient production are:

- Ability to forecast the evolution of the demand-offer-competition ecosystems

- Capability to rapidly change production and provisioning.

- Efficiency to become profitable with high-mix, low-volume production.

- Capacity to operate, even with decreased operational capability.

- Enable rapid concrete innovation, not exclusively via rapid integration and product evolution but also re-engineering the overall process and components production.

- Limit deterioration in performance, reliability, maintainability and interoperability when plants face disturbances.

Chips JU will play a lead role in this evolution to more responsive, robust and resilient factories. From sensors integrated in wearables and prosthetics, to SOS that enable self-healing and self-reconfiguration, responsive and resilient manufacturing has always been an important challenge.

AI will also play a key role in increasing the flexibility of manufacturing systems. One example is AI applied to real-time scheduling that allows a production process to flex around rush orders and disturbances in the line or supply chain. However, while the current trend of deep learning is opening up limitless possibilities in some areas, there is a need to apply other AI approaches that are more explainable, more aware of the environment and the task at hand.

The impact of Covid-19 and recent war in Ukraine with the worldwide impacts expected for the future years has highlighted many of the reasons why a flexible factory needs to adapt better in times of change to be a more useful part of the European response to such crises by:

- Modifying production based on medical needs and exogenous inputs.

- Scheduling production with less human resources and social distancing constraints.

- Empowering agile working and telepresence.

- Adapting to changes in the supply chain, promoting European independence.

- Developing capacity for in-kind, or inside a shorter supply chain for the production of components that usually come from the worldwide market-based supply chain.

- Developing capacity for redesign and re-engineering, due to lack of raw materials and electronic components.

Although automation and digitisation are the building blocks for building a flexible, resilient manufacturing industry, the importance of a well-trained and agile workforce cannot be overestimated. Workforce agility and flexibility, achieved, for instance, through cross-skilling, empowered by smart technologies like AR and VR, make humans indispensable in any production process.

In terms of standardisation, standards are a significant and necessary part of all industrial applications. The modern digitalisation of industry could not exist without standards, as without standards interoperability would not be possible. They enable extensive industrial projects while ensuring quality, safety and reliability. Many engineering methods are standardised, and provide textbook consistency across professional engineering. However, standards must also be supported by the relevant engineering tools, etc., as those required for design or development are different from those required at the operation stage.

### 3.3.4.1.2 Key focus areas

- **Robust optimal production, scalable first-time-right production**: future manufacturing plants should become more robust in the sense they can continue production even when facing a disturbance. This will require advances in, for example, self-healing and redundant automation systems, first-time-right, zero-defect manufacturing, and predictive maintenance empowering very adaptable production.

- **Mass customisation and personalised manufacturing, customer-driven manufacturing**: progress in recent years towards lot-size-one manufacturing and personalised product design will continue to grow in the next few years: IoT sensors will self-correct for disturbances, real-time warehouse connectivity will allow to optimise the shop-floor, edge devices will perform predictive analytics. All of these advances will allow greater flexibility.

- **Resilient and adaptive production, including the shortening of supply chains and modular factories**: Resilience is a critical property for systems that can absorb internal and/or external stresses and adjust their functional organisation and performance to maintain even with a reduced productivity the necessary operations. A resilient factory will continue to operate without any breaks to achieve its objectives under varying conditions and with the ability to overcome that stress to return to ordinary condition of functionality and productivity.

- **Cognitive production**: This involves deploying both natural and artificial cognition alongside IoT devices and data analytics to enable new analytics and learning that can enable responsive and sustainable adaptable production. For example, real-time monitoring against lifecycle assessment (LCA) criteria can be facilitated by the implementation of AI. More generally, it is important for cognitive production to support the emergence of simplicity rather than the combinatorial growth of complexity when complex cyber-systems are combined with complex physical systems.

- **Manufacturing as a service**: Technological advances have the potential to expand the geographical distribution of manufacturing and facilitate manufacturing as a service, MaaS (a well- known example is 3D printing). The trend to move part of labour-intensive production into high value manufacturing exploits MaaS, allowing to outsource parts of the production chain, replacing the need to have dedicated lines and even the whole factory (factory less goods). Another interesting opportunity for MaaS is moveable factories, which circumvent the need for new industrial infrastructure. The scope for moveable factories is enhanced by the range of manufacturing machines and power sources that are becoming increasingly small and light enough to fit into trucks, trailers, carry cases, etc. MaaS empower the dynamic aspects of outsourcing, provisioning, making the supply chain ecosystem more resilient.

- **Embedded/Edge/Cloud architectures**: Nowadays system architectures mainly consist of three layers of computing devices, see Fig. 2.1.1 in Chapter 2.1. *Embedded computing* reside very close or attached to the machinery or process. *Near Computing* devices (2) are often called *edge computers*, routers, or local servers. Near computer nodes are powerful computers themselves and communicate both to the embedded computing cards and to the *cloud* (3) via internet. A special boost in the picture comes from the **5G** technology. There, the 5G communication technology takes care of the edge-to-cloud and edge-to-edge communication which will be faster than anything before. The 5G base stations, called peripheral structures and/or edge nodes, are no longer mere antenna poles but equipped with very powerful computing nodes, and the densely installed 5G base stations will take the role of edge computers. Workload and services are moved from the centralised data centres (core network) to the proximity, benefiting mainly latency which is crucial for time critical application and services.

- **Standardisation**: Due to the ongoing legacies of the many existing standards and their installed base (number of units of a product or service that are actually in use), focus should be on bridging the systems of the various standards. This should involve developing semantic technologies to master these diverse and numerous standards, including software or platforms that enable effective connectivity at a high application level, as well as respective digital testing, development environments and licencing. This is key to ensure there is wide acceptance and support of software vendors, engineering offices and end-users.

## 3.3.4.2 Major Challenge 2: Sustainable production

### 3.3.4.2.1 Status, vision and expected outcome

This **Major challenge** focuses on how Industry 4.0 should address the future regulation or market requirements emerging from the European Green Deal and zero-carbon (or below carbon-neutral) operations.

Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2°C. The rapid transformation of all sectors is therefore required. In fact, many European countries have set even more ambitious targets, and Chips JU could have a great bearing in reducing environmental impact through sustainable manufacturing, including energy- and resource-efficiency and by applying circular economy strategies (eco-design, repair, re-use, refurbishment, remanufacture, recycle, waste prevention, waste recycling, etc).

There are some so-called rare earth metals to save, and any kind of careless materials usage can be proven uneconomical and risk to the environment. The vision of Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) categorises the high-level goals discussed above into more practical action, as follows.

- Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
- Re-use waste streams and energy within and between different sectors, including recovery, recycling and the re-use of post-consumer waste.
- Replace current feedstock (raw material to supply or fuel a machine or industrial process) by integrating novel and renewable feedstock (such as bio-based) to reduce fossil, feedstock and mineral raw material dependency while reducing the CO2 footprint of processes or increasing the efficiency of primary feedstock. Replace current inefficient processes for more energy consumption reduction
- Resource-efficient processes when sustainability analysis confirms the benefits.
- Reinvent materials and products to achieve a significantly increased impact on resource and energy efficiency over the value chain.

ManuFUTURE Vision 2030 combines these objectives as shown in Figure 3.3.3.

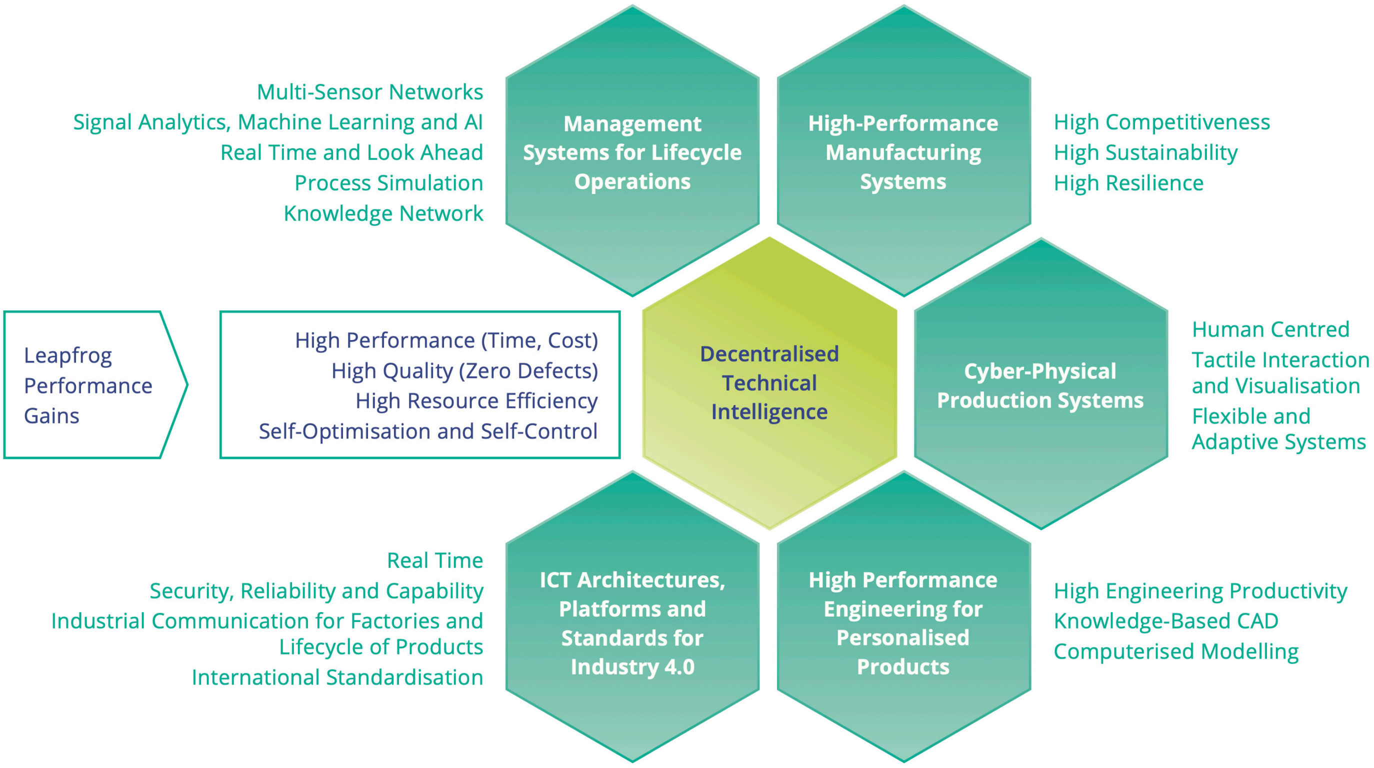


*Figure 3.3.3 - The visionary manufacturing system for adding value over the lifecycle with decentralised technical intelligence (Source: ManuFUTURE, "Strategic Research And Innovation Agenda (SRIA) 2030"[10])*

## 3.3.4.2.2 Key focus areas

- **Monitoring flows of energy, materials, waste and Lifecycle assessment**: It is already commonplace in many industry sectors (food, medicine, etc) that material and energy streams need to be fully traced back to their starting point. As more and more products, raw materials, etc, become critical, this implementation strategy must be expanded. Flows need to be monitored. Sustainable manufacturing needs comprehensive environmental data and other measurements that may have been in place when the relevant manufacturing or production was initiated. On the other hand, this is a very typical application for many types of IoT sensor and systems that can be informed by careful LCA. LCA is a prerequisite for holistic environmental evaluation, and it is a simple but systematic method, that requires a mixed combination of extensive and comprehensive models and data.
- **Virtual AI assistants**: Discharges or losses mostly happen when production does not occur as planned, due to mistakes, the bad condition of machinery, unskilled operation, and so on. Human factors cause most of the variation in the running of continuous processes. There should therefore be a focus on how an AI assistant or AI optimiser could be used to help operators by providing advice and preventing less than optimal changes.
- **Human–machine interfaces and machine-to-machine communications**: Augmented reality (or virtual reality) will be used to support a number of tasks. Enhanced visualisation of data and analytic results will be required to support decision-making.

- **Human operators in more autonomous plants and in remote operations**: the relationship between machines and the human factor needs to be rethought. In terms of the logic of human-machine interface, from touch displays, to wearable devices and augmented reality, but also to maintain the centrality of the human factor within the new contexts. The "Skills 4.0" are necessary for the management of new technologies for data administration, for privacy, for cybersecurity and much more.

- **Human safety**: With the localisation of personnel, machines and vehicles, situation-aware safety (sensing of safety issues, proximity detection, online human risk evaluation, map generation, etc) will become increasingly vital.

- **Competence and quality of work in a human-centred manufacturing**: At a strategic level, the European automation and industrial IT industry depends on its ability to attract skilled personnel to maintain their competence over time. A higher level of formal training may be required for workers in production and maintenance. Greater specialisation is constantly introducing products and processes that require greater company-specific training.

- **Green Deal**: Policy initiatives aimed at putting Europe on track to reach net-zero global warming emissions by 2050 are key to the European Commission's European Green Deal. The Commission the highly challenging objectives of the Green Deal, all industries must focus on high efficiency, low energy usage, carbon-neutrality or zero-carbon usage, zero waste from water, soil and air – all measured, calculated or estimated on product, factory, global and lifecycle levels. European industry must research and discover new materials while paying a great deal of attention to recycling, re-use, and de- and re-manufacturing. NOTE: New RICS-V based computing hardware will be needed to reduce energy used at data centres. Extra 3 x performance will be gained compared to ARM Cortex-A75.

Many of these advances will require extensive development in the other engineering, business or social domains, even at the individual level, that are outside of the Chips JU focus. However, it is also obviously the case that a growing part of these approaches will be implemented through the significant help of electronics and software technologies. The need for Chips JU technologies is diverse, and it is not useful to indicate one single technology here. High performance, high precision, careful and professional engineering and decision-making are needed – often at a much higher level than today.

### 3.3.4.3 Major Challenge 3: Artificial Intelligence in digital industry

#### 3.3.4.3.1 Status, vision and expected outcome

Major challenge 3 focuses on connected and smarter cyber-physical systems (CPS), industrial internet, big data, machine learning and AI. Local edge-based intelligence is seen as an opportunity for Europe. AI optimised and Open hardware becoming more important to support European AI Framework. This Major challenge extends toward AI-enabled, adaptable, resilient factories, including the human as a part of a "socio-technical" system. AI in combination with (predictive) condition monitoring and maintenance will be applied to not only support reconfigurable first-time-right/zero-defect manufacturing, but also to support human decision-making (considering uncertainties), as well as enabling resilient manufacturing ecosystems based on new business models, increasing safety & security in working environments and improving productiveness and quicker return from investments. In this context, Explainable AI (XAI) is another an emerging field for better understanding of decision making to increase human trust. An important challenge here is to lead not only the digital transformation of Industry 4.0, but also the next generation of Chips JU platforms supporting AI-driven human-centric autonomous Industry 4.0 operations. Condition monitoring techniques can be applied to many types of industrial components and systems, although often at additional cost. Commonly, the business value required from condition monitoring depends on the higher availability of equipment and, for production processes, information provision to be able to plan and act on maintenance proactively instead of reactively, as well as to offer decreased cost and improved on-time delivery. Other business values that may be of interest are safety and the optimal dimensioning/distribution of spare parts and maintenance staff. Thus, serious breakdowns and unplanned interruptions to production processes can largely be avoided using condition monitoring.

AI will impact several main areas, all of which are relevant to Digital Industry improving:

- Productivity, by exploiting AI in the design, manufacturing, production and deployment processes.

- Flexibility, by using AI throughout the value stream, from supply to delivery, increasing the autonomy and resilience of each process in the value chain.

- Customer experience, by using AI to make products faster and with better quality, and to provide more efficient services.

- Assistance to human operators in circumstances of rising complexity by using AI to support the decision-making process with ever-increasing levels of complexity and dynamics.

These fundamental impacts will be experienced in all areas of every market sector. In manufacturing and production, AI will deliver productivity gains through a more efficient resources, energy and material use, better design and manufacturing processes, and inside products and services, enhancing their operation with more refined contextual knowledge.

The agenda here is cross-sectorial, focusing on AI applied in any domain. However, the impact of AI in Digital Industry is of particular significance. Manufacturing is in one of the three top industries for AI investments in 2021[11]

#### 3.3.4.3.2 Key focus areas

**European AI framework**

Figure 3.3.4 sets out the context for the operation of AI public/private partnerships (PPPs), as well as other PPPs or joint undertakings (JUs). It clusters the primary areas of importance for AI research, innovation and deployment into three overarching areas of interest. The European AI framework represents the legal and societal fabric that underpins the impact of AI on stakeholders and users of the products and services that businesses will provide. The AI innovation ecosystem enablers represent essential ingredients for effective innovation and deployment to take place. Finally, the cross-sectorial AI technology enablers represent the core technical competencies that are essential for the development of AI systems.

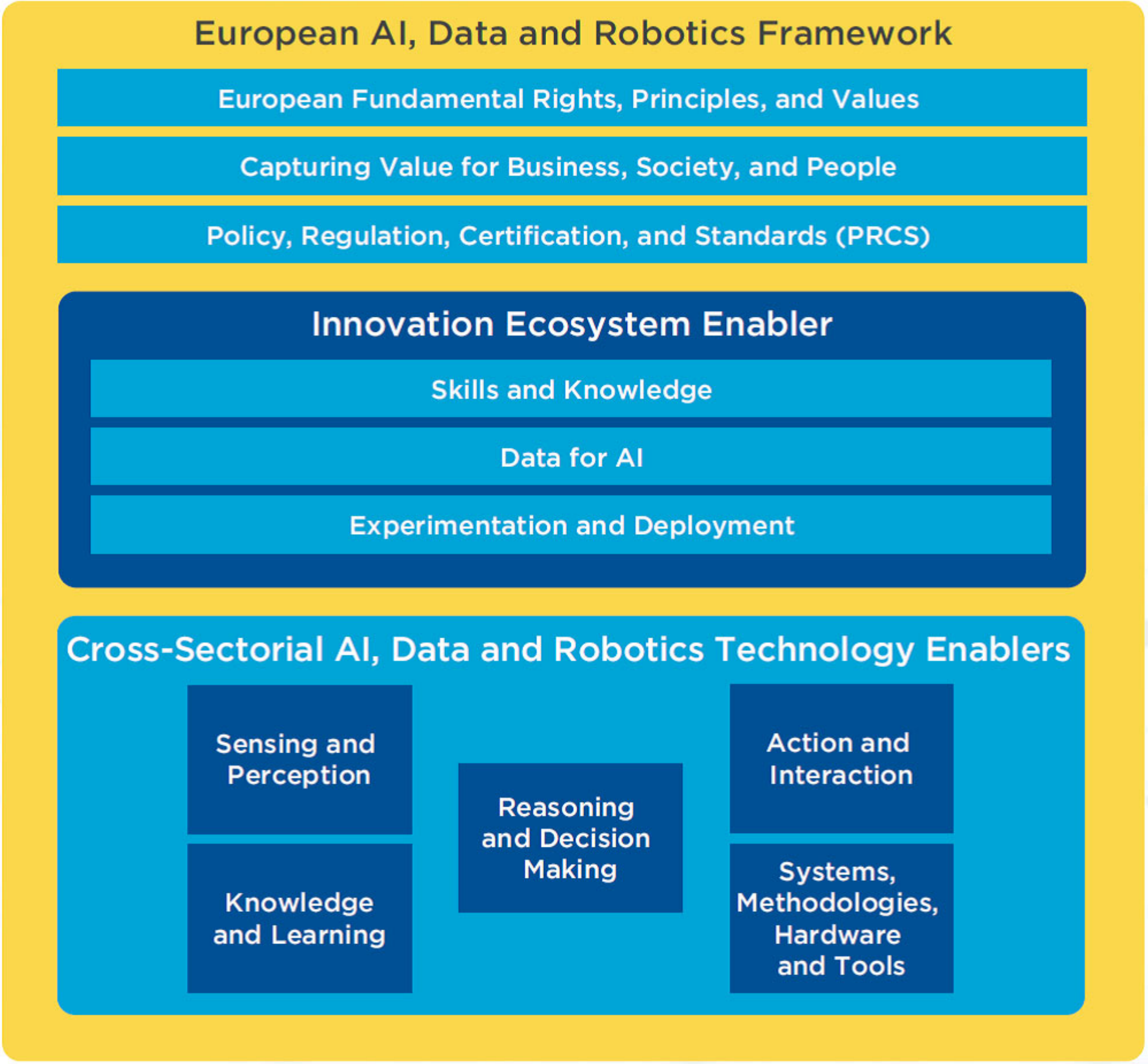


*Figure 3.3.4 - European AI framework and enablers –SRIDA on AI, Data and Robotics Partnership*[12]

**AI in manufacturing**

- AI for dynamic production planning and management: This involves taking real-time decisions to optimise the factory operation by quickly modifying the productions schedule, based on the current state of the shop floor, predicted sales orders, unexpected events such as machine breakdowns or changes in job priorities, etc.
- Virtual models spanning all levels of the factory life and its lifecycle: A holistic and coherent virtual model of the factory and its production machinery will result from the contribution and integration of modelling, simulation and forecasting methods and tools that can strategically support manufacturing-related activities.
- AI for green/sustainable manufacturing**:** The development of software-based decision-support systems, as well as energy management, monitoring and planning systems, will lead to overall reduced energy consumption, more efficient utilisation and optimised energy sourcing.
- AI applied in supply chain management**:** Planning and managing logistics for real-time operations, collaborative demand and supply planning, traceability, and execution, global state detection, time-to-event transformation, and discrete/continuous query processing would therefore be a challenge in view of the distributed nature of these elements.
- AI for advanced manufacturing processes**:** The ability to design functionality through surface modifications, functional texturing and coatings, enabling improved performance, embedded sensing, adaptive control, self-healing, antibacterial, self-cleaning, ultra-low friction or self- assemblies, for example,

using physical (additive manufacturing, laser or other jet technologies, 3D printing, micromachining or photon- based technologies, physical vapour deposition, PVD) or chemical approaches (chemical vapour deposition CVD, sol–gel processes) will deliver high functionality and hence high-value products.

- AI for adaptive and smart manufacturing devices, components and machines**:** Embedded cognitive functions for supporting the use of machinery and robot systems in changing shop floor environments. Open Hardware based AI solutions will also support European AI Framework

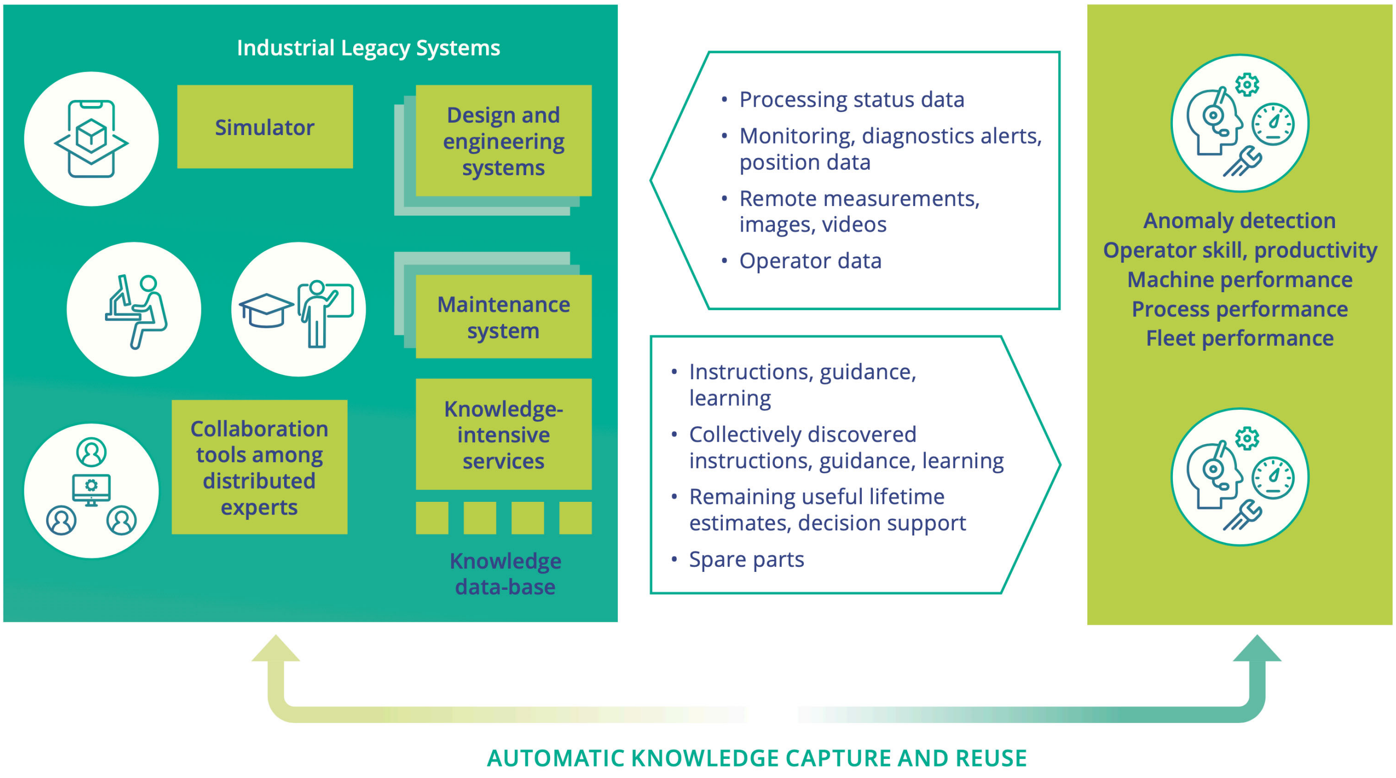


*Figure 3.3.5 Industrial service business between a machine or system vendor or service provider and an end-customer. Services or lifecycle businesses deal with, for example, anomaly detection or condition management, operator skills development, productivity issues, machine or system performances, and fleet performances.*

**AI for decision-making**

Decision-making is at the heart of AI. Furthermore, Explainable AI will increase "human-centric" approaches in autonomous industry.

- AI can support complex decision-making processes or help develop hybrid decision-making technologies for semi-autonomous systems.
- Human decision-making, machine decision-making, mixed decision-making and decision support.
- Sliding or variable decision-making, dealing with uncertainty.
- AI for human interaction with machines.

**AI for monitoring and control**

- AI for control technologies.
- AI for monitoring services.
- AI for maintenance systems for increased reliability of production systems.
- AI services for continuous evaluation and mitigation of manufacturing risks.
- AI for quality inspection.

### 3.3.4.4 Major Challenge 4: Industrial service business, lifecycles, remote operations and teleoperation

#### 3.3.4.4.1 Status, vision and expected outcome

The volume and value of industrial services are increasing by between 5% and 10% every year. The share of services has exceeded the share of machinery for many machines, system and service vendors – not just for a final assembly factory, but also for companies in supply chains. Companies are willing to take larger shares of their customers' businesses, initially as spare part suppliers, but increasingly for remote condition monitoring, as well as extending this to a number of those tasks previously considered as customer core businesses. From a customer point of view, such a shift in business models lies in the area of outsourcing.

Industry as services is changing the production through use of externalisation moving local tasks to external and ever more specialised providers, benefiting of greater flexibility, resilience and adaptability on production; a new proposition of supply chain is embedding all production phases, from the procurement of raw materials and semi-finished products up to the customer services and/or the design of parts or whole final product.

While many businesses have become global, some services are still provided locally, at close to customer's locations, while other services are provided centrally by the original vendor or companies specialised in such services. Similarly, as there may be extensive supply chains underpinning the vendor companies, the respective services may also extend to supply chain companies. The industrial era is becoming a service era, enabled by high-end Chips JU technologies. This distributed setting conveniently fits into modern edge-to-cloud continuum innovative architectures as computing power engines and infrastructures enabling emulation, training, machine learning and communication platforms enabling real-time interconnections.

The importance of service businesses to the future is evident as they enable a revenue flow beyond traditional product sales, and more importantly they are typically much more profitable than the product sales itself.

The service business markets are becoming more and more challenging, while high income countries are focusing on the high-skilled pre-production and lifecycle stages. Fortunately, in the global service business market, Europe can differentiate by using its strengths: a highly skilled workforce, deep technology knowledge and proven information and communications technology (ICT) capabilities. However, to ensure success it needs new innovations and industry-level changes.

#### 3.3.4.4.2 Key focus areas

**Remote operations, teleoperation**

- Remote engineering and operations, telepresence: Operating or assisting in operations of industrial systems from remote sites.
- Edge/cloud solutions: Implementing distributed service applications on effective edge cloud systems.
- 5G with very low latency will be used for remote operations.

**AI Services for monitoring and collaboration**

- Collaborative product-service engineering, lifecycle engineering: Extending R&D to take into account how products and systems will be integrated into the industrial service programme of the company. This should possibly be enhanced by obtaining further knowledge to provide services for other similar products (competitors!) as well their own installed base.
- Training and simulation: Complex products such as aircrafts, drones, moving machines and any tele-operated machineries need a simulation environment for proper training of the human driver/operator.
- Condition monitoring, condition-based maintenance, anomaly detection, performance monitoring, prediction, management: The traditional service business sector is still encountering major challenges in practice. It will therefore require an extension to the above, as targets of services are expanded to other topics in customer businesses in addition to spare parts or condition monitoring.

**Fleet management, Edge and local/global decision making**

- Decision and operations support: In most cases, decision-making is not automatic, whereas in the future it could be based on remote expert assistance or extensive diagnosing (AI-based, etc), engineering, and knowledge management systems.
- Fleet management: This could benefit on the basis of sold items, by obtaining knowledge and experience from range of similar components and machines in similar or different conditions.

**Business services integration**

- Local and global services: Organising services locally close to customers and centrally at vendors' sites.
- Full lifecycle tutoring: Monitoring activities, level of stress and performance-oriented behaviour during the product's life, from anticipating its end of life to properly handling its waste and recycling, including improved re-design for the next generation of products.

### 3.3.4.5 Major Challenge 5: Digital twins, mixed or augmented reality, telepresence

#### 3.3.4.5.1 Status, vision and expected outcome

A "digital twin" is a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance and behaviour of their machines, and also to find new revenue streams. Currently, connectivity to the cloud allows an unprecedented potential for the large-scale implementation of digital twin technology for companies in various industries. A physical asset can have a virtual copy running in the cloud, increasing revenue through continuous operational data.

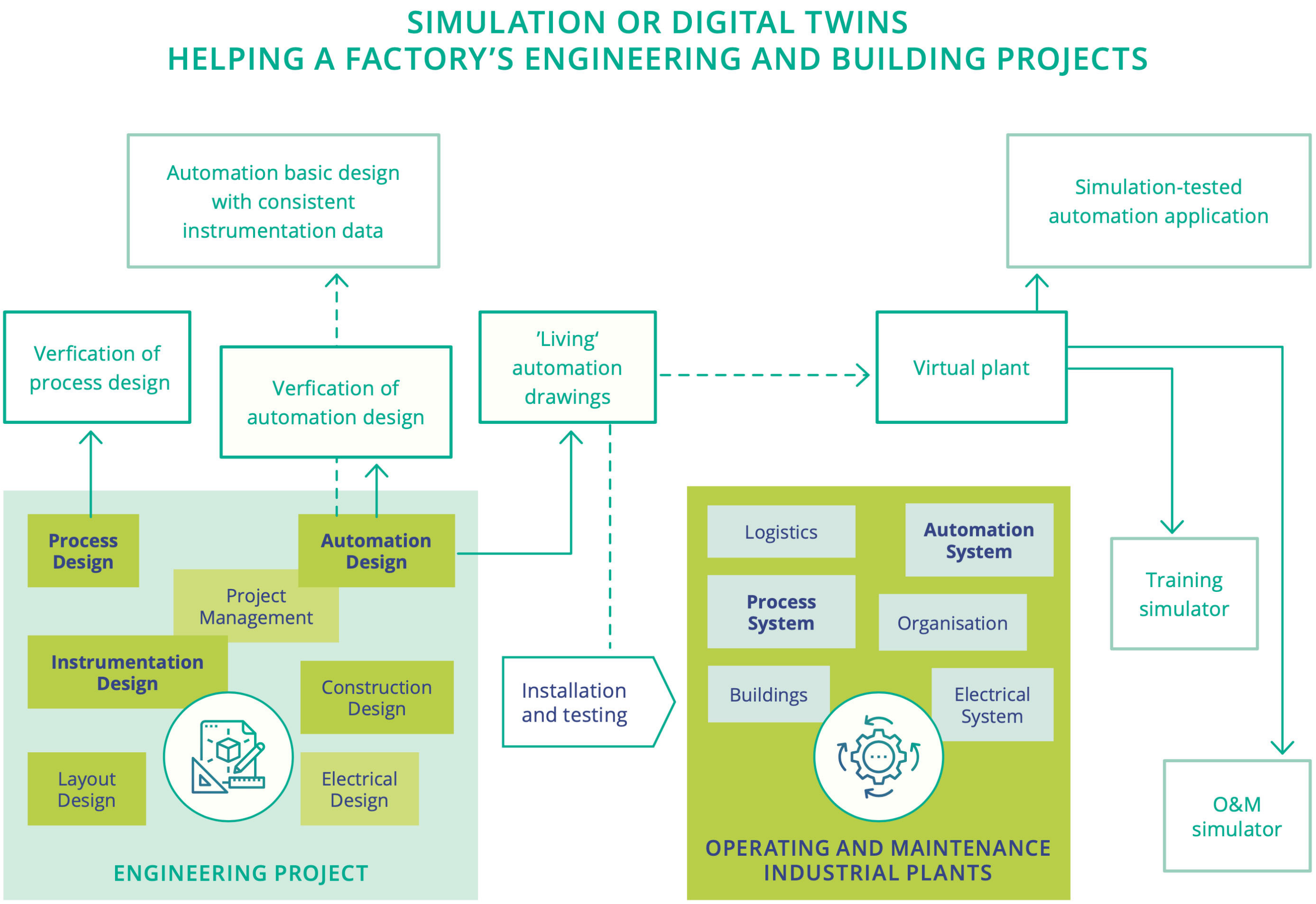


*Figure 3.3.6 - Simulation or digital twins helping a factory's engineering and building projects*

Simulation capability is currently a key element in the European machine tool industry's attempt to increase its competitiveness. In the Industry 4.0 paradigm, modelling plays a vital role in managing the increasing complexity of technological systems. A holistic engineering approach is therefore required to span the different technical disciplines and provide end-to-end engineering across the entire value chain.

In addition to virtual commissioning, modelling and simulation can more widely respond to many digitalisation challenges:

- visualising physical or real-world phenomena of products, production, businesses, markets, etc.
- helping designers to perform their core tasks – i.e., studying alternative designs, optimising solutions, ensuring safety, and providing testing for automation and Internet of Things (IoT) solutions.
- The effects of changes can be safely and more comprehensively assessed in advance in a virtual domain rather than using real plants, equipment or even mock-ups.
- Simulators offer versatile environments for users or operator training.
- It is evident that former computer-aided design (CAD)-driven digitalisation is shifting the focus towards simulation-based design.

Simulators may be used online and in parallel with its real counterpart to predict future behaviour and performance, provide early warnings, outline alternative scenarios for decision-making, etc., although they have years of research behind them, such tracking simulators are to be co-designed and improved exploiting also recent investments in computing infrastructures (e.g. HPC EU families, EPI initiative), with a special focus on the industrial context.

Telepresence technologies can also be considered as the predecessor for an extended reality (XR) presence. The combination of new and advanced technology like e.g. XR, AIoT, Edge, HPC, 5G and open integration platforms offers significant potential for innovation, which would benefit the evolution of European digital industry.

As an example, XR is a combination of virtual and augmented reality, and an XR presence is a continuum between a physical reality presence and a virtual reality presence. The main driver here is improving competitiveness through better productivity, more effective worker safety and better quality. The industrial applications have followed the prospects offered by the gaming industry and consumer applications. One of the reasons for its increased take-up is the declining cost of electronic components and sensors.

As some major smart glass producers will provide technology and a platform for consumers, other EU industrial groups could do the same, and the EU industrial ecosystem could take benefit of such devices and provide industrial use cases. These can be extended then to state-of-art applications. Back-end services are Digital Twins and Condition Monitoring systems that will provide critical and useful information for the Field Worker. Longer vision for the integration human actions and back-end data servers can be used to build knowledge graphs to help other users to work like experts. As a summary; smart glasses can extend human understanding and knowledge if services and information flow can be utilised and formed to usable knowledge.

### 3.3.4.5.2 Key focus areas

**Digital Twin: Design process digitalisation, telepresence**

- Heterogeneity of systems: Information sharing and standards and means to ensure interoperability of digital twins and their information sources are important to facilitate information synchronisation. Having all relevant engineering disciplines (processes, assembly, electronics and electrical, information systems, etc.) evolving together and properly connected over the lifecycle phases is therefore crucial. This also involves multi-domain simulation, joint simulation of multi-simulation systems coupling.
- Immersive telepresence for industrial robotics from design toward production lines and any other operational scope.
- Digital twins applied to sustainability and circular economy: Simulate the usage of energy, use of raw material, waste production, etc., with the goal of improving energy efficiency and circular economy performance.

**Virtual commissioning, interoperability:**

- Virtual commissioning: Digital twins applied to virtual commissioning to bring collaboration between different disciplines and models from domains of engineering (mechanic, electronic, automation) in the same environment.
- Interoperability: Applications cannot yet be used across platforms without interoperability.

**Simulators: Tracking & Simulator based design**

- Tracking mode simulation: Model adaption based on measurements. Generating simulators automatically from other design documentation, measurements, etc. Generation of simulators from 3D, data-driven models, etc.
- Simulator-based design: Digital twin for testing the designed model by replacing the required physical components with their virtual models. This offers continuous design improvement (the digital twin provides feedback and knowledge gained from operational data), design optimisation, etc.

**Digital twins combined with data-driven models (knowledge and data fusion):**.

- Combination of data-driven and knowledge-based models along the complete lifecycle (product and production). The real challenge is to combine physics and knowledge-based models (digital twins) with data- driven models (models created using AI from massive acquired experimental data), capitalising on the strength of information present in each of them.
- New ways to generate large 3D scenes have been based, for example, on NeRF (Near Radial Field) and/or the Gaussian Splats.

**Humans & Knowledge integration:**

- Human-in-the-loop simulations: Methods and simulations for human-in-the-loop simulations and integration of digital twins in learning systems for workers.
- The 3D Internet platform: to integrate all of the aforementioned aspects into a single powerful networked simulation for humans to get the Situational Awareness for an industrial process as a whole.
- Live 3D Digital Twins: to provide the state awareness (animation & color etc.) in AR/VR/XR.

## 3.3.4.6 Major Challenge 6: Autonomous systems, robotics

### 3.3.4.6.1 Status, vision and expected outcome

Machines are usually more precise and efficient than humans when carrying out repeatable tasks. Thus, replacing or aiding work processes susceptible to human errors, quality defects and safety issues with machines will have an impact on quality and redundant waste. The application of AI in robotics and the same robotics without AI extends the opportunity for automation of manual tasks, increasing the sustainability, safety & security of the production and its green transition. This will reduce the environmental impact -efficient reduction of the waste and optimise product quality toward zero-defect, process, and manpower. This will also achieve a more safe and secure working area to ease the human-machine, and machine-machine coworking.

There are many kinds of autonomous systems, robots and working machines. Just to give an insight into their widespread adoption, can be categorised by purpose, as follows:

- Industrial machines and robots:
  - Manufacturing (e.g. welding, assembling, spray gun robots).
  - Material handling (e.g. conveyors, warehouse robots, trucks).
- Consumer robots:
  - Domestic (e.g. robotic lawn mowers or vacuum cleaners).
  - Care (e.g. lifting or carrying robots).
- Healthcare and medical robots:
  - Robotic surgery, hospital ward automation.
  - Medical tests and hospital care, remote healthcare.
  - Medical imaging, exoskeletons.
- Moving machines:
  - Mining machines (e.g. drilling machines, dumpers, conveyors).
  - Forestry (e.g. forest harvester), agriculture (e.g. tractors, appliances).
  - Construction (e.g. excavators, road graders, building robots).
  - Logistics and sorting centres (e.g. cranes, straddle carriers, reachers, conveyor belts, sorting machines, trucks).
  - Military robots and machines.
- Transport:
  - Vehicles, trucks and cars, trains, trams, buses, subways.
  - Aviation (e.g. aeroplanes, helicopters, unmanned aerial vehicles, UAVs).
  - Marine (e.g. vessels, ships, auto-piloted ships), submarine (e.g. auto-piloted submarines).
- Utilities and critical infrastructures:
  - Extraction (e.g. drills for gas, oil).
  - Surveillance (e.g. quadcopters, drones).
  - Safety, security (e.g. infrared sensors, fire alarms, border guards).
  - Energy power plants sensors and actuators (e.g. production and distribution).
  - Transportation (e.g. moving bridges, rail exchanges).

The main aims and evolution trends of robots and autonomous systems in digital industry are oriented toward:

- Production efficiency, speed and reduced costs,
- Higher precision and quality, safety in working conditions,
- To scale up "smart and high-end manufacturing".

As is evident from the above, robots and machines and in particular autonomous systems are involved in all application chapters of this SRIA in addition to **Digital Industry** – i.e. Digital Society, Health and Wellbeing, Mobility, Energy, and Agrifood and Natural Resources- and are positively impacted by any improvement on both technological layers of the SRIA; foundational and cross-sectional technology.

There is undoubtedly a move to increase the level of automation and degree of digitalisation in industry, which will ultimately lead to fully autonomous systems.

However, between low and high technology manufacturing (two extremes: entirely manual and fully autonomous), there will always lie a large area of semi-autonomous equipment, units, machines, vehicles, lines, factories and sites that are worth keeping somewhat below 100% autonomous or digitised. The reasons for this include:

- A fully autonomous solution may simply be (technically) near to impossible to design, implement and test.
- If achievable, they may be too expensive to be realised.
- A fully autonomous solution may be too complex, brittle, unstable, unsafe, etc.
- A less-demanding semi-automatic solution may be easier to realise to a fully satisfactory level.

When the extent of automation and digitalisation are gradually, reasonably and professionally increased, often step by step, they may bring proportionally significant competitive advantages and savings that strengthen the position of digital industries overall. However, since the extent of automation and digitalisation remains well below 100%, any potential negative effects to employment are still either negligible or non-existent. On the contrary, the competitive advantages due to the adoption of robotics and autonomous system solutions increases the market positions of companies and, generally, enhances the need for more people in the respective businesses.

### 3.3.4.6.2 Key focus areas

**Autonomous functions of systems:**

Advances in Artificial intelligence made it easier to achieve fully autonomous systems solutions, exploiting the automation of knowledge and service work into operative physical layers on different application domains, in which to automate work tasks. This is increasingly reducing the need for human intervention and, at the same time, allowing to highlight additional innovative functions, such as in automotive in which more autonomous vehicles are expected to play a key role in the future of urban transportation systems. Such a challenge in a so complex scenario will promote significant advances in any autonomous functions of the many systems which are integral part of the Digital Industry ecosystem.

Autonomous robots are key enabling systems towards implementation of autonomous functions shopfloors. Immediate benefits will be additional safety, increased productivity, greater accessibility, better efficiency, and positive impact on the environment. Here follows a modified picture from giving a generalised view of autonomous systems technologies and functionalities focused on autonomous vehicles, but with a rich affinity with any sort of autonomous system required building blocks.

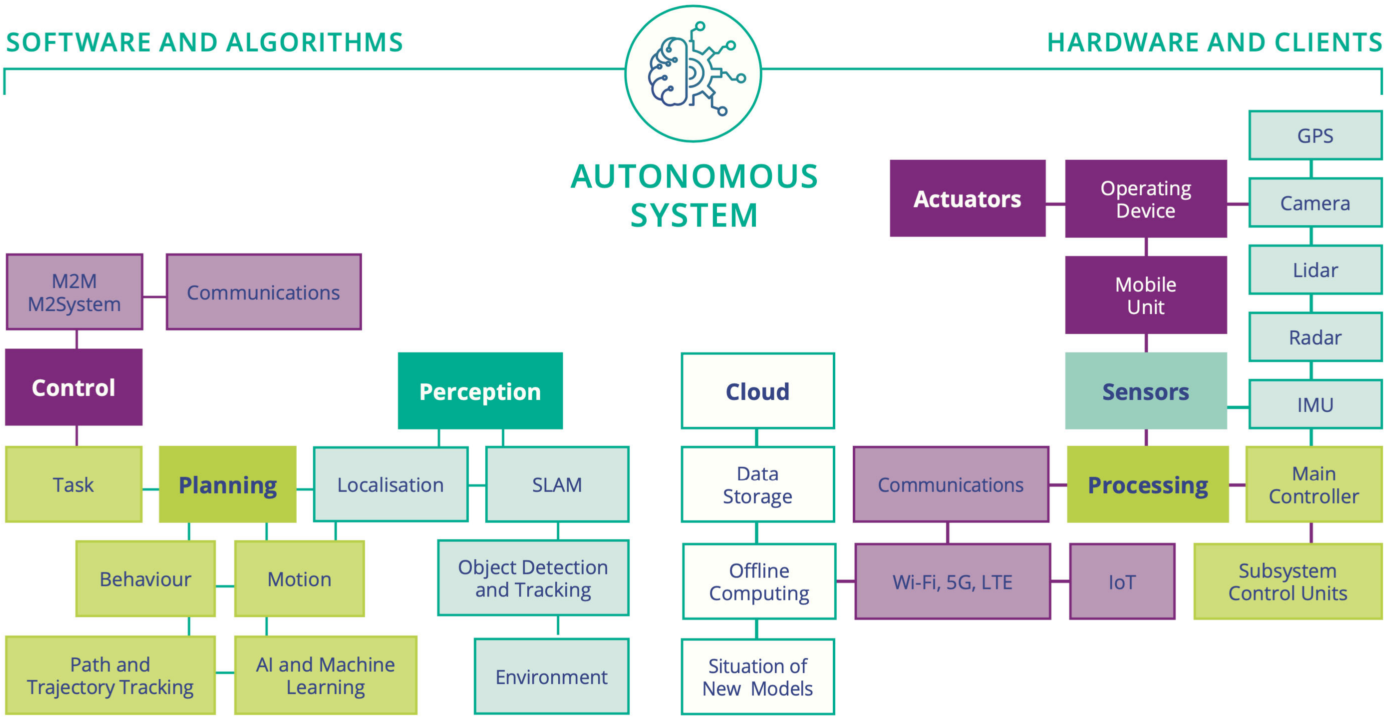


*Figure 3.3.7 - A generalised overview of autonomous system (AS) technologies and functionalities. Adapted from Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). "Perception, Planning, Control, and Coordination for Autonomous Vehicles. Machines", 2017.*

The following picture shows matching of ISA95 standard that define control functions and other enterprise functions with building blocks of autonomous systems. The autonomy is expected to increase in the level 2 and Level 3 of ANSI/ISA95[13].

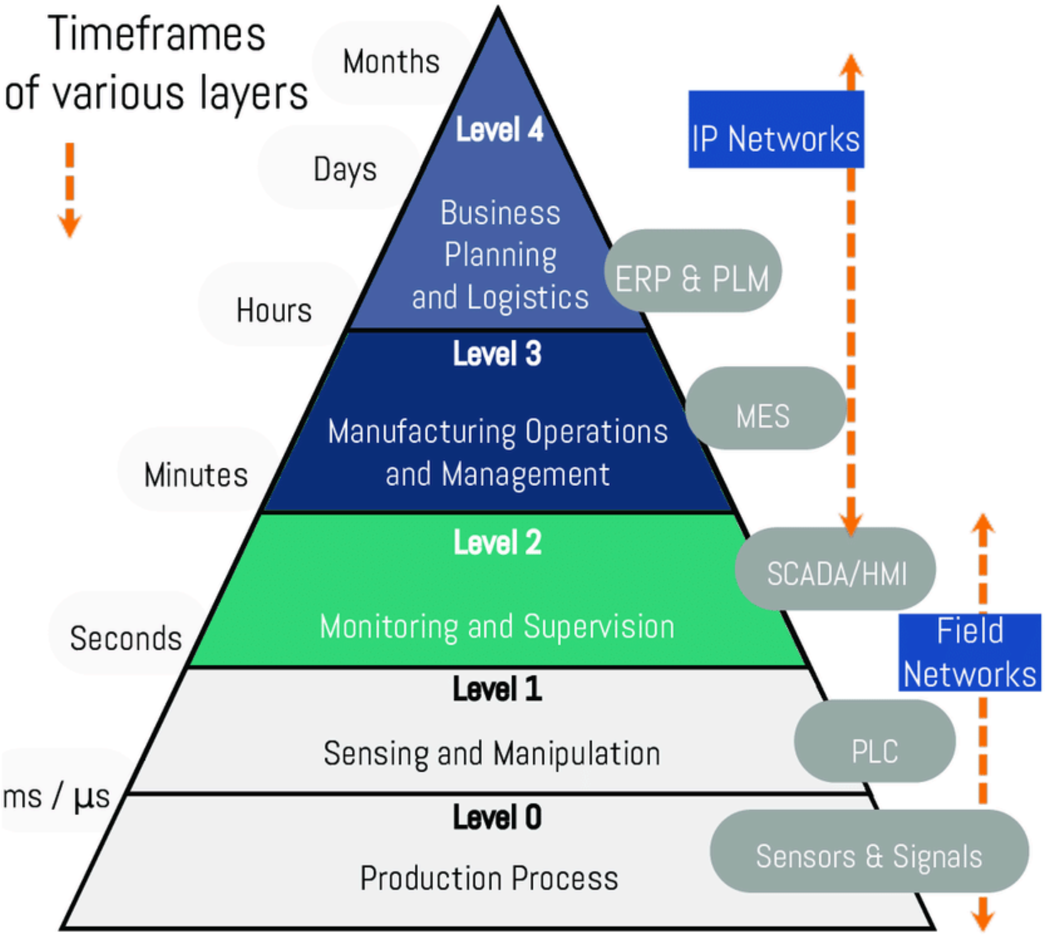


*Figure 3.3.8 - ISA95 Hierarchy Model with building blocks of Autonomous Systems according to the 5 levels of the conventional automation pyramid*[14]

**Safety and security in autonomous systems:**

Current standards of safety requirements for autonomous machines categorise safety into four approaches.

- On-board sensors and safety systems for machines that work among humans and other machines but is restricted to indoor applications.
- An isolated autonomous machine that works in a separated working area, mostly an intensive outdoor environment where other machines or humans are monitored.
- Machine perception and forecast of expected and/or unexpected human activities aimed at:
    - (i) assisting human activities and movements with a proactive behaviour;
    - (ii) preserving human health and safety;
    - (iii) preserving the integrity of machinery.
- An operator is responsible for reacting to a hazardous situation encountered by the autonomous machine when being provided with enough time between alert and transferring responsibility.

**Requirements management and conceptual modelling of autonomous systems:**

With the increasing complexity of autonomous functionality in both AV and ADAS systems, traditional methodologies of developing safety critical software are becoming inadequate, and not only for autonomous driving, but in any industrial field of application of autonomous systems. Since autonomous systems are designed to operate in complicated real-world domains, they will be expected to handle and react appropriately a near endless variety of possible scenarios, meeting expectations from various stakeholders such as the internal engineering teams, people involved in the autonomous systems managements (e.g. passengers, drivers, workers, e-Health patients), regulatory authorities, and commercial autonomous vehicles/robots fleet operators.

**Human–machine interaction in autonomous systems:**

Improvements on sensing capabilities, on actuation control, IIoT and SoS distributed capability are, in robotics and autonomous systems, the key enabler for:

- Human–robot interaction or human–machine cooperation.
- Transparency of operations between human and advanced machine systems (AMS) in uncertain conditions.
- Remote operation and advanced perception, AS oversight and tactical awareness.
- Autonomy intended to enhance human capabilities.
- Natural human interaction with autonomous systems.
- Assisted, safety-oriented and proactive robot interaction with humans.

**Digital design practices including digital verification and validation (V&V):**

- Automatic or semi-automatic V&V.

- A digital design environment, digital twins, physical mock-ups.
- Sub-task automation development, generation of training data and testing solutions and field data augmentation, according to a handful of global machine manufacturers.
- Machine state estimation (assigning a value to an unknown system state variable based on measurements from that system).

**Simulators and autonomous systems:**

- Process model based and product 3D-models approaches, environment and object models, and simulation tools.
- Early design phase simulators.
- Robotic test environments.
- Empirical or semi-empirical simulators, making use of both real and simulated data collected from previous experiments.
- Off-road environments.

**Autonomous capabilities development in a digital environment**

- Autonomous decision taking.
- Self-evolving capabilities.
- Exploitation of knowledge in cognitive flexibility and in adaptability of the reaction.

## 3.3.5 Requirements Overview

The most obvious requirement for Digital Industry is the availability of all technologies, components and systems as described in other parts of this document both as foundation technologies and cross-sectorial areas serving and enabling the European Digital Industry mission.

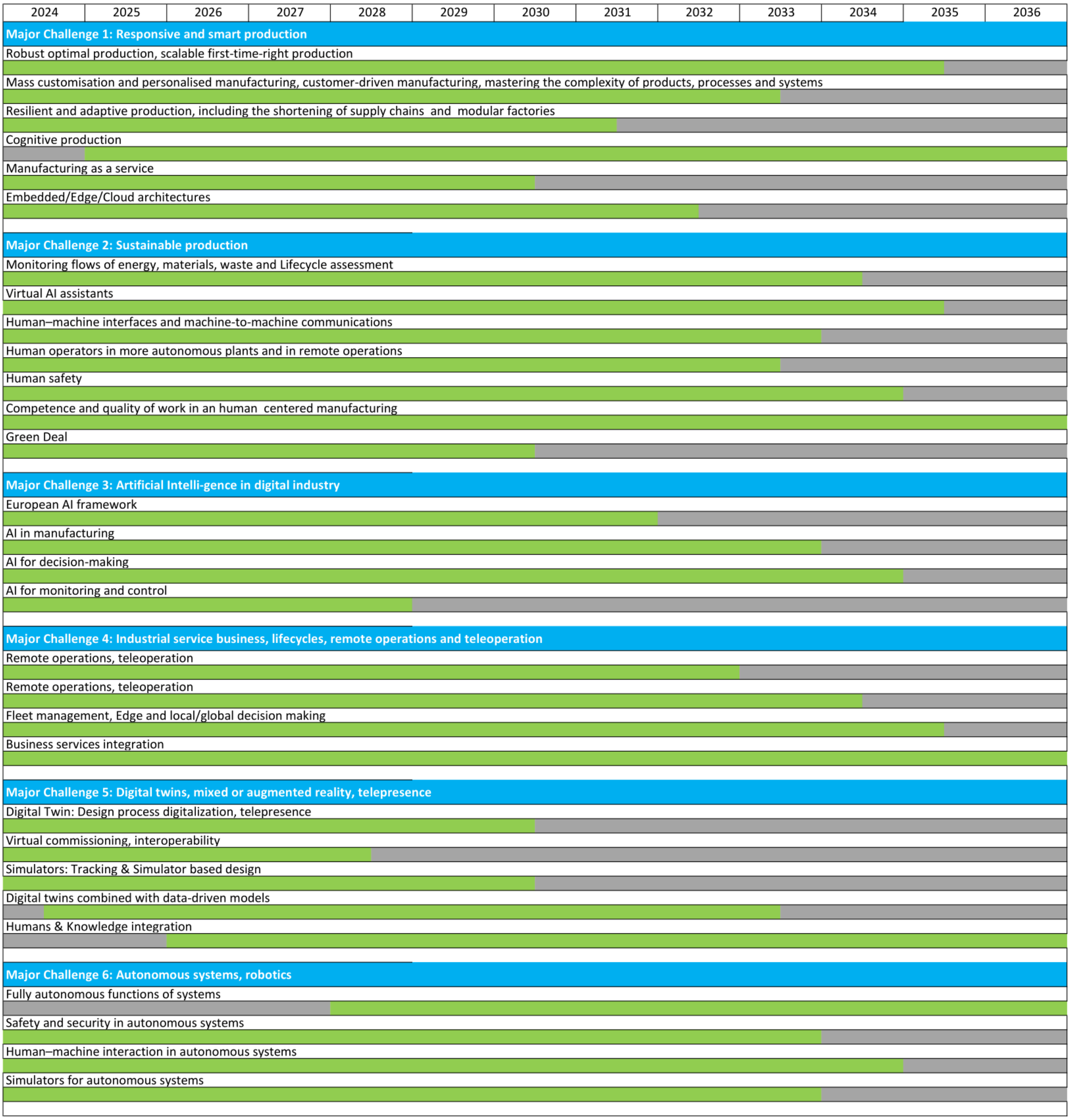
It is extremely important that also a number of societal and policy needs are met, particularly the following aspects of EU legislation, related to working environments:

- Adoption of trustworthy, responsible AI, XR and robotics.
- To foresee exploitations of next generation HW architectures and new chip design (e.g. RISC-V, PIC).
- Adoption of any type of technology safeguarding safety and security of workers.

and the following aspects related to EU policies for the promotion of:

- **Resilience** of EU production capabilities and supply chain towards Industrial EU sovereignty.
- **Sustainability** of EU manufacturing renovation and evolution towards a greener and safer EU.
- **Digitalisation** of EU Industry towards a quicker and better Innovation vocation, cost production and energy consumption saving and capacity to forecast market and societal needs.

## 3.3.6 Timeline



## 3.3.7 Synergy with other themes

**About engineering tools**

Digital twins are commonly characterised by modelling and simulation (the finite element method, FEM, computational fluid dynamics (CFD), etc.) or by virtual or mixed reality techniques, and their numerous applications. However, the product processes, manufacturing design and management of the operative lifetime of a product or factory is much broader. Typical examples of these are: managing the multi-technologies (mechanical, electronics, electrical, software); safety, security and reliability engineering; managing interactions with the contexts of the target (humans, environment); managing testing and quality; the various types of discharges or footprints; managing projects, logistics, supply chains, etc. These tasks are increasingly being managed by software tools and systems, and through the use of standards, regulations and engineering handbooks, which generally require extensive domain knowledge and experience.

The respective engineering disciplines are well distinguished, developed and understood. Key examples here – such as factory design, electronics design, engine design and car design – are well-known and significant as regards success. These disciplines are going through a tremendous and demanding digitalisation process, sometimes called the “other twins” to underline their importance and high value. A narrow focus on digital twins will certainly play a growing role in implementing the concomitant increase in types of “other twin”.

There is also a notable discipline called “systems engineering”, which describes both aspects and the whole of the instantiated subfields such as factory design and engine design. Similarly, many notable software tools – such as product lifestyle management (PLM), supply chain management (SCM) and CAD – are actually families of tools with significant versions for the actual subdomains:

- Parallel joint engineering of products, processes, safety, security, cybersecurity, human factors, sustainability, circular factors, etc.
- Mastering the deep linkage and complexities in multiple engineering domains and technologies, along with product and process lifecycles in the digital domain.
- Multiplying the engineering extent, efficiency and quality in the digital world.

**About trust, security, cybersecurity, safety, privacy**

Increasingly, industrial technologies are being regarded as critical applications by law, meaning that extensive validation, verification, testing and licensing procedures must be in place. Security must also be embedded in all engineering tools, which strongly suggests that safety is not achieved by testing alone, but should be built or integrated into every lifecycle stage.

Security and cybersecurity are the other side of the coin in the distributed, remote or networked applications that contemporary communication technologies effectively enable. Lacking useful security could easily be a showstopper.

Since safety or security is difficult to achieve and prove, industries prefer to talk about trust and how they expect (and assume) safety and security will be in place for their business partners. Nevertheless, there must be no nasty surprises between trusted partners in terms of security issues.

As regards privacy, there is much idealistic urging by researchers, software enthusiasts, etc., for open data and open software from industrial actors. However, certain data must be kept private by law. In addition, critical applications have been sealed and protected once they have been finalised, otherwise their safety, security, functionalities, etc., cannot be guaranteed. Most industrial applications also involve a great deal of engineering effort and creativity, are very extensive and constitute the core asset of companies that must be protected. Competitive business situations could therefore result in a cautious attitude towards open data and software. Nonetheless, industries sometimes do not entirely know what data is beneficial to keep private, and what should be open. In the era of AI, it may be a challenge to know in advance what could be discovered, for example, in the vast amount of factory or machine data available. It is better to be safe than sorry! Open interfaces, standards, etc., are good examples of practical openness.

**About digital platforms, application development frameworks and SoS**

Analysis of the different roadmaps confirms that the platform landscape is still very fragmented, with open and closed, vertical and horizontal platforms, in different development stages and for various applications. There is a strong need for interoperability/standardisation and the orchestration/federation of platforms. The trend is towards agile, composable, plug-and-play platforms (also that can also be used by SMEs), and more decentralised, dynamic platforms supporting AI at the edge. In addition, future (ledger-based) technologies could provide common services on trusted multi-sided markets/ecosystems.

Existing gaps can still be found in the following topics.

- Moving the focus to industrial and engineering applications. It is important to win the global platform game in various application sectors (which are strong today), and to effectively develop high-level outperforming applications and systems for actual industrial and business requirements.
- Preparing for the coming 5G era in communications technology, especially for both its manufacturing and its implementation within the edge-to-cloud continuum.
- Long-range communication technologies optimised for machine-to-machine (M2M) communication and the large numbers of devices – low bit rates are key elements in smart farming, for instance.
- Solving the IoT cybersecurity and safety problems, attestation and security-by-design. Only safe, secure and trusted platforms will survive in industry.
- Next-generation IoT devices with higher levels of integration, low power consumption, more embedded functionalities (including AI capabilities) and at a lower cost.
- Interoperability-by-design at component, semantic and application levels.
- IoT configuration and orchestration management allowing for (semi)autonomous deployment and operation of large numbers of devices.
- Decision support for AI, modelling and analytics, in the cloud but also in edge/fog settings.

## 3.3.8 References

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# 3.4

*ECS Key Application Areas*

# HEALTH AND WELLBEING

## 3.4

# Health & Wellbeing

## 3.4.1 Scope

**Technological effervescence**

The starting point of this Chapter is a simple statement (dating from 2006…) we have borrowed to the Harvard Business Review: "*Why innovation in healthcare is so hard?*". Thousands of digital health solutions are on the market and thousands more are being developed, mostly by tech companies (including start-ups) entering the sector for the first time rather than traditional healthcare companies.

Many of these companies have great expectations, but they are learning that these expectations can be hard to realise in such a complex sector, particularly when it comes to securing payment for a solution.

Another issue lies in the conventional practices regarding the manufacturing of medical devices, considering that medical devices are developed in this context as a dedicated instrument for a specific application, limiting the expected return-on-investment.

However, gradually, change is coming. The objective of the Chapter is to highlight the business opportunity that the current acceleration of Health Digital Transformation should bring for the ECS community.

*Figure 3.4.1 - Harvard Business Review: "Why innovation in healthcare is so hard?"*

**Healthcare systems sustainability**

Current megatrends highlight the ubiquity of healthcare in our society. Urbanisation is directly correlated to population density with healthcare associated issues. The ageing demographic means more health issues like chronic diseases. The COVID 19 pandemics has disrupted access to health services at global level, while it already needed to be improved for several categories of the world population.

Healthcare costs are escalating worldwide. In 2040, the world will be collectively spending an estimated $20 trillion every year on healthcare, representing a 150% increase compared with 2014, according to a study published in The Lancet. This explains why almost all countries have established an explicit national Digital Health strategy associated with a roadmap to deploy solutions. Technology adoption, through the healthcare digital transformation, is considered as a pivotal element to secure the sustainability of health systems worldwide.

**Opportunity for the European Electronic & Components System industry**

The emergence of so-called P4 healthcare – predictive, preventive, personalised, participatory – as opposed to reactive healthcare, is blurring the lines between medical technology (MedTech), the pharmaceutical industry and electronic components and systems (ECS) industry, opening the way for healthcare innovation. This is a huge opportunity for the European ECS industry, its worldwide MedTech and pharma market leaders, as well as the 25,000 SME MedTech companies across Europe, since the new healthcare ecosystem will rely on digital instruments, advanced electronic sensors and photonics, microelectromechanical systems (MEMS), and the large volume, high-quality, low-cost production capabilities of the ECS industry.

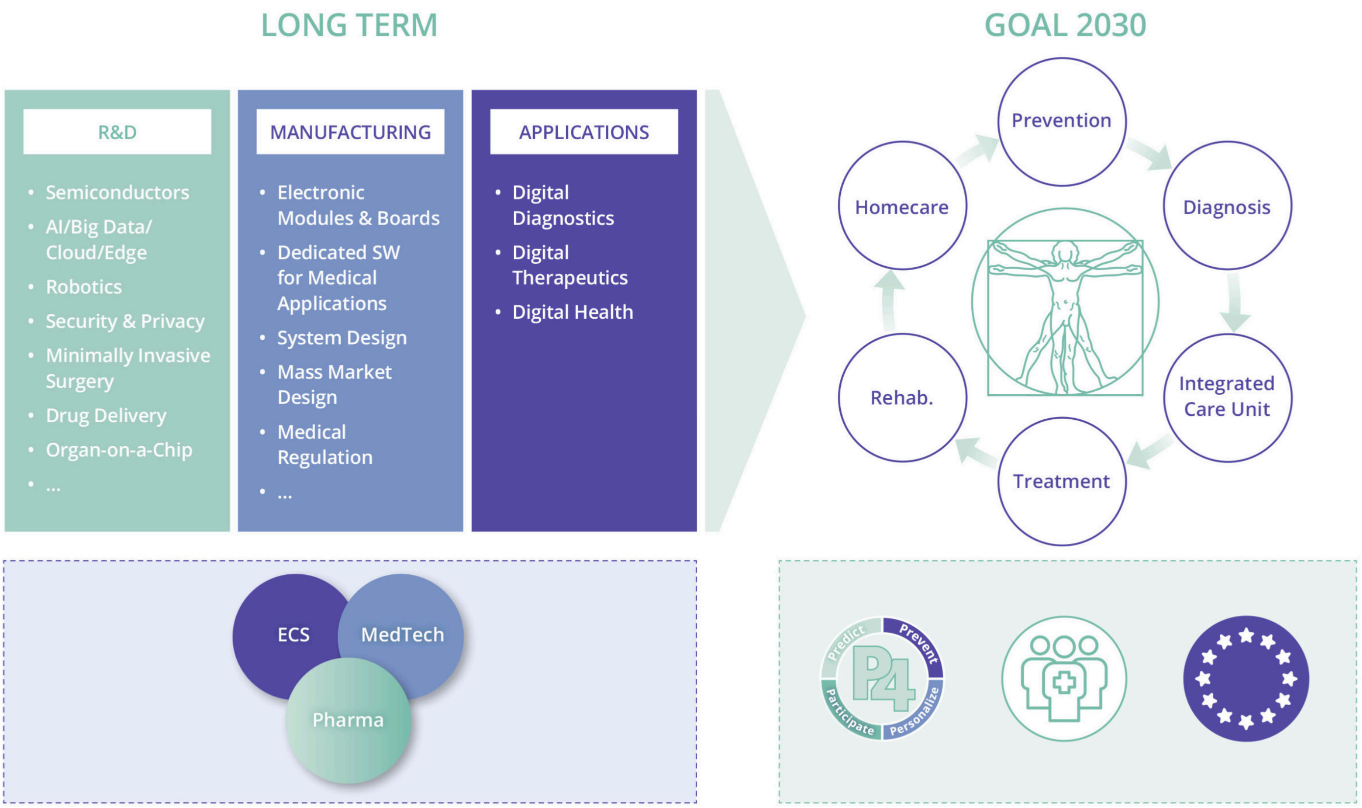

*Figure 3.4.2- ECS Industry impact in Healthcare Digital Transformation*

## 3.4.2 Application trends and societal benefits

### 3.4.2.1 **Application Trends**

Digital health is a relatively new field that is still in its early stages of development.

Wearable devices, remote patient monitoring, prevention, ageing well, P4 medicine are showing great promise for health and wellbeing. The technologies enabled by the chip industry have the potential to significantly disrupt the healthcare industry. They will change the way healthcare is delivered, make healthcare more accessible, and improve patient outcomes.

We already see some effects on projects and proof of concepts, some of them initialised from European public funding. This trend should be amplified for the following reasons.

First, innovation in healthcare is connected to “Industry 4.0”.

“Healthcare 4.0" and "Industry 4.0" are related concepts influenced by different factors specific to their respective industries. Healthcare 4.0 refers to the application of Industry 4.0 technologies specifically within the healthcare sector. The adoption rate of these technologies is slower in health and care due to different regulations, ethical considerations and infrastructure.

“Healthcare 4.0” technologies are fundamentally changing the way healthcare is delivered and received, leading to a more connected, personalised, and data-driven health landscape leading to “integrated care” e.g., the integration of various components of healthcare facilitating coordinated care, multidisciplinary collaboration, personalised medicine…

“Healthcare 4.0” means moving away from centralised clinical models, with a greater focus on patient care outside of hospitals and on behavioural health. “Healthcare 4.0” also has the potential to break down the fragmentation between disciplines. Remote patient monitoring is for instance a cross-cutting application to different pathologies and use cases and opens broader perspectives for manufacturers than the dedicated medical device for a specific pathology. Another correlated and important aspect amplifies this “platform effect”. The boundaries between Pharma, MedTech and Chips companies are blurring due to the digitisation and technologisation of healthcare, e.g., “Healthcare 4.0”. MedTech’s are focusing on the development of advanced wearable devices, implantable sensors, diagnostic tools, and connected healthcare solutions to improve patient monitoring, diagnostics, treatment, and overall healthcare delivery. Pharmaceutical companies are leveraging digital health solutions, such as mobile applications, wearable devices, and remote monitoring systems, to enhance patient engagement, monitor treatment adherence, collect real-time health data, and provide personalised support.

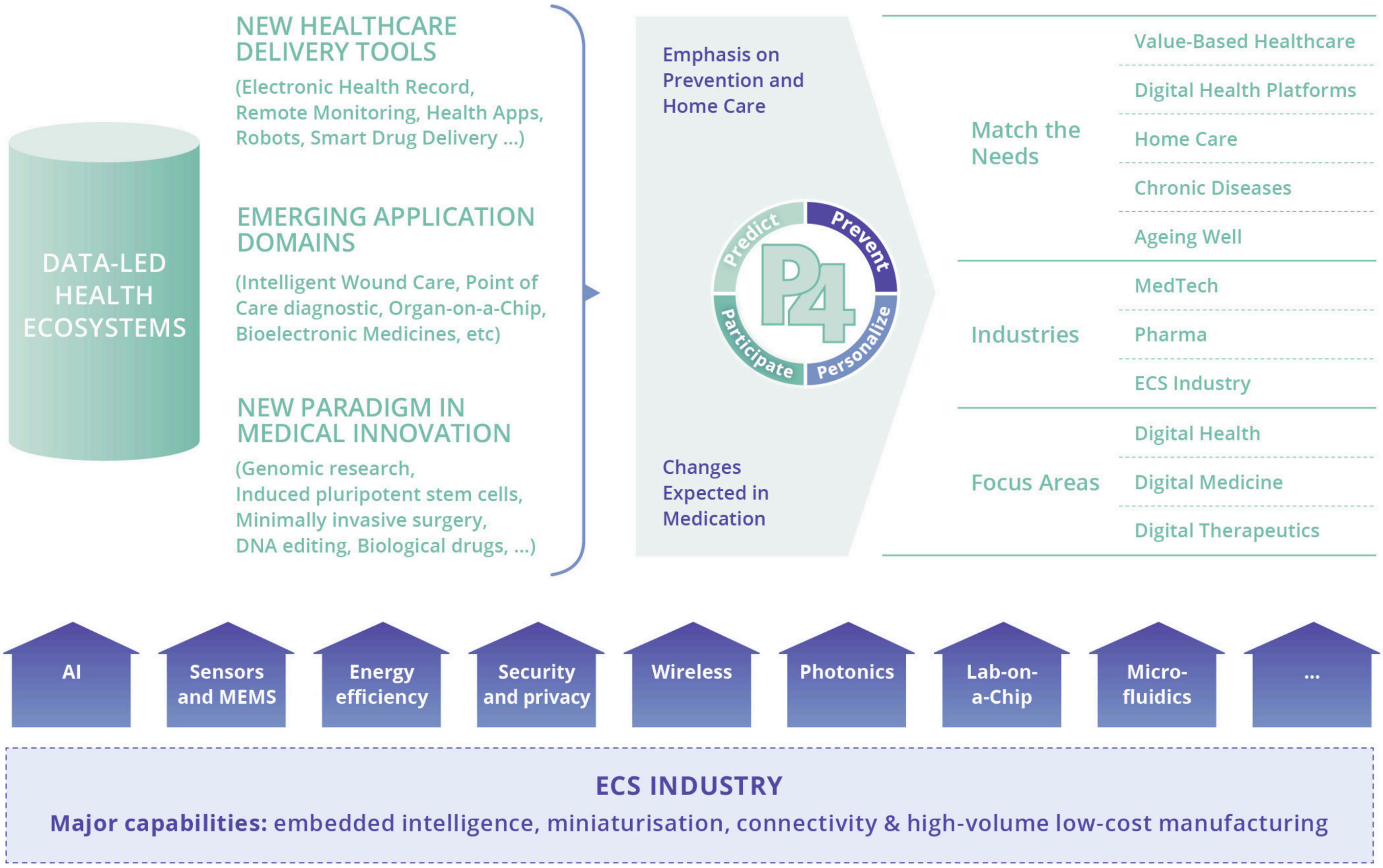

*Figure 3.4.3 - Synergies in Data-Powered Health: Unveiling P4 Medicine & Future Use Cases through Industry Convergence (Source: STMicroelectronics)*

Second, the consumerisation of medical devices leads to an increased demand for and usage of chips. The consumerisation of day-to-day health is tech-driven, with both the involvement of "Big Tech" (Apple Computer, Google, Amazon...) and its most obvious illustration under the form of wearables and consumer apps, is changing the way "Health Consumers" or even "Patients" expect to interact with healthcare.

*Figure 3.4.4 - Healthcare consumerisation: GAFAM's Preponderant Role in Reshaping the Future of Health Tech*

Consumerisation is essential for healthcare systems sustainability, as it emphasises preventive care and early intervention. Consumerisation also encourages innovation and disruptive technologies within healthcare, enabling new care models where patients actively participate in treatment decisions and care plans. Digitisation of healthcare systems is severely lagging the consumer domain and needs reinforcement due to its 'under-the-hood' nature and high complexity and custom requirements, further complicated due to the typically, small product volumes. Consequently, all benefits that we know so well from the consumer domain are missing with many healthcare systems.

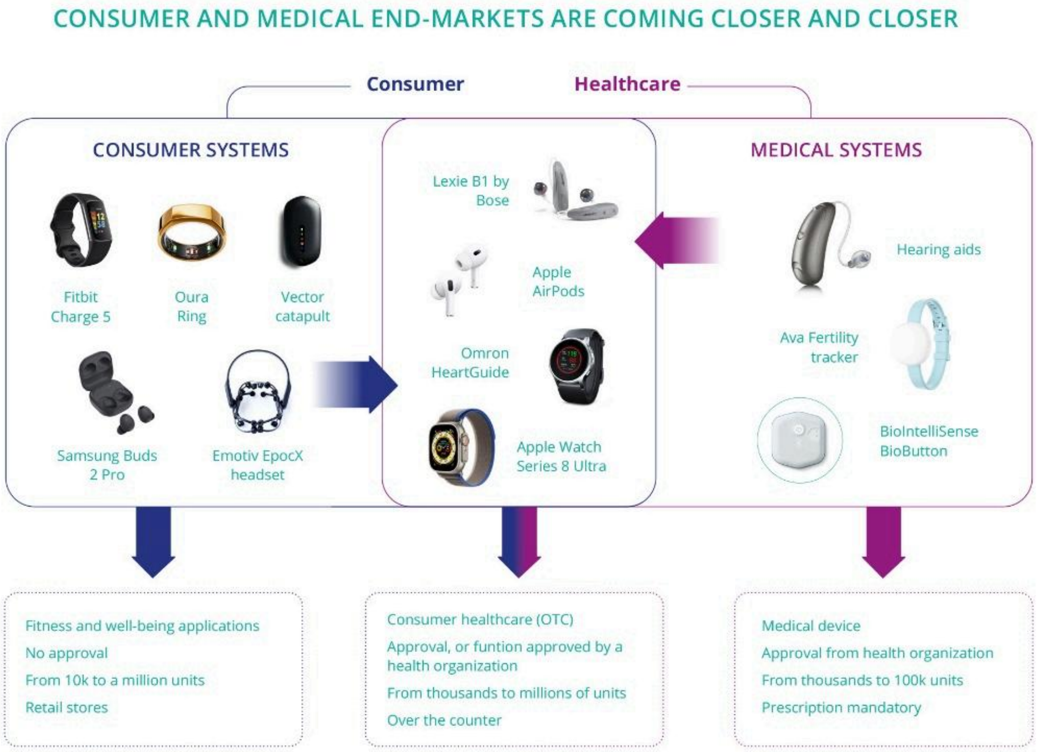

*Figure 3.4.5 - The Merging Paths of Consumer and Medical domains (source: Yole Group)*

Third, data makes customisation on a large scale possible. Customisation is the driving force behind the trend towards P4 medicine. Mass customisation combines the advantages of mass production (high volume, efficiency, and cost-effectiveness) with the benefits of customisation. Mass customisation in healthcare is closely linked to wearable devices and the Internet of Things (IoT), requires AI and machine learning, allows personalised treatment plans through smart drug delivery systems, and may involve point-of-care diagnostic solutions that enable rapid and personalised testing.

#### 3.4.2.2 **Application Trends**

Companies in the MedTech and Pharma industries are transitioning from focusing on individual therapies to providing all-inclusive healthcare solutions, develop scalable platforms that can host a range of digital health services utilising smart devices and data analysis to enhance therapy outcomes and align with value-based healthcare principles.

These initiatives will improve the general well-being and quality of life for many people.

Beyond increased accessibility and cost efficiency, incorporating artificial intelligence and advanced data analytics facilitates better collaboration among healthcare professionals to make highly informed decisions, resulting in enhanced patient outcomes. Moreover, the implementation of predictive analytics aids in the timely identification of diseases, promoting early intervention and preventing further complications. Patients have a more interactive and engaged healthcare experience.

Hospitals and clinics can use data analytics to predict patient inflow and manage their resources more efficiently.

Big data analytics can provide valuable insights into disease patterns, treatment outcomes, and patient behaviours, driving research and innovation, and also monitor and respond to global health crises, like pandemics.

A well-known issue in the Digital Health transformation is that regulation must keep pace with innovation. Innovation is potentially limited by a lack of regulations, specifically in innovative areas such as mobile health, digital therapies, and technologies such as big data or AI.

In the European landscape, regulatory hurdles, ecosystem transformation, accurate and redesigned payment schemes are currently addressed to allow the EU to take a strategic advantage in the Healthcare digital transformation.

### 3.4.3 Strategic Advantage for the EU

There are 27 countries in the EU, and 27 health systems.

This fragmentation in the European market for digital health and care exposes innovators to different requirements and processes to achieve market access across the EU. Additionally, patients are limited in using new solutions outside their country of residence.

But there is a political will to develop uses of digital health by moving towards a European single market through a harmonisation of market access. There are currently a bunch of initiatives conducted at European level to enhance the health digital transformation through a European convergence on Digital health and Care.

According to a 2022 “EY” study – “Study on Digital Health implementation in the EU” - almost all countries have established an explicit national Digital Health strategy associated with a roadmap to deploy solutions. The objectives are quite similar:

- Deployment of core services to the public, either through digital services or by giving access to platforms where health data are stored.
- Improving patients’ empowerment.
- The priority service for most European countries is the National Patient Record, which is the core building block and driving force of the digital health strategy.

The creation of a broad “Digital Health Market” beyond the national markets – namely the “Health Digital Single Market” - is a major milestone to overcome the current fragmentation and scale up digital health solutions in Europe. The purpose is to promote and accelerate the adoption of digital health technologies. These technologies are creating a disruption, considering that the life and innovation cycle of digital medical devices are shorter and faster than that of non-digital medical devices. To adjust to this disruption, the usual market access processes for medical devices must be revised. New tools must be implemented to ensure technology acceptance as well as improving health services and research.

a. Data is at the centre of this digital transformation. Currently, the most successful economic business models are almost exclusively data-based platforms and have generated numerous innovations, including in the healthcare sector. These business models promote practices known as “data colonisation”, e.g., promoting the lock-in of valuable data.

   Initiatives are conducted in Europe to re-examine the value creation of platform-based business models. The current creation of the European Health Data Space, a unified, interoperable system to share health data illustrates the positive initiatives in the EU healthcare landscape.

b. Reimbursement is a springboard for innovation and must be generalised.

   Some countries have now started to establish innovative payment schemes (IPS). They provide a fast-track process for innovative technologies for early market access. It creates a temporary framework that allows innovative technologies to be funded in anticipation of a permanent reimbursement, as it is usually the case with existing market access protocols. Teleconsultation is not part of IPS (this is a digital health service largely reimbursed in the EU).

   The 3 main principles of innovation funding are the following:

   - exceptional funding, ahead of coverage by the mainstream health system,
   - limited period,
   - conduct a clinical or medico-economic study.

   Acceptance into the innovation funding scheme provides fast-track access to the market. A technology accepted into the innovation funding scheme is usually disseminated across the market via the inclusion of patients in the study, with the assurance that there won’t be any interruption of funding for patients between the clinical study and the request for coverage by the mainstream health system.

   According to a survey conducted in 2022 by MTRC across 32 countries, 21 innovative payment schemes were identified in 8 countries (Austria, Belgium, England, France, Germany, Netherlands, Spain, Switzerland). The largest number of schemes were identified in France (n=6), Germany (n=4) and England (n=3).

   Beyond these IPS, which are usually covering non-mature solutions, France has introduced common law reimbursement for clinically mature telesurveillance activities, meaning it enables reimbursement by health insurance since July 2023. The scope covers chronic pathologies (heart failure, renal failure, respiratory failure, diabetes, and implantable heart prostheses). France is the first country in Europe to make it happen.

   Compared to the Digital Healthcare Act – Digital Health Applications Fast-Track introducing since 2019 apps on prescription in Germany -, the French reimbursement covers the full solution, including wearables or other IoT devices. Another difference lies in the larger coverage regarding the medical device classification, since the reimbursement covers only class I and IIa in Germany, while it is covering all classes in France.

   It means overall that progress is made regarding reimbursement and that best practices should be shared all over the EU in a near future.

   We summarised the major building blocks of the European digital health market transformation, with some examples of milestones already established or in progress, in the graph below:

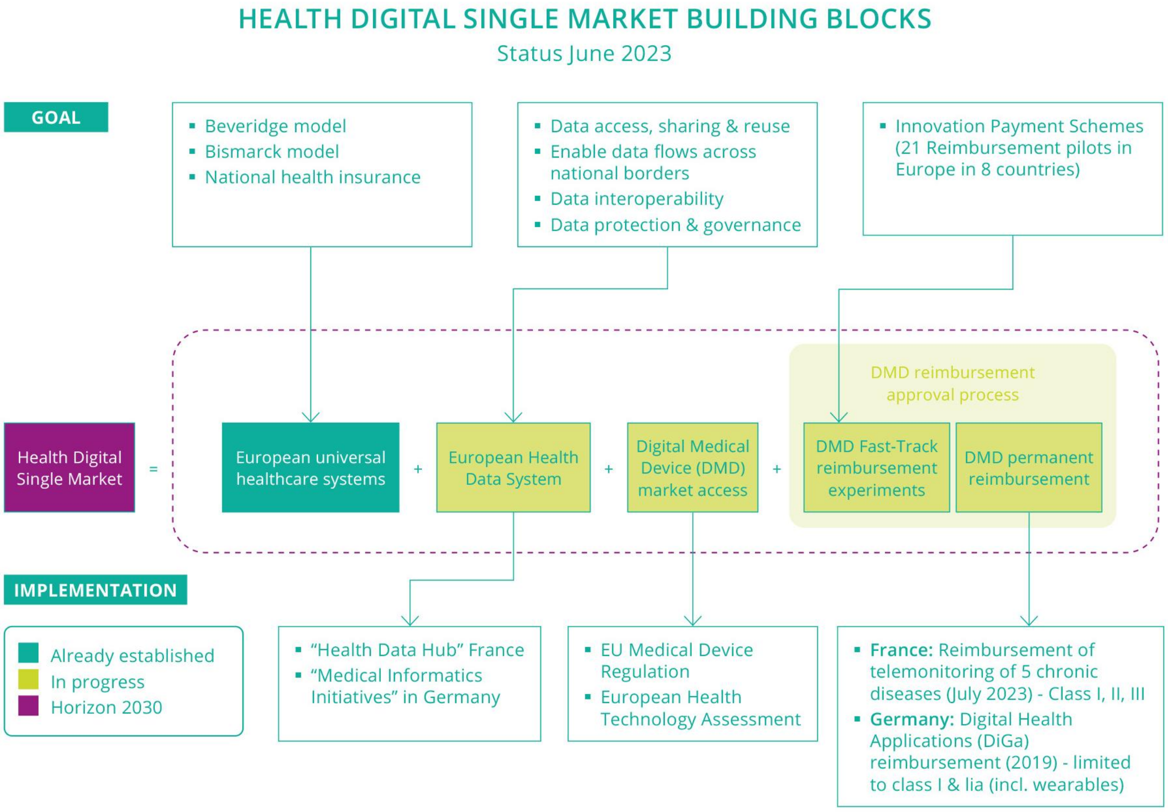

*Figure 3.4.6 - European digital health transformation: towards a health digital single market (Source: STMicroelectronics)*

c. European Digital Health use case integration

It is accepted that wearable technology, miniaturised and connected devices embedding intelligence at the edge can serve as valuable tools for prevention, treatment, and management of chronic conditions such as diabetes and heart disease. Their utilisation for prevention and disease management is promised for substantial growth, which explains why the European healthcare system is currently under a major reconfiguration.

What is currently missing, especially from the Chip industry perspective, is scale.

Integrating digital health use cases creates more opportunities for the adoption of connected devices. When digital devices are seamlessly integrated into healthcare workflows and processes, healthcare providers are more likely to incorporate them into their practices. This adoption can drive the volume of connected devices.

Digital health use case integration involves the incorporation of various digital health solutions and applications into healthcare systems to improve patient care, enhance efficiency, and optimise health outcomes.

Understand healthcare customers' needs requires to collaborate with the hospitals. The hospital is at the centre of the care system. Remote monitoring, home care or ambulatory care are driven by the hospital. Digital health transformation is perceived as a mean to reduce the burden on hospitals and optimise healthcare resource utilisation. This is why it is a great benefit for technology providers to collaborate with entities promoting digital health in the hospital. It is possible to implement frameworks of co-creation, based upon use cases identified by healthcare professionals.

For technology providers, upper in the value chain, an important aspect lies therefore in the end users' interactions, to understand the use cases where technology can provide an efficient value added, which means (specifically from a technology enabler perspective) avoiding techno-push generating weak return on investments.

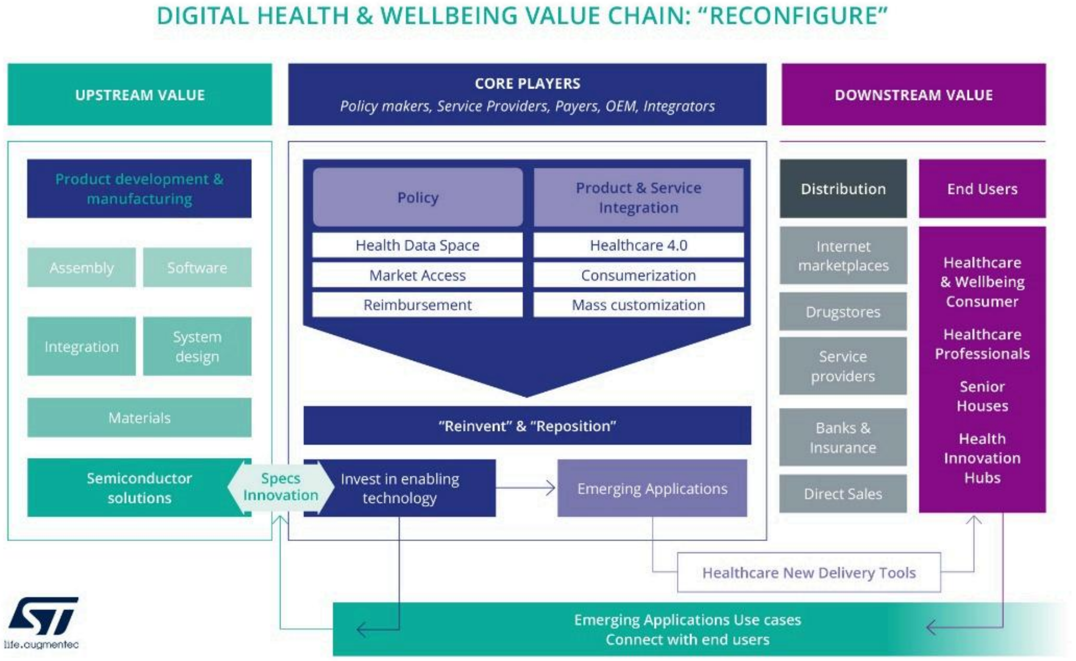

*Figure 3.4.7 - Health Value Chain Reconfiguration: Engaging Stakeholders Across Upstream and Downstream Sectors (Source: STMicroelectronics )*

To give EU this strategic advantage, it is essential to converge towards digital health initiatives harmonisation and collaboration among EU countries by fostering the development of common standards, guidelines, technical frameworks, and collaborative projects, allowing the exchange of best practices and knowledge sharing among countries, enabling the implementation of digital health use cases across borders.

As more use cases integrate connected devices, the volume of health data collected increases, leading to a richer dataset for analysis and decision-making.

This shift - leveraging connected medical devices and health data – allowing early detection of health issues, preventive care towards personalised and remote care - is driving the demand that can facilitate the achievement of sustainable healthcare systems across the EU.

## 3.4.4 Major Challenges

Five Major Challenges have been identified for the healthcare and wellbeing domain:

- **Major Challenge 1**: Enable digital health platforms based upon P4 healthcare.
- **Major Challenge 2**: Enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies.
- **Major Challenge 3**: Support the development of the home as the central location of the patient, building a more integrated care delivery system.
- **Major Challenge 4**: Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases.
- **Major Challenge 5**: Ensure more healthy life years for an ageing population.

### 3.4.4.1 **Major Challenge 1: Enable digital health platforms based upon P4 healthcare**

#### 3.4.4.1.1 Status, vision and expected outcome

The MedTech industry is in the process of transitioning from an industry primarily producing high-end hospital equipment to one that will increasingly serve point-of-care (PoC) professionals and "health consumers", thereby moving from a product-based approach to the provision of "integrated services".

Electronic medical technology, such as the Internet of Medical Things (IoMT), minimally invasive implants, energy-efficient devices, advanced analytics, cognitive computing for advanced clinical decision support, cybersecurity, enhanced network capabilities for continuous data access (to mention only a few of those listed below in the section "Key focus areas"), will support the deployment of P4 healthcare in a data-led environment.

The P4 healthcare vision is therefore not only placing doctors and other health professionals at the centre of the care process, but all those relevant to the health consumer. Even if the healthcare ecosystem is operating in a highly regulated environment, by 2030 we can expect this trend to progressively become the norm. The ECS community should participate in the development of dynamic healthcare systems that learn in real time from every result, achieve a better understanding of treatment response and prognostic heterogeneity, and introduce more refined, patient-tailored approaches to disease detection, prevention, and treatment.

The P4 healthcare vision, enabling for instance early diagnostics based upon merged data and machine-learning techniques through the detection of weak signals, allows preventive treatments that are far less intensive than acute treatments and increase the chances of survival and quality of life. The MedTech industry is not alone on this journey. New pharmaceuticals and treatments will be developed for personalised medicine settings by embedding connected devices and exploiting the potential of the IoT and AI.

This is all creating a new industry, one that revolves around digital health platforms. This platform-based new-market disruption will enable the emergence of specialised platforms, and new players will enter the health domain. This will impact current business models in healthcare, using aggregated data to create value rather than devices – supporting, for instance, proactive services, facilitating outcome evaluation for the treatment of different therapies, and paving the way for outcome-based or pay-per-use reimbursements. This is a potential path to reducing the burden of healthcare expenditures.

### 3.4.4.1.2 Key focus areas

The addition of AI capabilities – person-centred AI-based consumer devices/embedded AI-based medical devices and systems – to Smart Things will significantly enhance their functionality and usefulness, especially when the full power of such networked devices is harnessed – a trend that is often called "edge AI". AI enables much more efficient end-to-end solutions by switching from a centralised to a distributed intelligence system, where some of the analysis carried out in the cloud is moved closer to the sensing and actions.

This distributed approach significantly reduces both the required bandwidth for data transfer and the processing capabilities of cloud servers. It also offers data privacy advantages, as personal source data is pre-analysed and provided to service providers with a higher level of interpretation. It also offers greater reliability and safety.

A high level of digital trust – for privacy and security by design, hardened and embedded AI models – is of course required for executing transactions in healthcare and wellbeing. Securing the IoT ecosystem is a multiple level problem. Privacy should be "by design". In general, integrating security features into an existing system can become very complex, sometimes impossible, and often increases the cost of the final product significantly. A more efficient approach is to consider those security requirements at the very beginning of a project, and then integrate them in the design and development phase. The ECS industry can assist with end-to-end solutions by providing on-chip security, supplying comprehensive hardware and software services, including authentication, data encryption and access management.

Next-generation connectivity – better performing, more ubiquitous, accessible, secure, and energy-efficient networks – will contribute to unleashing the potential of digital health. One of the main characteristics of future networks will be their increased intelligence to improve the performance of the networks, and offer sophisticated and advanced services to the users, due to edge computing and metadata, for instance.

With the significantly growing number of wearables and other small form-factor, battery-operated devices, very low power consumption is a major technology challenge for product designers. The transition from linear to circular economy will require innovative designs for the lifetime of electronic components and systems, and disruptive changes in ECS supply chains, to reduce the ecological footprint. The ECS industry will contribute to improving energy efficiency – including new, sustainable, and biocompatible energy harvesting – to locally process data and the transmission of pre-processed data as opposed to the transmission of high-volume data (such as imaging data).

As a result of improved integration and analysis of multimodal data, new tools for clinical decision-making and precision medicine will emerge, supporting early diagnostics, personalised medicine and potential curative technologies (e.g. regenerative medicine, immunotherapy for cancer).

## 3.4.4.2 Major Challenge 2: Enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies

### 3.4.4.2.1 Status, vision and expected outcome

A major trend in healthcare is the transformation of large healthcare systems to an optimised hospital workflow: a shift from general hospitals treating any diseases towards integrated practice units that specialise in specified disease types. These units, organised around a medical condition, aim to maximise the patient's overall outcomes as efficiently as possible, increasingly through remote access, for patients anywhere in the world.

Pay-for-cure rather than pay-for-treatment can be an effective way to increase the efficiency of healthcare by avoiding unnecessary tests, therapies, and prescriptions. Combined with empowered patients, care-givers should be able to make better informed and more effective choices for treatment. To achieve this, outcomes need to cover the full cycle of care for the condition and track the patient's health status aftercare is completed. This first involves the health status, relying for instance on EHRs supporting precise communication between different care-givers' PoC diagnostic systems or AI-based clinical decisions. Early diagnosis is key for the successful treatment of both modest and challenging medical conditions.

Health outcomes are also related to the recovery and the sustainability of health. Readmission rates, level of discomfort during care, and return to normal activities should be taken into account for both providers and patients. Humanoid robots applying interpreted human body language and emotion in care delivery, sensors, the deployment of companion devices anticipating and contextualising acute or chronic conditions in EHRs involving health models describing the outcome health values for the patients, both in the short term and long term, will have a direct positive effect on readmission prevention.

To achieve this transformation, a supporting IT platform is necessary. Historically, healthcare IT systems have been siloed by department, location, type of service, and type of data (for instance, diagnostic imaging). An innovative and efficient healthcare information infrastructure – integrating IoT with big data learning for optimising workflow, usage, capabilities and maintenance, and of course digital trust – will aggregate the different areas for efficient value-based healthcare, combining prevention tools, early detection, and treatment. This will enable better measurement and facilitate the design and implementation of new bundle-based reimbursement schemes, reducing costs while improving health outcomes. By 2030, value-based healthcare will enable the adoption of optimisation practices already supported by ECS technologies in the industry.

### 3.4.4.2.2 Key focus areas

By 2030, clinical decision-making will be augmented by electronic medical records. Digital centres will enable advanced capabilities for clinical decision-making where AI, real-time data from portable Point-of-Care devices, 3D printing for surgeries, continuous clinical monitoring – including robotics to improve treatments either in the operating room, minimal invasively inside the body, at the general practitioner or at home – will support the integration of specialised care units. A large number of images will be combined with other sensor data and biomedical models to obtain precise, quantified information about the person's health condition, preventing and providing, for instance, early warnings for (combined) diseases supported by patient health models on complex health conditions. Low–latency, massive image processing is a major information source for AI-based automation, visualisation, and decision support within the whole care cycle. Precise quantified and annotated imaging is needed at many levels: from molecular imaging up to whole body imaging. The development and use of accurate digital twins of the human body will enable clinical trials, individualised computer simulations used in the development or regulatory evaluation of a medicinal product, device, or intervention. While completely simulated clinical trials are not yet feasible, their development is expected to have major benefits over current in vivo clinical trials, which will drive further research on the subject. Moreover, "digital twins" will help in combining all the data on a personal level, and enable personalised clinical decision-making.

Europe is a leading producer of diagnostic imaging equipment. In diagnostic imaging, the ECS industry has begun to place great emphasis on accurate radiation dose monitoring and tracking. Healthcare providers are already applying dose management as part of the quality programme in their radiology departments, and patient-specific computed tomography (CT) imaging and personalisation of scan protocols will be a key aspect of patient-centred care in radiology departments, facilitating the management and control of both image quality and dose with the optimisation of 3D X-ray imaging protocols. In particular, CT and X-ray systems based on the emerging spectral X-ray photon counting technology will enable new ways of imaging in order to reduce dose, improve tissue differentiation, enhance visualisation, or quantify materials.

The enormous capabilities of the ECS industry in miniaturisation, integration, embedded intelligence, communication and sensing will have a major impact on the next generation of smart minimally invasive devices:

- Highly miniaturised electrical and optical systems realised using advanced cost-effective platform technologies will bring extensive imaging and sensing capabilities to these devices, and enable the second minimally invasive surgery revolution, with smart minimally invasive catheters and laparoscopic instruments for faster and more effective interventions.
- Sensing and diagnostics solutions need to achieve appropriate sensitivity, specificity, and time-to-result.
- Reducing waste is possible through sensors made of biological materials, combining a biological component with a physicochemical detector.
- Fusion of diagnostics and surveillance will help reducing system and operational costs.
- To realise next-generation smart catheters, a broad spectrum of advanced ECS capabilities will need to be brought together, foremost in dedicated platforms for heterogeneous miniaturisation and integrated photonics. These can be complemented with platforms for embedded ultrasound, low-power edge computing, and AI and digital health platform integration.
- Optical coherence tomography (OCT) is another example where ECS technologies make a critical impact, in shrinking devices and reducing costs, allowing devices to be used in wider fields beyond ophthalmology.

Finally, it should be noted that the development of the next generation of smart minimally invasive instruments will go hand in hand with the development of new navigation techniques:

- Breakthrough innovations in photonics are enabling optical shape-sensing techniques that can reconstruct the shape of a catheter over its entire length.
- MEMS ultrasound technology will enable segmented large-area body conformal ultrasound transducers that are capable of imaging large parts of the body without the need for a trained sonographer, to guide surgeons in a multitude of minimally invasive interventions.
- Combined with other technologies, such as flexible and conformal electronics, low power edge computing, AI, and data integration into clinical systems, new optical and acoustic- based technologies may eliminate the use of x-rays during both diagnosis and interventions, enabling in-body guidance without radiation.
- Augmented reality can be used for image-guided minimally invasive therapies providing intuitive visualisation.

As mentioned above, outcomes should cover the full cycle of care for the condition and track the patient's health status once care has been completed. Biomarkers derived from medical images will inform on disease detection, characterisation, and treatment response. Quantitative imaging biomarkers will have the potential to provide objective decision-support tools in the management pathway of patients. The ECS industry has the potential to improve the understanding of measurement variability, while systems for data acquisition and analysis need to be harmonised before quantitative imaging measurements can be used to drive clinical decisions.

Early diagnosis through PoC diagnostic systems represents a continuously expanding emerging domain based on two simple concepts: perform frequent but accurate medical tests; and perform them closer to the patient's home. Both approaches lead to improved diagnostic efficiency and a considerable reduction in diagnostic costs:

- Point-of-care testing (PoCT) methodology encompasses different approaches, from the self-monitoring of glucose or pregnancy, to testing infectious diseases or cardiac problems. However, it should be remembered that disposable PoC devices will need to be environmentally friendly in terms of plastic degradation and the replacement of potentially harmful chemicals.
- The key enabling components of current PoCT devices must include smart and friendly interfaces, biosensors, controllers, and communication systems, as well as data processing and storage.
- The emerging lab-on-a-chip (LoC) solutions, embedding multiple sensor platforms, microfluidics, and simple processing/storage elements, are currently the most promising basis for the realisation and development of accurate, versatile, and friendly portable and wearable PoCT devices. Their simplified operation mode eliminates the constraint of molecular biology expertise to perform a real-time reverse transcription polymerase chain reaction (RT-PCR) test, will enable innovative in vitro diagnostic (IVD) platforms, making possible decentralisation from highly specialised clinical laboratories to any hospital lab and near-patient sites, with dedicated sample prep cartridges, a more efficient prevention (referring to the recent Covid-19 pandemic) and prompt personalised diagnosis.

In addition, digital supply chains, automation, robotics, and next-generation interoperability can drive operations management and back-office efficiencies. Using robotics to automate hospital ancillary and back-office services can generate considerable cost and time efficiencies, and improve reliability. Robotic process automation (RPA) and AI can allow care-givers to spend more time providing care. For instance, robots can deliver medications, transport blood samples, collect diagnostic results, and schedule linen and food deliveries – either as a prescheduled task or a real-time request. Robotic processes also can be used for certain hospital revenue cycle and accounting/finance functions, such as scheduling and claims processing.

### 3.4.4.3 **Major Challenge 3: Support the development of the home as the central location of the patient, building a more integrated care delivery system**

#### 3.4.4.3.1 Status, vision and expected outcome

The trend towards integrated practice units specialising in specific disease types as described in the previous challenge means that certain procedures can move out of the hospital environment and into primary care and home care. Medical equipment that was previously used only in the hospital or clinic is finding its way into the home. For example, tremendous progress has been made since the "consumerisation" of the MEMS in developing compact, accurate, low-cost silicon sensors and actuators. This continuous innovation will support diagnostic and treatment in integrated practice units, while supporting recovery and health sustainability at home. This trend will be supported by the integration of solutions and services for specific disease groups with hospital units to optimise patient-generated health data (PGHD: continuous monitoring, clinical trials at home, etc), enhanced by the integration of heterogeneous devices and systems used at home covering parts of the care cycle (smart body patches, monitoring implants, remote sensing, etc). Solutions are needed that can be integrated into secure health digital platforms, portable end-user devices, remote e-healthcare and AI front-ends.

In addition, the pharmaceutical market is experiencing strong growth in the field of biologics (genomics and proteomics, as well as microarray, cell culture, and monoclonal antibody technologies) that require preparation prior to administration. Smart drug delivery solutions are now based on innovative medical devices for the automated and safe preparation and administration of new fluidic therapies and biologic drugs. These use advanced ultra-low power microcontrollers that control the process reconstitution of the drug based on parameters identified by the practitioner, together with wireless communication modules to transmit data and ensure the patient and treatment are monitored. Smart drug delivery will improve drug adherence as patients will be empowered to administer expensive and complex drugs in their own home.

In this emerging context, care solutions need to be integrated, combining information across all phases of the continuum of care from many sources – preventing, preparing, and providing care based on person-specific characteristics. This will support the development of applicable biomedical models for specific disease groups, for customer groups and for populations, taking heterogeneous data involving history, context, or population information into account.

#### 3.4.4.3.2 Key focus areas

Supporting prevention, diagnosis and aftercare with sensors and actuators to ensure efficient medical decision, leveraging edge computing and imaging as described in the previous section, will be crucial. The next generation of devices will incorporate increasingly powerful edge computing capabilities. Analysing PGHD from medical devices can be synchronised with a web-based monitoring system. When aggregated, this data can be then sent to the organisation's health data analytics system to process the results and compare them to previous measurements. If the analysis uncovers negative trends in the patient's health status, it will automatically notify the care team about possible health risks. The ECS industry can play an important role here in bringing ambulatory monitoring to the next level. The following enabling technology platforms can contribute to this:

- Low-power technology for sensors, microprocessors, data storage and wireless (microwave, optical, sound) communication modules, etc.
- Miniaturisation and integration technologies for sensors, microprocessors, data storage, and wireless communication modules, etc.

- Advanced sensing technologies for multiplex, painless sensing with high sensitivity and reliability.
- Printed electronics technology for textile integration and the patch-type housing of electronics.
- Low-power edge AI computing for data analysis and reduction.
- Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis, and with patient follow-up systems for feedback).
- Data security technology for interoperability between security hardware and software components (end-to-end information security).

The development of next-generation drug delivery systems will form part of the IoMT – medical devices and applications that link with healthcare systems using wireless connectivity. Smart drug delivery will improve drug adherence so that patients can administer expensive and complex (biological) drugs in their home environment. Enabling platforms are required to facilitate a transition from the legacy mechanical components seen in current autoinjectors and wearable drug delivery pumps, to highly integrated, patch-like microsystems. These include:

- High-performance sensors and actuators for drug delivery, monitoring and control.
- On-board microfluidics for in-situ preparation and delivery of formulations.
- Minimally invasive needles and electrodes for transdermal interfacing, delivery, and diagnostics.
- New materials, containers and power sources that will meet stringent environmental and clinical waste disposal standards.
- Body-worn communication technologies for IoMT integration and clinical interfacing.
- Edge AI for closed-loop control, adherence assessment and clinical trial monitoring.

The development of low-cost, silicon-based MEMS ultrasound transducer technologies is bringing ultrasound diagnostics within the reach of the ECS industry. The ECS industry has the instruments and production technologies to transform these into high-volume consumer products, something no other industry is capable of. Personal ultrasound assisted by AI data acquisition and interpretation will allow early diagnoses in consumer and semi-professional settings, as well as in rural areas. As such, they present a huge opportunity for the ECS industry. It is expected that MEMS ultrasound will enable a completely new industry, with MEMS ultrasound transducers being the enabling platform technology that will drive things on.

Among the emerging applications of advanced MedTech, "smart wound care" – i.e. the merger of highly miniaturised electronic, optical and communications technologies with conventional wound dressing materials – will allow the treatment of chronic wounds of patients in their home without the intervention of daily nursing and/or constant monitoring of the status of the wound. While much progress has been made in wearable technologies over the past decade, new platforms must be developed and integrated to enable the rapid rollout of intelligent wound care. These include:

- Flexible and low-profile electronics, including circuits, optical components, sensors, and transducers, suitable for embedding within conventional dressings.
- Advanced manufacturing techniques for reliable integration of microelectronic technologies with foam- and polymer-based dressing materials.
- Biodegradable materials, substrates, and power sources that will meet stringent environmental and clinical waste disposal standards.
- Body-worn communications technologies for low-power transmission of wound status.
- Edge AI to assist the clinical user in data acquisition and data interpretation.

### 3.4.4.4 Major Challenge 4: Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases

#### 3.4.4.4.1 Status, vision and expected outcome

According to the World Health Organisation (WHO) definition, chronic diseases are those of long duration and generally slow progression. Chronic diseases such as heart disease, stroke, cancer, chronic respiratory diseases, and diabetes are by far the leading cause of mortality in Europe, representing 77% of the total disease burden and 86% of all deaths. These diseases are linked by common risk factors, common underlying determinants, and common opportunities for intervention.

One of the crucial means of coping with the prevalence of the chronic diseases is to achieve a more participative and personalised approach, as such diseases require the long-term monitoring of the patient's state, and therefore need individuals to take greater ownership of their state of health. Most chronic disease patients have special healthcare requirements and must visit their physicians or doctors more often than those with less serious conditions. Technological innovation has already been identified as a great medium to engage chronic patients in the active management of their own condition since digital health offers great convenience to such patients. Access to biomedical, environmental and lifestyle data (through cloud computing, big data and IoT, edge AI, etc) are expected to better target the delivery of healthcare and treatments to individuals, and to tailor each decision and intervention, especially for the treatment of those with multiple chronic diseases.

Patients will be connected seamlessly to their healthcare teams, care-givers and family, as treatment adherence will be more efficient with the innovations mentioned in previous sections. Remote sensing and monitoring offer great promise for the prevention and very early detection of pathological symptoms. Remote sensing and monitoring have the potential to become embedded into everyday life objects, such as furniture and TV sets, while bearing in mind the constraints related to security and privacy. Remote patient monitoring will support clinical decisions with a reduced potential for false alarms, especially for the long-term monitoring and data analysis of patients with chronic diseases.

#### 3.4.4.4.2 Key focus areas

The ECS industry will need to take the initiative in the development of the next-generation treatment of chronic diseases. The field of remote sensing holds great promise for the lifelong and chronic monitoring of vital signs. The deployment of remote monitoring system relies on sensors integrated into bed or chair. Optical sensing techniques, for instance for remote reflective photoplethysmography, as well as capacitive and radar sensing support this approach. This will be multimodal, with fusing techniques to smart analytics to unify the data into usable information. The strength of remote sensing not only relies on the quality of the acquired signals, but also its potential to reveal slowly changing patterns – possibly symptoms from underlying physiological changes. The analysis of such datasets, currently largely unexplored, will provide new insights into normal versus pathological patterns of change over very long periods of time:

- Treatment of chronic diseases will be enhanced by an upcoming generation of small and smart implantable neuromodulator devices, which are highly miniaturised, autonomous, and cost-effective. These will be implanted, wirelessly powered by radio frequency (RF), microwave, ultrasound or energy harvesting with minimal side effects on the selected nerve through a simple and minimally invasive procedure to modulate the functions of organs in the treatment of pain management, brain disorders, epilepsy, heart arrhythmia, autoimmune diseases (immunomodulation), etc.
- Organ-on-a-chip (OOC) platforms, which lie at the junction of biology and microfabrication and biology for personalised and safer medicines, are another treatment approach, addressing, for instance, pathologies currently without effective treatment (rare diseases). Often rare diseases are chronic and life-threatening, and they affect approximately 30 million people across Europe. In an OOC, the smallest functional unit of an organ is replicated. The essential capabilities underlying the OOC field are primarily embedded microfluidics and the processing of polymers in a microfabrication environment. Smart sensors can be used as readout devices, while edge AI will be essential in data interpretation and reduction.

For chronic diseases diagnoses, LoC-based technologies – relying on miniaturisation – show promise for improving test speed, throughput, and cost-efficiency for some prominent chronic diseases: chronic respiratory diseases, diabetes, chronic kidney diseases, etc.

### 3.4.4.5 **Major Challenge 5: Ensure more healthy life years for an ageing population**

#### 3.4.4.5.1 Status, vision and expected outcome

In the last two decades, effort has been made to enhance two important and specific objectives of smart living environment for ageing well:

- Avoid or postpone hospitalisation by optimising patient follow-up at home.
- Enable a better and faster return to their homes when hospitalisation does occur.

The following list includes some typical examples of assistance capabilities related to major chronic diseases covering the first main objective (optimisation of patient follow-up at home):

- Vital signs checker: blood pressure meter, oximeter, thermometer, weight scale.
- Hospital's software interface, the patient’s file, the patient's risk alarm centre with automatic call to healthcare practitioners.
- Video communication support (between the patient and their nurse, doctor, and family), and interactive modules for the patient (administrative, activities, menus, medical bot chat, etc.).
- Authentication and geolocation of patients, with patient or patient’s family consent.
- Teleconsultation for nights and weekends at the foot of the bed of patient’s hospital or retirement home.

The second objective – smooth home return – relates to suitable technical assistance in addition to human assistance:

- Enhance the patient's quality of life and autonomy.
- Improve the patient's safety and follow-up in their room through a reinforced work organisation.
- Allow monitoring of the patient’s progress to motivate them during their rehabilitation period.
- Minimally invasive therapies allowing for shorter hospital stays and improved patient wellbeing.
- First-time-right precision diagnoses to prevent hospital readmissions.

- Prepare for the return home: patient support in appropriating technical aids by integrating these solutions into rehabilitation.

Efforts are being made to enhance medical and social care services through different kinds of robots. The purpose here is to provide advanced assisted living services via a general purpose robot as an autonomous interaction device that can access all available knowledge and cooperate with digital appliances in the home. In this sense, autonomous mobile robots offer several advantages compared to the current (stationary) Ambient Assisted Living (AAL) solutions. Due to sensor-augmented user interfaces, human computer interaction is becoming increasingly natural. As a consequence, robots will come to represent a familiar metaphor for most people.

Neurorehabilitation is sometimes required after hospitalisation and is generally a very complex and challenging undertaking resulting in both "successes" and "failures" (setbacks). Neurological patients typically report having "good days and bad days", which affect performance, motivation and stamina, and where cognitive stimulation (AI-based speech producing programs, social robots, etc), for example, has the potential to improve the efficiency of neurorehabilitation and relieve some of the pressure on health systems. Robotics is well suited for precise, repetitive labour, and its application in neurorehabilitation has been very successful. This is one of the main reasons why the rehabilitation robotics market has tripled over the last five years and, today, rehabilitation robotics is one of the fastest growing segments of the robotics industry. This industry is dominated by European companies that can deliver highly innovative solutions with a strong scientific basis and exceptional manufacturing quality. Based on market size and need, it is projected that the compound annual growth rate (CAGR) for rehabilitation robotics will soon reach between 20% and 50%.

### 3.4.4.5.2 Key focus areas

The ECS industry can significantly upscale the "ageing well" area, as it is enabled by most of the focus topics developed in the previous sections. The industry is playing an important role in bringing ambulatory monitoring to the next level. Important aspects here are reducing costs, improving user friendliness (e.g. easy to wear/use devices, interoperable gateways, reduction of patient follow-up systems) and data security.

The enabling technology platforms detailed below are expected to significantly contribute to this prevalence of the ECS industry in ageing well, taking into account that ageing well is very much related to "ageing in place":

- Low-power technology for sensors, microprocessors, data storage and wireless communication modules, etc.
- Miniaturisation technology for sensors, microprocessors, data storage and wireless communication modules, etc.
- Printed electronics technology for textile integration and patch-type housing of electronics.
- Low-power edge AI computing for data analysis and data reduction.
- Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis and with patient follow-up systems for feedback).
- Data security technology for interoperability between security hardware and software components.
- Robotics systems enabling patients to overcome loneliness or mental healthcare issues.

Interoperability is surely the main challenge faced by the ECS industry in achieving full impact due to the vast heterogeneity of IoT systems and elements at all levels. Interoperability and standardisation need to be elaborated in relation to data and aggregated information. Thus, it is not enough to be able to receive a message, i.e. to understand the syntax of the message, but it is also necessary to understand the semantics. This requirement implies the development of a data model that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons. It must be based on several relatively simple principles: creation of formats and protocols for exchange of data records between healthcare information systems; format standardisation and connected interface unification; improvement of communication efficiency; a guide for dialogue between involved parties at interface specification; minimisation of different interfaces; and minimisation of expenses for interface implementation.

## 3.4.5 Timeline

The following table illustrates the roadmaps for Health and Wellbeing.

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Enable digital health platforms based upon P4 healthcare** | **Topic 1:** establish Europe as a global leader in personalised medicine deployment | • IoMT-enabling patient-generated health data<br>• Expansion of AI on the edge<br>• High level of digital trust – privacy and security by design, hardened embedded AI models | • Development of multimodal data analysis<br>• Improvement of energy efficiency (energy harvesting, etc.)<br>• Secure digital health platforms, portable end-user devices, remote e-healthcare, and AI front-ends | • New tools for clinical decision-making and precision medicine<br>• Scalable digital health platforms |
| **Major Challenge 2:**<br>**lead the healthcare system paradigm shift from treatment to health promotion and prevention** | **Topic 2:** enable the shift to value-based healthcare | • Disease detection from biomarkers derived from medical images and sensors<br>• Predictable and repeatable outcome of diagnostic imaging<br>• Digital supply chains, automation, robotics, and next- generation interoperability<br>• Early diagnosis through PoC diagnostic systems | • Clinical decision-making augmented by a combination of electronic medical records[1], imaging, biomedical models<br>• EHRs supporting precise communication between different care-givers, PoC diagnostic systems or AI-based clinical decisions<br>• Efficient healthcare information infrastructure, lowering costs while improving health outcomes | • Shift from general hospital to specialised integrated practice units<br>• Next generation of smart minimally invasive devices<br>• Disease detection from biomarkers derived from medical images<br>• Outcomes cover the full cycle of care for the condition, and track the patient's health status after care is completed |
| **Major Challenge 3:**<br>home becomes the central location of the "healthcare consumer" | **Topic 3:** build an integrated care delivery system | • Use heterogeneous data from more sources (patient- generated health data, edge computing, and imaging to ensure efficient medical decisions, etc.)<br>• Remote decentralised clinical trials development (smart body patches, monitoring implants for continuous monitoring, etc.) | • Next-generation drug delivery systems (highly integrated, patch-like microsystems) will form part of the IoMT | • Care solutions integrated, combining information across all phases of the continuum of care, preventing, preparing, and providing care based on person-specific characteristics<br>• Holistic healthcare involving all imbalanced health situations of the patient |
| **Major Challenge 4:**<br>**ECS industry supports EU strategy to tackle chronic diseases** | **Topic 4:** enhance access to personalised and participative treatments for chronic and lifestyle-related diseases | • Accurate long-term monitoring and data analysis of patients with chronic diseases and co-morbidities<br>• Make treatment adherence more efficient (smart drug delivery based on innovative medical devices, etc.) | • Development of active or passive implantable medical devices | • OOC platforms addressing pathologies currently without for chronic disorders effective treatment (rare diseases) |
| **Major Challenge 5:**<br>**ECS industry fosters innovation and digital transformation in active and healthy ageing** | **Topic 5:** ensure more healthy life years for an ageing population | • Optimisation of patient follow-up at home to support ageing in place (remote patient monitoring, geolocalisation, etc.) | • Suitable technical assistance in addition to human assistance (humanoid robots, advanced assisted living, rehabilitation robotics, etc)<br>• Precision diagnosis to prevent hospital readmissions | • Data model diffusion that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons |

## 3.4.6 Synergy with other themes

Close collaboration will be useful in all application areas – for example, **Energy, Mobility, Digital Industry, Agrifood** and **Natural Resources,** and **Digital Society** – based on cross-sectional technologies such as **Edge Computing and Embedded Artificial Intelligence, Connectivity** and, of course, **Quality, Reliability, Safety and Cybersecurity**.

More specifically:

- Related to digital industry, "bio-production", which has the objective of developing an innovative field to produce the biologic products of the future through the implementation of disruptive technologies, should be an important topic to address in future years.
- The relationship between food systems and health is obvious and well-identified, especially in preventive health. This is an aspect that needs to be followed to reinforce health prevention in the long term.
- In terms of energy and connectivity, it is important to consider the impact of innovative wearables and implantables, sensors and actuators in general, as they represent a crucial sector with a direct impact on the further development of digital health.

- Embedded systems are an essential enabler of healthcare digital transformation. Medical systems have special requirements regarding hardware quality and reliability, dependability in connected software and human/ systems interaction. Also, privacy and cybersecurity are required to support the expansion of digital health. Related challenges are defined in the transversal Chapter **Quality, Reliability, Safety and Cybersecurity**.

## 3.4.7 References

1. *Electronic medical record (EMR): A computerised database that typically includes demographic, past medical and surgical, preventive, laboratory and radiographic, and drug information about a patient. It is the repository for active notations about a patient's health. Most EMRs also contain billing and insurance information, and other accounting tools.* ↩

# 3.5

*ECS Key Application Areas*

# AGRIFOOD AND NATURAL RESOURCES

3.5

# Agrifood And Natural Resources

## 3.5.1 Scope

In 2022, the conditions of the planet changed abruptly as foreseen by the Intergovernmental Panel on Climate Change (IPCC). According to the latest report from IPCC[1], global warming is causing major changes in precipitation patterns, oceans and winds, in all regions of the world and, in some cases, irreversibly so. The intensification of natural phenomena is putting the viability of life on Earth at risk, and from now on will have serious repercussions on food security, health, and sustainable development. Extreme hot temperatures in normally cold countries; melting of the poles at an accelerated rate, and consequently, rising sea levels threatening coastal areas; prolonged droughts in previously fertile and productive places on different continents; scarcity of fresh and affordable water for human consumption in large cities are just some of the issues we are now facing. Moreover, forest fires have doubled worldwide in the last 20 years destroying around 3 million hectares each year particularly in boreal forests, leaving the largest climate change related carbon deposits on the planet so far according to a study conducted jointly by three institutions: Global Forest Watch (GFW), World Resources Institute (WRI) and the University of Maryland (UMD). The study concludes that we will lose or degrade these important lungs in the medium term despite these forests being one of our best defences against climate change.

There is a strict relationship between climate change and agriculture. The two-way relationship of climate change and agriculture is of great significance because we need to adopt effective practices to mitigate risks to human health and crop production.

On one hand, as explained above, impact of climate change on agriculture is mainly related to extreme heat events and reductions in precipitation and water availability, that result in decreased crop productivity. On the other hand, the contribution of agricultural activities to climate change is related to two specific factors:

- Farming in particular releases significant amounts of greenhouse-gas emissions, in particular methane and nitrous oxide. The agriculture sector alone represents almost a quarter of global emissions.
- Agrochemicals released to fight against pests contaminate soils and waters as a direct consequence of the use of these substances.

However, climate change is only one of many problems that agriculture must face[2]. In fact, growing global demand and competition for resources, food production and consumption need to be redesigned in a proper way, linking agriculture, energy, and food security.

Consequently, contemporary economic and ecological challenges mean our food production must support a new balance between production in quantity and production of quality. Achievement of this new balance in food production exposes us to risks in various forms (war, market fluctuations, large scale public health and animal health) including climate variability. These risks must be immediately addressed to obtain a transition towards a more sustainable and inclusive food system from farm to fork. This will require significant actions such as reducing food loss and waste, adopting dietary changes, and adapting how we use arable land. These actions will help industry meet global food needs while safeguarding farmers' livelihoods as well as contributing to decarbonisation and climate change stabilization.

As a primary sector, digitalization of agriculture is not trivial because of the great variability (e.g. climate or other natural phenomena) of events on crops and lands. Moreover, farmers will need to change their behaviour. Service support and maintenance with adequate education on new technologies must be introduced, as well as a robust and reliable precision farming infrastructure.

The recent G20 Ministers of Agriculture, assembled on 16-17 June 2023 in Hyderabad, India[3], again emphasized their commitment to food security and nutrition for all, through the development of inclusive, resilient, and sustainable agriculture and food systems, with the need to work together to promote food security and nutrition. The G20 meeting recognized that the current crises (lastly the war in Ukraine) are multi-dimensional and therefore, require a multi-layered approach, combining coherent and effective short-, medium-, and long-term responses in the spirit of "One Earth, One Family, One Future", tackling all crises with the same urgency.

Among the high-level principles established by G20, Principle 6 is related to the need of Acceleration of Innovation and the Use of Digital Technology in Agriculture. This is relevant because it is a further emphasis to promotion of development and safe application of digital tools tailored to the various needs of the agriculture sector. The importance of strengthening digital solutions to empower all farming communities, including smallholders, was recognised.

All of this creates lots of opportunities for the ECS community to contribute to the disruption of the agrifood sector. Innovation and digitalization of agriculture are becoming more and more relevant due to the need for building a new level of agri-food system resilience, capable of having a more productive, decarbonised, and sustainable agriculture globally.

Smart Internet of Things (IoT) systems have become very important for sustainable production and consumption of safe and healthy food, as well as for sustainable practices in agriculture, livestock, aquaculture, fisheries and forestry. They can foster access to clean water, fertile soil and healthy air for all, in addition to helping fighting against pests while preserving biodiversity and restoring the planet's ecosystems. In short, the use of these connected objects (IoT) helps the stakeholder to increase productivity while ensuring sustainability. Finally, IoT systems should provide innovative GHG emissions tracing solutions to facilitate decarbonization.

In this Chapter, five Major Challenges have been identified. The first two Major Challenges relate to livestock and crop health, connected to farming systems and food supply chain assurance and management. For instance, IoT system technologies can be used in pest management or towards minimising the use of pesticides, fertilisers and antibiotics. Farming systems and food supply chain management benefit from smart IoT systems, including the use of traceability frameworks with trustworthy and security features[4], as well as from robots and drones, to revolutionise modern agriculture and food production. The third Major Challenge addresses issues such as soil health, air quality and the environment, all in terms of smart integrated monitoring technologies, and the use of smart waste management systems and remediation methodologies. The objective is to protect the environment to reduce the destruction of ecosystems caused by a myriad of anthropogenic activities and reduce GHG emissions. The fourth Major Challenge refers to the key role that IoT systems can play in water quality monitoring and access to clean water. An important aspect here is the overall management of water usage, as well as smart treatments to foster the circular use of wastewater, rainwater and storms/floods.

The fifth Major Challenge relates to biodiversity restoration for ecosystem resilience, how electronic components and systems (ECS) can contribute to the restoration/preservation of a greater variety of crops, and greater fauna and flora species diversity, to ensure the natural sustainability of healthy ecosystems (agriculture, aquaculture, fisheries and forestry) by enabling them to better withstand and recover from misuse, abuse or disasters.

All five Major Challenges in this chapter align with key Horizon Europe missions, as well as the European Green Deal and existing and emerging digitalisation technologies. To efficiently address these challenges, significant advances are crucial in the fields of new materials, manufacturing technologies, information and communications technology (ICT), Artificial Intelligence (AI), robotics, energy management, harvesting and transfer, electronics and photonics, and other technologies, as well as in circular industries. These challenges also address most of the technologies required to support the decarbonization actions in the farm proposed by McKinsey[5] to achieve the IPCC 1.5° C pathway[6].

Figure 3.5.1 illustrates the main challenges that our society is faced with a) the demand shift from resource-intensive consumption, i.e. to resource-efficient consumption and b) markets shift from low-connectivity to high-connectivity solutions. Both are required to reach an open-source sustainability.

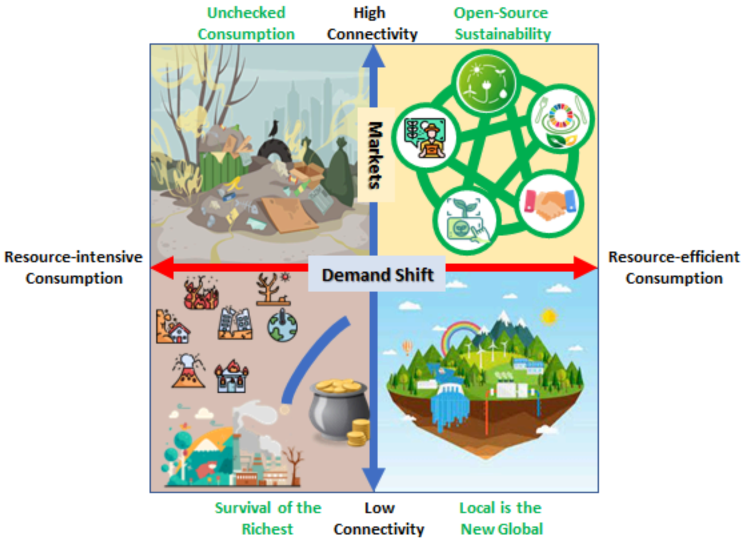

*Figure 3.5.1 - The Scenarios: Four Potential Future Worlds*[7]

## 3.5.2 Application trends and societal benefits

**External requirements**

According to the UN[8], if the global population reaches an expected 9.8 billion by 2050, the equivalent of almost three Earth planets could be required to provide the natural resources needed to sustain current lifestyles. Increasing food production is driven not only by population growth, but also by more demanding and sophisticated diets, with zero net emissions, as populations become wealthier. On the other hand, productivity is being hit hard by climate change in regions where food scarcity and inefficient resource management is most prevalent. The necessary acceleration in productivity growth is being hampered by the degradation of natural resources, a reduction in biodiversity, and the spread of transboundary pests and diseases of plants and animals, some of which are becoming resistant to antimicrobials[9]. Investments in changing agricultural practices and incorporating technological innovation has boosted productivity, but the yield growth is far from sufficient. A more holistic and innovative approach is needed to reduce the strain on natural resources and enhance their quality, while also increasing food productivity. At the same time, food losses and waste claim a significant proportion of agricultural output, whereas poor bio-waste management and packaging increases environmental pollution.

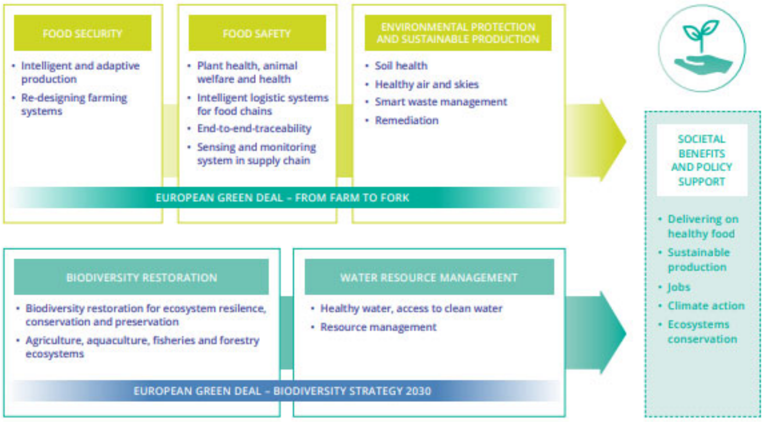

*Figure 3.5.2 - Main Agrifood and Natural Resources goals and associated challenges*

Addressing key issues on food security and sustainable production would lessen the need for production increases while improving the natural resource base. For instance, reducing GHG emissions is a priority because they significantly contribute to climate change. Three major sources (land-use change, enteric fermentation and energy use) combined account for almost 74% of the total. Other examples are, mitigating the effect of natural and human pressures on water bodies, namely by reducing general pollution and plastics, eutrophication, acidification and warming-up as much as possible. Less than 2.5% of the world's water is fresh[10], and water pollution in rivers and lakes is occurring faster than nature can recycle and purify. Currently, more than 2 billion people live with the risk of reduced access to freshwater resources[11], and by 2050 at least one in four people is likely to live in a country affected by chronic or recurring shortages of freshwater. Now, 2.6 billion people are economically dependent on agriculture[12] despite 52% of arable land being moderately or severely affected by soil degradation. Air quality has also been deteriorating in both rural and urban areas because of the spread of particulate matter in addition to the release of greenhouse gases (GHGs) all of which have detrimental effects on the population[13] and on the climate.

Today, farmers still spread much more fertiliser than is required on their fields. Consequently, excess nutrients such as nitrates and phosphates accumulate in the soil and filter into groundwater with a dramatic impact on the environment and public health. Therefore, there is increasing pressure on the agricultural sector to find decarbonized and sustainable solutions for reducing environmental pollution caused by fertilisation, pesticides, livestock and energy production emissions. Smart production processes and intelligent logistic systems across the whole supply chain are some of the solutions that can yield optimisations to reduce emissions with increased productivity, while ensuring safe food production. This is particularly important given that currently, every year, almost one in 10 people will fall ill due to food-borne diseases.

The pandemic crisis has shown the vulnerability of the overall agri-food supply chain when compromised by employee illness or travel restrictions enforced by the lockdown constraints. These circumstances appear unprecedented, but they are relevant for every type of pandemic that could occur worldwide, crossing international borders and affecting large populations.

New epidemiological methods that utilize dynamic network analysis[14] to analyse the key drivers of emerging pathogen movement are needed. In the agrifood sector, this is compulsory, because the overall agrifood elements are strictly interconnected (from seeds and plants to livestock management and crop production, as well as postharvest transportation are single point of risks of pathogen and mycotoxin movement in stored food).

Effective surveillance strategies are essential to support agrifood health programs, crisis prevention, improvement in biosecurity and agriculture decarbonization. Here also, ECS solutions are the efficient way to contribute in all these topics.

Societal Benefits

In response to an ever-increasing set of challenges faced by the world, the UN defined 17 Sustainable Development Goals (SDG) to act as a blueprint for achieving a better and more sustainable future for all. The SDG implementation plans (SDG 2, 6, 12 and 15 are particularly relevant) to address the global challenges we face in protecting biodiversity, our natural resources and acting on climate change. Furthermore, it includes actions relating to socioeconomic drivers aimed at eliminating poverty, hunger, inequality, and achieving responsible consumption and production, sustainable prosperity, peace and justice. In Europe, national and EU policies such as the **"From Farm to Fork"**[15] and "Biodiversity Strategy 2030"[16], reflect and amplify the underlying SDG objectives with a set of measures – from regulatory frameworks to incentives and investments for development, and the deployment of holistic innovative approaches in a circular economy, agroecology, agroforestry, climate- smart and sustainable agriculture, bioeconomy, and the Blue Economy.

## 3.5.3 Strategic Advantage for the EU

Within the Horizon Europe framework programme on research and innovation, it is envisioned that Europe will make significant progress with respect to high-impact missions on: "adaptation to climate change including societal transformation", "cancer", "healthy oceans, seas, coastal and inland waters", "climate-neutral and smart cities" and "soil health and food".

Innovative solutions based on IoT systems have a significant socioeconomic impact for the EU in rural, coastal and urban areas. For instance, agriculture is being transformed by the IoT revolution, with the use of reliable sensors/actuators and smart devices, as well as cost-effective and secure interoperable IT systems allowing farmers to better control the process of raising livestock and growing crops. As a result, safety and quality in food production are rapidly evolving, becoming more predictable and more efficient than ever. According to the European Innovation Partnership "Agricultural Productivity and Sustainability" (EIP-AGRI)[17], the digitalisation of rural areas can help to improve the economic and environmental sustainability of the agricultural sector. Moreover, it can make farming more attractive for young people, improve the quality of life of farmers and multiply the number of rural businesses. Consequently, rural depopulation could be greatly reduced. For instance, the Smart Water Management (SWM) project[18] points to an acceleration in the deployment of smart water networks with the aim of upgrading the reliability, efficiency, quality control, sustainability and resilience of drinking water supply services while also educating end-users on the benefits of water conservation. Strategies of this nature could represent the solution for urbanisation-related issues (scarcity, pollution, etc.) by providing a better use of our water resources while protecting the most vulnerable places, and by creating innovative types of economy and management.

Developments in smart IoT systems for agriculture and food production based on innovative and advanced ECS will strongly contribute to reaching the objectives set by the European Green Deal and the following three main actions and respective targets:

1. **From Farm to Fork**

   Moving towards a fair, healthy and environmentally friendly EU food system by 2030 through the targets listed in Topic 1[19]

2. **Natural resources**

   Topic 2: Targets set for natural resources.

3. **EU Biodiversity Strategy for 2030**

   Topic 3: Targets set in Biodiversity Strategy for 2030

| | | |
|---|---|---|
| **Topic 1**: From Farm to Fork | **Target actions 1.1:** Reduce the use of pesticides in agriculture that contribute to pollution of soil, water and air | • Reduce the use and risk of chemical pesticides by 50% by 2030<br>• Reduce the use of more hazardous pesticides by 50% by 2030 |
| | **Target actions 1.2:** The excess of nutrients in the environment as a major source of air, soil and water pollution, negatively impacting biodiversity and climate | • Reduce nutrient losses by at least 50%, while ensuring no deterioration on soil fertility<br>• Reduce fertilizer use by at least 20% by 2030 |
| | **Target actions 1.3:** Antimicrobial resistance linked to the use of antimicrobials in animal and human health leads to an estimated 33,000 human deaths in the EU each year | • Reduce the sale of antimicrobials for farmed animals and in aquaculture by 50% by 2030 |
| | **Target actions 1.4:** Organic farming as an environmentally friendly practice that needs to be further developed in the EU each year | • Boost the development of EU organic farming areas to achieve 25% of total farmland under organic farming by 2030 |
| **Topic 2**: Natural resources | **Target actions 2.1:** Optimisation and remediation towards climate-neutrality – first step for 2030 and then 2050, through | • Reduction of water pollution and GHG emissions, including. methane and nitrous oxide<br>• Reduction of European cumulated carbon and cropland footprint by 20% in the next 20 years, while improving climatic resilience of European agricultural and halting biodiversity erosion |
| **Topic 3: EU** Biodiversity Strategy for 2030 | **Target actions 3.1:** Establish protected areas | • For at least 30% of land in Europe.<br>• For at least 30% of sea in Europe. |
| | **Target actions 3.2:** Restore degraded ecosystems at land and sea across the whole of Europe | • Increasing organic farming and biodiversity-rich landscape features on agricultural land<br>• Halting and reversing the decline of pollinators<br>• Restoring at least 25,000 km of EU rivers to a free-flowing state<br>• Reducing the use and risk of pesticides by 50% by 2030<br>• Planting 3 billion trees by 2030 |

Figure 3.5.3 - Targets set in the Farm to Fork strategy, in Natural resources and EU Biodiversity Strategy for 2030.

Figure 3.5.4 depicts the agrifood value chain and the main actors involved, along with a list of the benefits obtained for farmers and consumers by using smart IoT systems. Moreover, the advanced technology applied throughout the whole chain will bring new market opportunities for the European semiconductor and ECS industries.

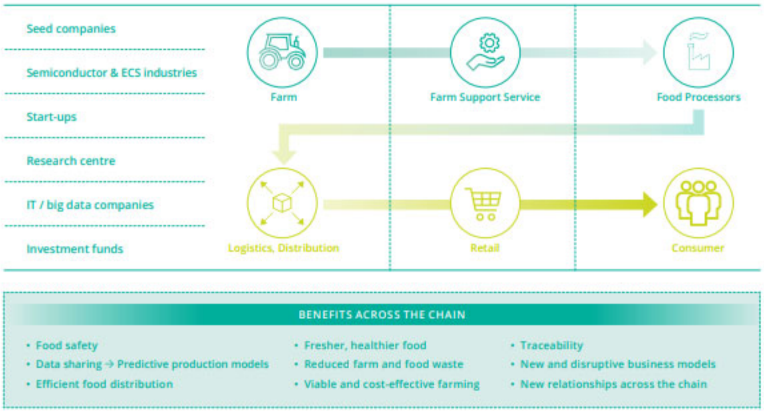

*Figure 3.5.4 - Agrifood value chain*

## 3.5.4 Major Challenges

This section discusses the five Major Challenges that need to be addressed in the domain of agriculture (food security, food safety, environmental protection, and sustainable production), natural resources and biodiversity, and how smart IoT systems and associated key enabling technologies can help achieve them.

- **Major Challenge 1**: Food Security.
- **Major Challenge 2**: Food Safety.
- **Major Challenge 3**: Environmental protection and sustainable production.
- **Major Challenge 4**: Water resource management.
- **Major Challenge 5**: Biodiversity restoration for ecosystems resilience, conservation, and preservation.

### 3.5.4.1 **Major Challenge 1: Food Security**

Food security[20] and food safety[21] are two complementary/interdependent concepts that are characterized in different ways: one indicates the economic and social security of availability of food supplies; the other indicates their health and hygiene safety. Together, these terms refer to the same processes linked to agricultural production, and it is relevant to manage them simultaneously.

Figure 3.5.5 presents the interrelation between food security and foot safety concepts, as well as their main constituent elements. This section and the next will address the challenges related to food security and food safety from an ECS perspective.

*Figure 3.5.5 - Food security and food safety*

## 3.5.4.1.1 Status, vision and expected outcome

Consolidated advances in Industrial Internet of Things (IIoT) have already started to shape smart manufacturing in the food and beverage[22] industry. Access to relevant and role-based information, in real-time or near real-time, is key to ensuring the efficient storage and processing of data, and their appropriate use for optimised decision-making at every level of next-generation automation systems and robotics, e.g. cyber-physical systems (CPS). Therefore, sustainable production, safety and quality do not only depend on the product itself, but they also depend on respective processes and their control as offered by key data gathering and monitoring, smart sensing, data analysis, diagnostics, and control systems. Ultimately, intelligent food production frameworks can consider consumer needs in specific markets, and such systems can provide intelligent recommendations for adjusting the amount and quality of food, accordingly, assuring food security (i.e. enough food for each market, avoiding food loss) and food safety (i.e., healthy food), while also considering environmental concerns and societal impact, paying attention to the food traceability process as well, because it is a real core of any quality assurance for agrifood sector.

Following the trend in manufacturing industries, digital twins[23] are the next step for the food industry and farming systems. In short, digital twins allow digital/virtual representations (models) of physical objects and processes, coupled with behaviour models that enable simulation and prediction upon changes to variables associated with the objects or the surrounding conditions. Digital twins are remotely and real-time connected to the objects in the physical world to reflect the dynamics of real systems. Thus, digital twins are expected to take the farming and food industry to the next level in terms of productivity and sustainability. As a use case example in precision farming, a digital twin can be used in the event of a plague infection for simulating the effect of applying multiple alternatives, taking into account the current condition of the crops, the available biological models, the expected evolution of weather conditions, etc. to figure out what is the optimal treatment against the plague in order to minimize both the impact in productivity and the environment footprint of the treatment. Essentially, digital twins will become ultimate decision-making optimisation tools by integrating production process variables and market and consumers variables thereby avoiding food loss. In any case, development of digital twins in farming is far behind its counterpart in the manufacturing industry for several reasons because physical objects in farming are "living" objects (crops, trees, animals…), and because variables of interest in farming are highly heterogeneous and are complex to model and measure.

**Intelligent and adaptive food production**

To develop intelligent food production systems, solutions are required in (but not limited to) the following fields:

- In-line inspection, networked packaging systems and robot technology in the warehouse to allow for a smart workflow to manage, monitor, optimise and automate all processes accordingly.
- Intelligent control room systems to enable correlations between machine malfunctions and load parameters to be detected immediately, thereby enabling maintenance work to be carried out early and on schedule, with a reduction in costly downtimes.
- Food industry imposes specific requirements (e.g. in food processing) that may take advantage of smart bio-sensing high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
- AI/machine learning (ML) and big data models must be devised and used to offer further intelligent decision-making and, whenever possible, should be employed directly at-the-edge for greater energy efficiency.
- IIoT systems, based on AI and digital twin technology, can provide the flexibility to tailor-make new products to help cope with ever demanding diets.

## 3.5.4.1.2 Precision Farming Systems

**Precision Farming Systems**

Advanced farming machines and robotic collaborative systems are needed for cost-effective land and livestock management, as well as for large-scale arable and fruit crops management. Tasks can be performed in parallel, enabling economies of scale. Advanced machines include the following:

- *Harvesting robotic systems*: autonomous robots or swarms of light(er) robots (causing less soil compaction) can replace intensive and strenuous labour practices as the worldwide population transitions from rural to urban areas and manual labour declines as farmers get older. Agricultural robots need to be equipped with improved capabilities for sensing and perception. This aspect should be accelerated to tackle this problem and increase efficiency. Special attention must be paid to safety and trustworthiness aspects for those robots expected to work collaboratively with humans or close to livestock.
- *Drones:* remotely piloted or autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, can mainly improve efficiency in two application areas: (i) monitoring large areas with intelligent computer vision devices to provide a higher level of detail and on-demand images, especially as drones can overcome limitations of satellite imagery (e.g. images below forest cover); and (ii) in the use of phytosanitary (plant health) products to increase efficiency and reduce environmental impact by avoiding indiscriminate chemical dispersion and following predetermined prescription maps.
- *Satellites:* these allow for improved information regarding fields, although a combination of data from further sensors with increased update frequency, improved performance and spatial resolution would also be needed. Moreover, small satellites (micro, nano) could provide larger IoT connectivity services when internet coverage may not be available at any location where a WSN network is to be deployed. Hence, low power and low-cost solutions are needed where either links can be established or where data can be collected for later processing in powerful backends.
- *Wireless sensor networks (WSNs)* and smart actuators deployed across fields will form the backbone of heterogeneous - multi-agent - collaborative approaches. Local parameters (e.g. ambient temperature, soil pH, soil salinity, relative humidity, etc.) measured from multiple sensors planted in the soil or attached to the plants could be retrieved remotely by e.g. drones and/or robotic systems to deepen the field analysis provided by image-based techniques. Coupled to the proper AI and decision systems, WSNs will also further help in automatically triggering the appropriate actions (e.g. drones could locally release agrochemicals after interrogating/analysing sensors, water irrigation systems could be activated only in some land areas, etc.).
- *Decarbonization:* To achieve zero net emissions in the different agriculture areas carbon verification and monitoring tools are required to measure carbon emissions and sequestration.
- *Digital farming Support as a Service (FAAS):* Most of the farms in Europe are small scale, below 10 hectares, whilst only about 1% of all farms are above 500 hectares[24]. An important challenge remains that all sizes of farms, including small and medium sized, should have access to digital solutions, namely cost-effective ones, and to facilities to easily exploit them. Whilst large scale farms have the means to setup and maintain large infrastructures and even robotic appliances, smart scale farms should benefit from the provision of digital support solutions, for instance, farm-monitoring via sensors, local maintenance, virtual cooperation, precision agriculture applications, etc. - as a service. This kind of services should be created and provided through local cooperatives or new service providers specialised in the HW infrastructure and SW applications involving several types of expertise in agronomy, communication, data analytics, computer science, etc. Having digital farming as a service, business models may help to

finance CAPEX while technology transition to provide better cost model scenarios and facilitate the deployment of this technology in the European farms. As with most non-ECS domain experts, famers would benefit by digitalization expertise being provided by ECS tools and services supporting e.g. experience sharing, education and remote assistance. This can include digital ecosystems, remote support via XR technology, or simple interactive support systems using technologies like LLM, e.g. ChatGPT, to facilitate existing knowledge which can be effectively queried

Couplings[25] between the technologies cited above and the data sources are possible and make it possible to enrich knowledge and respond to other field issues. Take the example of the drones above. Georeferenced imagery data by drones can be completed:

- on wider perimeters but with lower frequencies by satellite imagery.
- by images acquired by proximity sensors onboard self-propelled vehicles (tractors or robots) and their associated equipment during interventions in the plots as well as during pedestrian observation phases by farmers.
- by data collected via networks of communicating sensors covered by the Connectivity Chapter.

All the proposed solutions should meet important requirements such as cost-efficiency, compactness, reliability, lifetime, low power, security, interoperability with existing machinery and between systems implementing appropriate security schemes and taking human factors into account. Furthermore, training systems based on virtual, augmented, and mixed reality and simulators are needed for training people (e.g. operators), independent of seasonality or safety issues.

**Horticulture/greenhouses, urban and vertical indoor agriculture, and agrovoltaics**

Urban agriculture is being promoted as a promising option for sustainable food, a better quality of life, and community engagement. The goal of this modern version of agriculture is to grow and deliver high-quality food with a minimal waste of resources.

Many crops in vertical indoor farms are often cultivated using hydroponics, a technique where there is no need for soil and fertiliser as the growing plants are supplied with irrigation water. In fact, recent environmental challenges have promoted the intensification of "soil-less agriculture" in an urban context to decrease the negative impact on nature. Even if hydroponics produces quality crops with high efficiency, there is an area of opportunity here to better monitor and control the fertiliser components in the irrigation water, such as through the development of:

- novel and low-cost online sensors for optimised control, such as nutrient sensors to enable smaller discharge of fertiliser into natural waters.
- robots with a high precision level to perform automatic harvesting to reduce the overall production costs, which are currently high, to be competitive with traditional agriculture.
- autonomous indoor farming systems in which cultivation is controlled remotely via AI, based on measurements of crop properties with the help of intelligent sensors and AI-based digital twin models of such plants.

Climate change is causing high temperatures, torrential rains and hail, causing significant damage in large crops. The introduction of **Agrovoltaics** has the potential to sustainably increase agricultural yields, reduce water use, create additional revenue, and promote equity for small-scale farmers[26]. Additionally, solar panels can provide energy directly to farms, reducing their dependency on fossil fuels and encouraging energy independence for small-scale farmers in developing communities; excess energy can be sold to the grid. The shade provided by the panels and the possibility to add environment sensors and ad hoc irrigation systems can make farms more water-efficient and provide valuable shade for livestock, leading to greater productivity for both crop and animal yields.

## 3.5.4.2 Major Challenge 2: Food Safety

### 3.5.4.2.1 Status, vision and expected outcome

Application of high-tech sensors and AI to monitor, quantify and understand individual plants and animals, as well as their variability, to ensure food safety is key for next generation novel ecology-based agricultural systems. Smart sensors and monitoring technology that can adapt to the unpredictability and variation of living systems are required. This Major Challenge will require integrated digital technology solutions such as ecology-based robotic systems that can control the bio-physical processes (including growing conditions) and understand the biological environment (for plants and animals). However, innovative ecology-based robotic systems' manipulation of operations is a huge challenge in environments that are only modestly defined and structured. Furthermore, detection in the supply chain and "at the fork" should be also considered. This implies low-cost compact sensors, connected to information processing systems used in the food supply chain and by consumers, that allow, for instance, freshness and food safety detection for meat and vegetables (which could be integrated into smartphones).

### 3.5.4.2.2 Crop quality and health

**Integrated pest management (IMP)**

Novel IPM strategies are needed to detect diseases and prevent their spread on crop production for European organic and conventional agricultures, to increase organic farming and allow the development of horticultural systems that will use less/no pesticides. Improved IPM will require developments in the following fields:

- Smart systems based on portable real-time pest disease detection, diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced) e.g. weather/climate information for predictive models providing risk assessments and decision support for IPM.
- IoT devices specialized in pests and disease measurements, such as insect traps and other systems based on image recognition or AI models.

**Agro ecology based: Move from conventional to organic, regenerative agriculture**

To support the EU "*From Farm to Fork"* implementation, smart ECS can help farmers to drastically decrease the use of pesticides and their impact on human health and the environment. This will require:

- Development of cost-effective and intelligent intra-row, herbicide-free weeding techniques using advanced robots and robot fleets for individual plant recognition with high precision, based on advanced (vision) sensor technologies and AI algorithms working under in-field conditions.
- Development of smart and power efficient sensors to monitor the quality of spraying, as this is essential for biocontrol products and contact pesticides. Moreover, new sensors to monitor soil and plant health are needed such as pH, NO3 & EC, soil moisture, CO2, leaf wetness, surface temperature, airborne pathogens. They should be precise, low cost, highly miniaturized and biodegradable electronic and sensor components (printed antennas, organic batteries, biodegradable substrates, elimination of sensor/chip packaging) to avoid a negative Impact of electronic products on soil.
- Integration, into the same framework, of decision-support tools and precision agriculture tools to simplify farm management, improve crop quality and reduce costs.
- Advanced tools may yield on just farming 80% of the most productive soil leaving 20% for natural recovery reducing costs of fertilizers, energy to harvest and human time to collect, by this precision agriculture some complementary activities or species may be used to fix soil and reduce erosion and desertification.
- Dedicated services such as technical support (infrastructure deployment and maintenance), precision agriculture as a service, education, etc.

**Plant precision breeding and plant phenotyping**

The development of smart technologies can support precision plant breeding and phenotyping. This could be nanotechnology solutions or smart sensor solutions to support the following:

- Genomics and transcriptomics: DNA informed breeding, gene editing, genome prediction, breeding optimisation, phenotyping and seed sowing optimization.
- Large scale and high precision measurements of plant growth, architecture and composition: these measurements are required to optimize plant breeding by increasing our understanding of the genetic control and response of plants to their environment. Sensor systems should allow the study of plants in relation to biotic and abiotic factors, including plant-microbiome interactions, plant-plant competition, plant diseases and exposure to a multitude of variable abiotic environmental conditions such as light quality, irradiance levels, nutrient supply, temperature, humidity, soil pH and atmospheric CO2 levels. Plant health is also related to nutrients and the 4R strategy "right source at the right dose, at the right place, at the right time ", however, plant models, besides agri knowledge, are needed for nutrient content measurement and monitoring.

### 3.5.4.2.3 Livestock welfare and health

Livestock health is crucial for food safety. Different animal pathogens can be a serious threat for livestock management, because pathogens can be divided in those that can infect multiple species, and those that infect specific terrestrial and aquatic animal species (i.e., cattle, sheep, goats, equines, etc.). A great threat is represented by diseases that are highly transmissible, having the potential to spread rapidly across borders and cause significant socio-economic and public health consequences. All these lead to great economic loss to the farmers. Moreover, the use of antibiotics to treat animals increases the cost of production, as well as creating other problems like residues and resistance, which is of serious concern to public health.

In addition, best livestock management practices must reduce the release of pathogens into the environment and substantially reduce the risk of microbial contamination of surface and groundwater. As outlined in the literature[27], there is relevant impact of animal pathogens in four areas: animal health, economics, food safety and security, and public health. Consequently, there is strong interest in developing new advanced solutions systems with high sensitivity and specificity, for early detection of animal diseases and minimizing antibiotics use too.

Synergistic strategies can be applied to approach these challenges. Agronomic and technological solutions must be applied to:

- Minimise risks (e.g. release of pathogens into the environment, use of antibiotics for animals);
- Surveillance of the livestock environment through an efficient process of digitalization of livestock management to prevent diseases spread.

From a microbiological perspective, microorganisms can mitigate risk because specific beneficial microorganisms can be selected to work synergistically with other microorganisms already in the environment. Beneficial microorganisms can support the nutritional requirements of plants and reduce the incidence of pathogenic microorganisms, to solubilize minerals, to conserve energy, to maintain the microbial-ecological balance of the soil, to increase photosynthetic efficiency, and to fix biological nitrogen.

Research has also studied beneficial effects when these specific microorganisms are included in animal diets[28]. It has been shown that when they meet the organic matter that makes up the animal's diet, they secrete beneficial substances such as vitamins, organic acids, chelated minerals, and antioxidants, influencing an antibacterial effect through a selective blocking of pathogen colonization.

Animal welfare is also an important concern for a growing number of consumers.

We can assess that these synergistic strategies (risk reduction with agronomic solutions and surveillance) as explained above are drivers for investing in better sensing systems for animal monitoring. Combined with data analytics solutions, this will improve animal health and welfare, resulting in more animal-friendly production, higher efficiency, better quality, and improved food control safety:

- Wearable sensors at the farm/barn level, and ambient sensors during cattle transport.
- Smart sensor systems to monitor animal activity, such as individual or group behaviour, to provide useful information for early detection of diseases and to increase animal well-being.
- Smart sensor systems for rapid verification of bacterial infection together with behavioural observations to control disease spread and support clinical and veterinary stakeholders to effect suitable therapeutic interventions; body temperature can also be monitored for early disease detection to reduce antibiotics use.

A major source of GHG emissions in agriculture is related to livestock enteric emissions that must be reduced to achieve the 1.5°C pathway. The methane emissions from livestock increase atmospheric temperature approximately 80 times more than $CO_2$ on a 20-year outlook, but methane has a shorter atmospheric lifetime than other GHGs, making it an effective target for reducing global temperatures quickly.

New methods are emerging to reduce enteric emissions in livestock, and these should be largely introduced, particularly in grassland or mixed systems, where cattle might be centrally handled only once or twice a year for weighing and treatment, and where their feed rations are unpredictable and uncontrollable. In addition to the smart sensors systems mentioned above, the following tools can be added:

- Methane verification and monitoring tools to measure methane emissions and sequestration.

## 3.5.4.2.4 Food Chain

**Intelligent logistic systems including sensing and monitoring for food chains**

Logistics are a critical component of the food chain. They not only determine the reach of distribution, but logistics delays and conditions profoundly affect the quality and safety of products reaching consumers and can result in food loss and waste in the supply chain.

Smart real-time sensing, monitoring and control systems in the food supply chain will safeguard food quality and food safety, while eventually reducing food losses in the supply chain. Therefore, technological solutions are required, but not limited to:

- Systems for monitoring and controlling the quality of food products and ingredients during transport and storage (e.g. temperature monitoring in cold chain, moisture, controlled atmosphere, ethanol, ethylene), which should be reliable, contaminant-free, secure, power efficient and interoperable along the logistics chain.
- Predictive systems to assess quality of (perishable) food products in the supply chain, providing real-time decision-support based on actual sensor measurements, supply chain data and AI models.
- Transport route optimisation, considering not only time and cost, but also external conditions and the intrinsic properties of the products being transported.

These needs are strongly related with traceability, as shown in the following section.

**End-to-end food traceability**

Food and beverage manufacturers and producers are faced with increasingly complex and fragmented supply chains, stricter regulation, and more demanding consumers. Regulatory compliance, competitive advantage, brand reputation and costs have made product traceability a priority and end-to-end traceability a major challenge. In today's globalised world where people of any origin live across every country, the source of food products and ingredients, as well as their certification, are a major concern and priority for consumers, who want to be sure about the origin of food products. Therefore, traceability should also encompass certifying food origin, as well as making information available on any relevant process to which the food product has been submitted. This information should not be restricted to mere tracking across the supply chain. End-to-end traceability solutions are required, but should not be limited to:

- Integrating blockchain into current technology to increase safety while preventing fraud and counterfeiting.
- Traceability to increase alignment between production and individual consumer demands, leading to better provisioning and more personalised nutrition support.
- Traceability to optimise distance between farm and fork – although many products are produced preferentially in specific parts of the world, there are also many examples of food that could be produced economically closer to consumers.
- Smart tags.

To this end, as IoT/IIoT solutions are increasingly being deployed, integrated hardware systems need to deliver (apart from mobility and connectivity) long lifetime autonomous sensing and AI-based intelligence at-the-edge, as well as edge and/or cloud analytics and cybersecurity, complying with privacy regulations where applicable, on a plug-and-play, open, interoperable architecture, and platform.

Distributed Ledger Technologies (DLTs) such as blockchain allow secure storage and tracking of all kinds of information, including condensed sensing or monitoring data regarding crops and livestock. Examples include information on crop seeds, feed ingested by livestock (including medication and antibiotics), as well as recording of the whole process that any farm product is submitted to until it reaches the consumer, throughout the respective supply chain and involved actors. Such information increases the transparency of these supply chains and can reduce potential production issues, e.g. simplify the tracing of eventual product spoiling, or other issues, to the respective source, supporting possible decisions to recall product batches if necessary. Consumers can also benefit from such transparency, i.e., they can be given access to information to make better informed decisions about the offered goods they want or need to acquire, and they can use the information to provide feedback to farmers and producers incentivising their policies and practices further.

Nowadays, end-consumers are more concerned about the origin of the agriculture products that they consume. A complete system to manage traceability and to offer, to the end-consumers, a complete transparency of the actions taken in the farm (for instance in the vineyard) and during the transformation process (in the example of a winery) is required: a solution could use blockchain technology. However, it is important that small-scale farmers with low technological expertise, resources, and insufficient size to integrate blockchain could be supported, eventually through a dedicated ecosystem. This can be devised through blockchains implemented to include such farmers and respective food product chains, which would also allow the support of food safety assurance, namely in respective local markets, eventually involving less costs associated with logistics and distribution, and thus also contributing to sustainability and fair food systems. Nevertheless, the lack of regulations, standardization and interoperability are challenges for incorporating blockchain.

### 3.5.4.3 **Major Challenge 3: Environmental protection and sustainable production**

#### 3.5.4.3.1 Status, vision and expected outcome

EU regulations together with consumers' increased interest in organic food, is compelling farmers to drastically decrease the use of pesticides to reduce risks and impact on human health and the environment, as well as to undercut the maximum residue levels of pesticides. Pesticides are found not only in drinking water[29] but also in food and beverages. Lively debates have shown that our society demands alternatives to pesticides to help preserve the environment and improve food quality.

Drastic reduction in the use of pesticides is one of the major goals of the EU's agricultural policy, with some countries planning to halve their pesticide use by 2025 (e.g. ecophyto plans[30] in France, and the Aktionsplan Pflanzenschutzmittel[31] in Switzerland). The EU Farm-to-Fork strategy also aims to implement an action plan that significantly reduces risks from chemical pesticides, as well as the use of fertilisers and antibiotics, and to increase the amount of organic farming carried out in Europe.

In general, the new EU agriculture policies put a major focus on preservation of landscapes, biodiversity, and environmental protection, in a results-oriented model aligned with the Green Deal[32]. For instance, the reform of the Common Agriculture Policy (CAP) introduces measures for fostering the adoption of sustainable farming practices ("eco-schemes"), such as agroecology or organic farming. Farmers will need to provide "digital evidence" of compliance to the CAP rules and the implementation of good practices. The CAP evaluations will be largely based on the use of high-quality data collected directly from the field. This will require measurement and monitoring technology (for environmental performance, biodiversity monitoring parameters, etc.) which is accurate, highly scalable, and secure (certified monitoring information).

Areas of interest are often remote without sufficient connectivity – new approaches are required to flexibly deploy sensors and collect data.

#### 3.5.4.3.2 Soil Health

***In-situ* real-time monitoring of soil nutrients and herbicides**

The optimal use of chemical fertilisers and organic manures to deliver the ever-increasing food production requires a complete understanding of the nitrogen- and phosphorous-based nutrients applied in the fields with a much greater spatial and temporal resolution than is available today. Current methods of soil analysis do not provide real-time, precise and *in situ* nutrient analysis in fine detail, and delays in receiving soil results are common because of backlogs in commercial labs due to high sample volumes, thus reducing the value of the soil test results for the farmer. Moreover, herbicide application is another huge problem due to their environmental and health impact. To solve these issues, the following actions must be done:

- Intelligent sensors and bio-sensors (with miniaturised and ultra-low power consumption components) must be developed to deliver measurements of soil nutrients in situ and in real time at parts per million (ppm) concentrations. Such devices must have the appropriate packaging to extract water from the soil. Ideally, they should be buried in the soil for long periods of time or at least while sustaining operation capabilities for the entire growing season. To optimise effectiveness, low proximity sensors should be combined with optical sensors and high proximity sensors to retrieve the maximum amount of information on soil health.
- Likewise, smart actuators could prove to be highly beneficial. Such miniature units could be deposited on or buried into the soil. Coupled to sensing functionalities into the same module, critical actions (e.g. release of agrochemicals) could be triggered very close to the plant roots for maximized efficiency.
- Multidisciplinary approaches for developing novel sustainable smart ECS are needed. Indeed, current ECS contain a variety of toxic materials and chemicals. As such, they cannot be left in the soil. The optimization in the use of agrochemicals should not come at the expense of another ecological burden. New sustainable "green" ECS made of eco-friendly materials that will have benign environmental impact must be created.

IoT systems with edge and/or cloud-based data analytics are also necessary to provide farmers with decision-support regarding fertilisation strategies, by translating measurements into meaningful agronomic indicators and respective measures. These strategies should prioritise the use of organic fertilisers and the gradual reduction of chemical fertilisers until eliminated to restore the biodiversity contribution in the preservation of soil health. Furthermore, this type of system should detect weeds, preserve the "good ones" and eradicate those that are competing with the crop in question. This requires low-cost vision technologies (not only plain optical red/green/blue (RGB), but also 3D, hyperspectral imaging, etc.) and edge AI for in situ prompt recognition and decision-making.

## 3.5.4.3.3 Healthy air and skies

**Sensors and diagnostics for air quality monitoring (indoor, urban and rural)**

According to the World Health Organization, the air we breathe is becoming dangerously polluted. Nine out of ten people now breathe polluted air, which kills seven million people every year. There has been much progress on identifying and reducing the sources of air pollution at lower concentrations and with higher spatial coverage. This is necessary to provide adequate data on what people are breathing, and to provide localised as well as holistic solutions. Microsensors and/or mini-stations can be used during fieldwork campaigns in cities, but there are technical problems relating to power source, data transmission, data storage, and data handling and assessment. Besides, local measures are not always effective since local concentrations of particulate matter may be influenced by long-range transported pollutants from agricultural activities occurring outside city boundaries.

Similarly, while indoor air quality has been shown to unambiguously impact the wellness, health and performance of people as shown for instance with Covid-19 in schools due to lack of indoor air quality measurement, there is also a lack of spatial granularity and a significant lag between exposures and sensing, actuation and management interventions for risk mitigation. In addition to indoors, air quality is made more complex by the interaction between indoor and outdoor air, emissions from buildings and their contents (paints, furniture, heating, and cooling systems, etc.), human activities (breathing, cooking, cleaning, etc.) and the effects of long-term exposure to low concentrations of volatile organic compounds. These issues necessitate development and deployment of real-time intelligent multi-sensor technologies with high selectivity and embedded (re-)calibration techniques. These should be combined with a monitoring network (edge-based) as part of the indoor infrastructure to provide the spatial and temporal information needed for specific, targeted and appropriate actions. Such actions should also include public awareness and the promotion of behavioural changes.

**Smart systems for controlling and preventing GHG emissions**

Strong evidence has been accumulated on the climate emergency resulting from human activities that add GHGs to the Earth's atmosphere. The EU is the world's third biggest GHG emitter after China and the US. Although several measures have been taken since the Paris Agreement, breakthrough technologies and state-of-the-art deployment are still needed across the transport sector and other industries with a high emission footprint to achieve a further reduction in emissions. These would be facilitated by the following:

- Smart systems and digitalisation to improve industrial processes performance and energy/resource efficiency towards a low-carbon economy, while reducing the impact of mobility and agricultural processes on the environment and human health, thereby controlling and preventing GHG emissions.
- A focus on the GHG emissions from animals by investigating microbiological sensing technologies on or in animals (in their rumens or breath, for instance) to increase efficiency while reducing environmental impact, as well as performing analysis of the gathered data to support decision-making for mitigation measures (for instance, leading to change in feed).
- GHG verification and monitoring tools to measure GHG emissions and sequestration.

## 3.5.4.3.4 Smart waste management

**Integrated waste systems**

Despite proactive European policies and regulations[33], effective bio-waste management remains a challenge. Reducing, recycling and reusing food/kitchen waste requires significant progress in technological solutions along with strong policymaking and shifting community behaviour. These solutions could be based on the following:

- Smart monitoring, controlling waste treatment units in real-time as well as gas emissions in landfills and anaerobic digestion monitoring. Data analytics should include gamification for behavioural triggers.
- Smart waste collection bins (radio-frequency identification (RFID) tags, self-compacting bins, fullness level sensors, automated waste segregation), including automated robotic systems and optimised separation systems, which can be complemented by the upcycling of waste streams into usable resources and optimal routing systems, as well as vehicle tracking. These solutions should be integrated and interconnected into the product life cycle "from cradle to grave" to enable circular and resource-efficient methodologies.

**Intelligent sustainable / biodegradable packaging**

Intelligent and biodegradable packaging concepts have been gaining traction in the food industry to improve product safety and reduce environmental impact. Smart sensors in an IoT system can monitor environmental conditions and product quality, while communication devices can store and convey data throughout the product life cycle. While these concepts need to be further advanced for efficient, safe food production and waste management, intelligent packaging itself needs to become more sustainable. Novel ideas are required to solve the problem of the amount of plastic packaging produced by food manufacturers. The definition of biodegradable packaging should lead to a new generation of food packaging. Such novel ideas include:

- A synergetic interdisciplinary approach to cross the boundaries of novel materials for food packaging and smart sensors associated with analytical methods for the detection of harmful substances that can infiltrate into food, cause water contamination, etc.
- Fabrication and hybrid integration of eco-friendly nanostructured electrodes, sensors, energy harvesting and storage devices on rigid and flexible biodegradable substrates to reduce the waste from embedded electronics in smart packaging.

### 3.5.4.3.5 Remediation

**Efficient smart networks for remediation**

Remediation processes aimed at converting harmful molecules into benign ones can be undertaken in different ecosystems, such as water bodies (e.g. biotic, and abiotic farming by-products), air (e.g. GHGs) and soil (e.g. pesticides). Remediation processes are mainly carried out in wastewater treatment plants. Although some pollution sources are static and sufficiently well-known such that treatment can be undertaken effectively, other pollution sources are more mobile in both time and/or space, making treatment at single points unsatisfactory. Another limiting issue is that remediation technologies are often power-intensive and cannot be deployed for long in remote locations. Alternative high-efficiency remediation methods are needed, such as to transform/reduce the levels of CO2 in chemical products. Current devices are also prone to fouling. This means remediation processes cannot be run constantly in remote locations, and there is thus a necessity to undertake them only when and where they are most required. In this regard:

- A network of smart sensors (an IoT system) that can monitor relevant status in real time, and inform on the necessity of remediation, would provide unique decision support invaluable for efficient water, air, and soil management.
- Techniques used in the measurement and analysis of carbon sequestration by soils could also investigate the current potential of soils as a remediation mechanism to improve the sequestration capacity – such investigation should include the initiative of "four per 1000"[34] presented at COP21 in Paris.
- Likewise, tools and methods able to evaluate the performance of the carbon sequestration techniques employed should be developed to guarantee their efficiency.

## 3.5.4.4 **Major Challenge 4: Water resource management**

### 3.5.4.4.1 Status, vision and expected outcome

The quality of groundwater, surface water bodies (oceans, seas, lakes), waterways (rivers, canals, estuaries) and coastal areas has a great impact on both biodiversity and the quality of water that people consume every day. While natural droughts may lead to increased salinity in freshwater systems[35] and along with floods, impact or endanger the quality of water bodies, human activities in energy production, data centers, manufacturing and farming industries have a major detrimental effect through thermal pollution, chemical, microbiological and micro-plastic contaminants, and biotic and abiotic farming by-products. Moreover, the outdated and deteriorating water infrastructure is having a detrimental impact on both water quality and the amount of water lost through leakage.

In the context of climate change, increased water temperatures may cause (apart from extreme evaporation) eutrophication and excess algal growth in surface water bodies. Moreover, heavy storms may increase the amount of sediment nutrients in water sources, which have a direct impact on drinking water quality. Therefore, climate change jeopardizes the quality and safety of our water, making the development of new tools to deal with this problem more critical than ever.

### 3.5.4.4.2 Access to clean water (urban and rural)

**Healthy Water**

With the aim of reducing pollution-related problems, water utilities, water associations, academia and private industry have focused on developing new methods, policies and procedures to secure drinking water distribution by (1) detecting in real-time any compound, contaminant or anomaly that may represent a health risk for the end-users and (2) taking the required measures to mitigate these issues. This necessitates online information on the status of water sources at a larger scale than ever before. To mitigate both accidental and intentional contamination of freshwater resources, the deployment of sensors and diagnostic systems with rapid communication technologies and data analysis capabilities are needed to secure water quality and its distribution over the network. Such actions would provide:

Connected and highly integrated multi-parameter diagnostic sensors for real-time physico-chemical analysis (temperature, ionic electrical conductivity, pH, turbidity, inorganic pollutants as nitrates or heavy metals, etc.) in water distribution network and wastewater treatment plants, and biofilm growth monitoring in water pipes.Online monitoring systems at the edge, including devices with embedded AI for data analysis. The presence of a mesh of intelligent devices in drinking water networks will make it possible to identify and deal very quickly with drifts or anomalies (e.g, leaks, contamination events, etc.) while reducing the amount of data sent to the servers.Prediction in real-time of pollutant diffusion with simplified models, considering non-dense measurements from the multi-parameter diagnostic sensors and online monitoring.

**Integrated systems for demand reduction and conservation of water**

According to the UN Development Programme[36], dwindling drinking water supplies is affecting every continent. On the one hand, increased urbanisation and farming have amplified the demand of water for human consumption and for domestic and agricultural use. On the other hand, an increasing number of countries are experiencing water stress due to longer drought periods and the spread of desertification. In addition, approximately 25% of all urban drinking water is being lost forever[37] in global water systems, before it even reaches the end-user. Therefore, there is an urgent need to prevent losses from water abstraction as climate effects intensify. Leak localisation is currently very time-consuming, labour-intensive, and costly. Operators must manually place equipment that “listens” to the water flow during the night. Smart integrated systems can significantly contribute to key measures aiming at affecting consumer practices in water usage, delivering greater efficiency in detecting leaks and reducing water waste. Developments are needed in the fields of:

- Smart metering, time-of-use pricing and gamification to control consumption and appliances, along with interoperable solutions for a truly connected smart household (taps, lavatories, showers, appliances).
- Low-cost sensors for flow control, leak detection and auto shut-off, along with inexpensive actuators to remotely control valves for limiting water usage by volume/time. IoT systems can optimise the control of household, agricultural and industrial infrastructure/equipment in water-intensive processes.
- Smart systems able to automate leak localisation, and to respond promptly and cost-effectively. This can be a combination of in-pipe inspection (to locate the leak) and a network of low-cost, fine-grained sensors to allow predictive maintenance of distribution systems.

**Efficient and intelligent water distribution**

The main challenge for improving the use of water is to guide its distribution depending on its final application (drinking water, water for industry, water for the cooling of data centers, etc.). However, the existing sanitary regulations always look to optimise water safety regardless of its final use. To apply the most effective measures to make water distribution more efficient, it is necessary to thoroughly review the different supply protocols and quality criteria for each sector. Moreover, by continuously monitoring the quality and availability of water, it would be possible to better regulate its distribution depending on the final use and to adjust the price accordingly. Intelligent systems connected to smart grids will allow water inputs to be made in the network at the right times, optimising the energy cost as a result.

To address these challenges, there is a need for developing:

- Novel smart metering solutions based on various technologies, including electrochemical multi-parameter sensors (pH, chlorine, conductivity, etc.) with high stability, anti-fouling, high accuracy capabilities and cost-effectiveness, as well as optical sensors based on different principles (fluorescence, absorbance, etc.) integrated into miniaturised systems at a low cost.
- Robust IoT systems with adequate data analysis processing power and AI capabilities to handle the large volume of data generated by the different water management processes to satisfy quality, usage type and associated pricing.
- Efficient year-round water management in terms of storage to deal with some of the most urgent shortages, with better forecasting and warning systems based on extensive measurements – e.g. intentionally flooded areas could be used to store water in times of expected scarcity.
- Prediction of pollutant diffusion in water distribution systems.

## 3.5.4.4.3 Resources management

**Smart systems for irrigation management**

At a global level, agriculture consumes 69% of the world’s freshwater[38]. Because of this, precise control of irrigation is essential to guarantee water and food security for all. Irrigation water management is the practice of monitoring and managing the rate, volume, and timing of water applications according to seasonal crop needs, considering the soil intake and water holding capacities with the objective of using water in the most profitable way at sustainable production levels. To this end:

- Smart sensors are increasingly required as tools to implement irrigation management and monitor water levels. Sensors should be more intelligent to support real-time applications and/ or reduce latency, optimise power consumption of the overall system, and facilitate local (at the edge) cost-effective solutions for both outdoor and indoor use.
- Integration of systems monitoring water deficiency or surplus is also required. These could be based on narrow-band spectral reflectance of water and land surfaces for vegetation/habitat mapping, along with UAV utilisation in remote areas.
- Appropriate simplified models should allow to limit the number of sensors spread over a given landscape.

**Smart systems for flood management**

Flood management has been gradually integrating smart sensors. IoT systems with water-level sensors can also play a significant role in real-time monitoring and natural hazards predictive/forecasting capacity models. This requires:

- The monitoring of water levels and devising prediction models to identify areas at a high risk of flooding. This is possible through the development and deployment of more intelligent sensors in combination with smart predictive algorithms to integrate information from other sources, such as weather forecasts and regional georeferenced data.

- IoT interoperable systems are key for provision of real-time information to first responders, civilians and companies to proactively take countermeasures.

**Smart water treatments fostering circular use (wastewater, rainwater, storm water)**

Around 80% of all wastewaters is currently being discharged into the world's waterways, where it creates health, environmental and climate-related problems. Water from industrial, agriculture and domestic use contains organics, phosphates, nitrogen, cellulose, rare earth elements and other substances. In addition to its domestic use, purifying, distilling, or deionising water is essential for many agricultural and industrial uses – to ensure the consistency of products and to meet strict safety regulations. The global market for water and wastewater technologies reached US $64.4 billion in 2018 and is expected to rise to US $83 billion by 2023[39]. Technologies that allow resource recovery from wastewater to be commercially feasible are increasingly being developed, making transitioning to a circular economy an opportunity to accelerate and scale-up the most recent scientific and technological advances that support greater efficiency in the water sector. There is an increasing requirement for:

- A range of sensors in water systems to monitor water levels, the flow of water through different channels, temperature changes, chemical leakage, pressure level, chemical residues, etc.

- IoT-enabled water purifiers that can predict potential system failures to reduce downtime in public water systems, and to enable remote sensing for mapping groundwater resources and monitoring sustainable extraction levels.

- IoT-enabled increase of water recycling and development of the urban circular water economy. Watermaster from industry and data centers can be used for district heating or treated and recycled to yield not only water but also energy, fertilizer, and organic inputs.

- IoT-enabled increase of water recycling in the mining sector and reduction of the water footprint in manufacturing. Water-efficient processes must be implemented such as closed-loop systems, which capture and recycle the water used in the production process.

### 3.5.4.5 Major Challenge 5: Biodiversity restoration for ecosystems resilience, conservation, and preservation

#### 3.5.4.5.1 Status, vision and expected outcome

It has been stated that: "Biodiversity boosts ecosystem productivity where each species no matter how small, all have an important role to play"[40]. For example, increasing the number **of plant species means a greater** ensuring natural sustainability for all life forms.[41] Healthy ecosystems can better withstand and recover from a variety of disasters, anthropogenic or not. Healthy biodiversity offers many natural services for everyone.

It should be noted that there are many such services that we already get for free! However, the cost of replacing these, even, if possible, would be extremely expensive. More than ever, as noted in Section 3.5.4.3, the new EU agriculture policies promote sustainable farming practices that help to protect the environment, preserving landscapes and biodiversity. This is a consequence of the well-recognized correlation between the health of ecosystems and the health of farming production. It therefore makes economic and development sense to move towards sustainability. From this perspective, ECS will contribute to addressing some of the key challenges relating to biodiversity and sustainability for the four ecosystems described below.

#### 3.5.4.5.2 Biodiversity restoration for the agriculture ecosystem

Key focus areas Agriculture is one of the economic activities that has the highest dependence on nature and biodiversity[42]. On average, global mean crop yields of rice, maize and wheat are projected to decrease between 3% and 10% per Celsius degree of warming above historical levels. All crops depend directly on soil health and fertility, and more than 75% of global food crop types rely on animal pollination. However, the impact of agriculture activity on the environment must be as low as possible to preserve biodiversity. Efforts to conserve existing land resources (e.g. forests) and expand natural-based solutions (e.g. peatlands restoration) are required to reduce the GHG emissions, or to improve resistance by microbial biofertilisers [43] [44].In this regard, the EU Biodiversity Strategy 2030 establishes several objectives[45], summarized in *sub-section 3.5.5* Timeline. To address these objectives, there is a need to develop:

To address these side effects, there is a need to develop:

- Precision farming systems and services for optimal use of fertilisers and pesticides.

- Sensing and monitoring systems for soil nutrients measurement, connected insect traps and landscape monitoring.

#### 3.5.4.5.3 Biodiversity restoration for the aquaculture ecosystem

Aquaculture impacts biodiversity negatively in several ways[46]: (i) where antibiotics and hormones are used to reduce farm stock mortality and improve growth rates, but their use has side effects for the flora and fauna of water bodies receiving farm effluents; (ii) through eutrophication and changes in flora and fauna in waters receiving effluents from aquaculture facilities; (iii) through the risk of excessive exploitation of wild fish stocks for use in farm fish feeds; and (iv) by transfer of disease and parasites from farm animals to wild animals.

To address these side effects, there is a need to develop:

- Precision aquaculture systems for optimal feeding (minimizing waste and feed residuals), optimal use of antibiotics/hormones, and optimal use of freshwater.
- Smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents.
- Smart systems combining data collected from different sources (IoT networks, satellite, and drones) and data analysis based on AI/ML techniques to create predictive models leading to more confident decision-making, timely alerts, and automated systems in general.

### 3.5.4.5.4 Biodiversity restoration for the fisheries ecosystem

The EU's Biodiversity Strategy has set an objective of protecting a minimum of 30% of its sea area. Like agriculture, fishing is an economic activity with a strong dependence on biodiversity. Keeping fish stocks healthy is critical to guaranteeing ocean biodiversity and thus the economic sustainability of fisheries. According to recent studies, the preservation of marine stocks could increase the annual profits of the European seafood industry by more than €49 billion.

Fishing activities impact biodiversity negatively in several ways, particularly by: (i) increasing fish mortality, so measures must be taken to keep this under maximum sustainable yield levels; and (ii) damaging the ocean ecosystem due to the use of certain fishing techniques, currently the most damaging activity to the seabed. In addition, the effect of by-catching from non-selective industrial fishing methods endangers many species of marine animals not being fished for. It is therefore necessary to evolve towards more selective and less damaging fishing techniques, as well as the more effective control of illegal fishing practices.

To reduce these negative impacts, there is a need to develop:

- Oceanographic sensing and monitoring solutions (including unmanned vehicles, UXVs) for fisheries ecosystems to estimate biodiversity indices, fish stocks and species distribution, and to build fishery management systems consistent with conservation objectives and rules.
- Technologies to make fishing gear more selective and environmentally respectful.
- Technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc.).

### 3.5.4.5.5 Biodiversity restoration for the forestry ecosystem

The EU Biodiversity Strategy has set the objective of protecting a minimum of 30% of the EU's land area. At least one-third of protected areas – representing 10% of EU land – should be strictly protected. In particular, the strategy identifies the crucial need to strictly protect all the EU's primary and old-growth forests, which are the richest forest ecosystems removing carbon from the atmosphere, while storing significant carbon stocks. The strategy also calls for preserving the good health and increasing the resilience of all EU forests, especially against wildfires, droughts, pests and diseases. It is envisaged that the European Commission will develop a forest information system for Europe that integrates data from multiple sources and providers. To prevent more wildfires, we need to grow rural economies in a sustainable way and manage climate change, so a much better understanding and continuous assessment of EU forests is necessary. To this end, there is a need to develop:

- A precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests as well as early detection and prevention of threats to the forests (wildfires, pests, diseases, etc.).
- Smart systems for environment monitoring of forests and fields as well as C02 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and provide timely warning on illegal poaching activity.
- Customised services (similar to precision agriculture as a service as discussed earlier), not only to support the above-mentioned systems but also to further exploit the information they provide.

## 3.5.5 Timeline

| MAJOR Challenge | Topic | SHORT-TERM 2024 - 2028 |
|---|---|---|
| **Major Challenge 1:**<br>**food security** | **Topic 1.1:** intelligent and adaptative food production | • Advanced analytical processing based on several data sources.<br>• IoT devices with integrated firmware for implementing big data solutions |
| | **Topic 1.2**: redesigning farming systems | • A farm management information system (FMIS) thoroughly integrated with IoT and automated systems; all the data should be gathered automatically and digitalised |
| **Major Challenge 2:**<br>**food safety** | **Topic 2.1:** crop quality and health | • IoT for monitoring the key parameters related to plant health.<br>• DSS for recommendation/decisions related to agrochemical application; health and environmental care |
| | **Topic 2.2**: livestock welfare and health | • Advanced indicators of welfare, health and performance monitoring (integration of milking robot, wearable sensors data, etc.) at the individual and herd scale |
| | **Topic 2.3**: food chain | • IoT devices monitoring food transport from production to the retailer; end-consumers to have full access to this information; AI (ML/deep learning) models based on the recommendations and decisions that the IoT devices could take to monitor the whole supply chain<br>• Global accessibility for end-consumers to the traceability of the whole value chain – i.e. total transparency |
| **Major Challenge 3:**<br>**environmental protection and sustainable production** | **Topic 3.1**: soil health | • Autonomous recommendations done by the IoT devices directly related to fertilisation and phytosanitary application. |
| | **Topic 3.2**: healthy air and skies | • $CO_2$ capture materials in use |
| | **Topic 3.3**: smart waste management | • Forecasting models of potential waste that will be produced by the farm management system |
| | **Topic 3.4**: remediation | • Network of sensors for target pollutant with antifouling properties for use in real environments<br>• Development of capture materials for targeted pollutants, including $CO_2$ capture materials |
| **Major Challenge 4:**<br>**water resource management** | **Topic 4.1**: access to clean water (urban and rural) | • ICT solutions allowing greater societal involvement in water management through online knowledge of its consumption data (remote meter reading), and quality parameter monitoring for greater awareness about the optimisation of the freshwater as a limited resource<br>• Water quality monitoring systems based on hybrid technology (mono-parameter bulky probes and some miniature chips)<br>• Sensors for basic parameters such as chlorine, conductivity and pH are available for real-time monitoring; more complex parameters require lab analysis<br>• Cost and integration are still challenging for massive deployment in water distribution networks based on current IoT system applications<br>• Limited amount of data (systems are installed only at critical locations)<br>• Centralised control and data analysis based on AI on the cloud |
| | **Topic 4.2**: resource management | • Requirements identification and classification for biodiversity protection in the exploitation of aquifers for human supply<br>• Monitoring systems for the water lifecycle, including supply and sanitation through the development of digital tools allowing the intensification circular economy |

| MAJOR Challenge | Topic | SHORT-TERM 2024 - 2028 |
|---|---|---|
| | | • Progressive transformation of wastewater into raw materials for the generation of products and services |
| **Major Challenge 5:**<br>**biodiversity restoration for ecosystems resilience, conservation and preservation** | **Topic 5.1**: biodiversity restoration for agriculture ecosystem | • Sensing and monitoring systems for soil nutrients measurement, connected Insect traps and landscape monitoring |
| | **Topic 5.2**: biodiversity restoration for aquaculture ecosystem | • Smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents |
| | **Topic 5.3**: biodiversity restoration for fisheries ecosystem | • Technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc.) |
| | **Topic 5.4**: biodiversity restoration for forestry ecosystem | • Precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests, as well as early detection and prevention of threats to forests (wildfires, pests, diseases, etc.) |

| MAJOR Challenge | Topic | MEDIUM-TERM 2029-2033 |
|---|---|---|
| **Major Challenge 1:**<br>**food security** | **Topic 1.1:** intelligent and adaptative food production | • AI applied to food production to define advanced analytical processing related to prescriptive and predictive analysis |
| | **Topic 1.2**: redesigning farming systems | • Semi-autonomous agronomic systems (irrigation systems, climate control systems, etc.) based on expertise and farmers' decision-support systems (DSS) |
| **Major Challenge 2:**<br>**food safety** | **Topic 2.1:** crop quality and health | • AI for automatic decisions and action; ML and deep learning related to agronomic models and algorithms |
| | **Topic 2.2**: livestock welfare and health | • Reduce the use of antimicrobials for farmed animals by 50% by 2030 |
| | **Topic 2.3**: food chain | • Interoperability among all the systems that manage the whole value chain<br>• Normalisation and homogenisation of communication protocols and end-to-end security<br>• IoT devices integrated in the food chain where the end-consumers will be able to read them by mobile phone and directly access for complete traceability |
| **Major Challenge 3:**<br>**environmental protection and sustainable production** | **Topic 3.1**: soil health | • Combination of several data sources to establish and attain key performance indicators (KPIs) related to environmental protection and sustainable production |
| | **Topic 3.2**: healthy air and skies | • CO2 capture and conversion on site |
| | **Topic 3.3**: smart waste management | • Registration of the traceability related to residues management, including the residue management in food traceability and the environmental footprint |
| | **Topic 3.4**: remediation | • Coupled sensor and $CO_2$ capture/conversion system for $CO_2$ remediation<br>• Solar/thermoelectric in situ driven pollutant removal |
| **Major Challenge 4:**<br>**water resource management** | **Topic 4.1**: access to clean water (urban and rural) | • Smart monitoring systems at home to optimise household water spending and tools to improve performances through KPIs that allow for measuring progress at the microscale; water users must move from passive consumers to active management<br>• New generation of more integrated and miniaturised multiparameter autonomous sensors (e.g. pH, chlorine, and conductivity parameters)<br>• More complex sensors are available for real-time detection of pollutants in water, such as heavy metals and nitrates<br>• Edge computing and multiparameter devices allowing decentralised data analysis and control<br>• Massive deployment starts being cost-effective with more accurate solutions due to the availability of an increased amount of data |
| | **Topic 4.2**: resource management | • Improvement of knowledge through the accumulation of consolidated and valid data series, on the natural environment through the implementation of monitoring systems, for both the water and natural environment (fauna, ecology, sociological aspects, uses, etc.), as a basis for sustainable management through AI/ML tools, allowing for identification of the correlation between the evolution of the environment quality and water use<br>• Design of environmental evolution models in different use scenarios<br>• Industrial transformation of wastewater treatment plants in bio-factories |
| **Major Challenge 5:**<br>**biodiversity restoration for ecosystems resilience, conservation and preservation** | **Topic 5.1**: biodiversity restoration for agriculture ecosystem | • Precision farming systems for optimal use of fertilisers and pesticides<br>• Reduction of the use and risk of chemical and more hazardous pesticides by 50% by 2030<br>• Reduction of nutrient losses by at least 50% while ensuring no deterioration to soil fertility |

| MAJOR Challenge | Topic | MEDIUM-TERM 2029-2033 |
|---|---|---|
| | | - Reduction in fertiliser use by at least 20% by 2030<br>- Reduction in the sales of antimicrobials for farmed animals and in aquaculture by 50% by 2030<br>- Boosting the development of EU organic farming areas to achieve a 25% increase in total farmland under organic farming by 2030 |
| | **Topic 5.2**: biodiversity restoration for aquaculture ecosystem | - Smart systems combining data collected from different sources (IoT, satellite and drones) and data analysis based on AI/ML techniques and digital twin to create predictive models leading to more confident decision-making, timely alerts and automated systems in general |
| | **Topic 5.3**: biodiversity restoration for fisheries ecosystem | - Oceanographic sensing and monitoring solutions (including UXVs) for fisheries ecosystem to estimate biodiversity indices, fish stocks and species distribution |
| | **Topic 5.4**: biodiversity restoration for forestry ecosystem | - Smart systems for environmental monitoring of forests and fields, as well as $CO_2$ footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and provision of timely warnings about illegal poaching activity |

| MAJOR Challenge | Topic | LONG-TERM 2034 and beyond |
|---|---|---|
| **Major Challenge 1:**<br>**food security** | **Topic 1.1:** intelligent and adaptative food production | - AI applied to food production, not only in pre-harvest areas but also post-harvest – i.e. applied to the whole value chain integrally |
| | **Topic 1.2**: redesigning farming systems | - Automation of labour; resource optimisation (further targeting environmental care and social impact) |
| **Major Challenge 2:**<br>**food safety** | **Topic 2.1:** crop quality and health | - Robots with AI for managing plant health autonomously |
| | **Topic 2.2**: livestock welfare and health | - Fully automated herd performance control (growth and milk production, forage efficiency, early disease detection for antibiotics use reduction), and applications for genetic selection to optimise breeding performance and resilience |
| | **Topic 2.3**: food chain | - IoT devices making recommendations automatically and take autonomous decisions related to food safety, acting directly with the transport mechanism (cooling mechanism and others that impact food safety)<br>- Systems automatically and autonomously act in all the machinery located at each step of the supply chain |
| **Major Challenge 3:**<br>**environmental protection and sustainable production** | **Topic 3.1**: soil health | - Autonomous actions performed by IoT devices directly in systems related to fertilisation and phytosanitary applications |
| | **Topic 3.2**: healthy air and skies | - Low or no carbon fuel sources |
| | **Topic 3.3**: smart waste management | - AI and digital twin models providing recommendations for decision-making related to minimising farms waste |
| | **Topic 3.4**: remediation | - Real-time multiparameter sensing with AI and digital twin decision-support for management<br>- Efficient and low-cost general pollutant removal and conversion systems using energy harvesting towards in situ remediation |
| **Major Challenge 4**:<br>**water resource management** | **Topic 4.1**: access to clean water (urban and rural) | - Use of different water qualities for different usages (at home, industry, etc.) through secure monitoring systems, always guaranteeing the water quality (especially freshwater)<br>- Advanced multiparameter sensors supporting new capabilities, such as stability, antifouling, accuracy, etc.<br>- Real-time microbial- detection and removal are feasible<br>- Large-scale deployment of multiparameter devices allowing advanced data analysis in water distribution networks for more intelligent water management<br>- Freshwater quality prediction based on digital twin technology capabilities considering real-time environmental conditions |
| | **Topic 4.2**: resource management | - High-performance monitoring systems to identify and quantify the presence of emerging pollutants and high-risk chemical species derived from human action<br>- Integrated vision for all aspects related to water in systemic and non-cyclical areas; process reengineering and redesign of monitoring, control and exploitation systems based on advanced tools for decision-making through the generation of models<br>- Paradigm shift in the vision of water as a cycle to a system that must be optimised |
| **Major Challenge 5:**<br>**biodiversity restoration for ecosystems resilience, conservation and preservation** | **Topic 5.1**: biodiversity restoration for agriculture ecosystem | - Reduction of European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agriculture and stopping biodiversity erosion |

| MAJOR Challenge | Topic | LONG-TERM 2034 and beyond |
|---|---|---|
|  | **Topic 5.2**: biodiversity restoration for aquaculture ecosystem | - Precision aquaculture systems for optimal feeding (minimising waste and feed residuals), optimal use of antibiotics/hormones and optimal use of freshwater |
|  | **Topic 5.3**: biodiversity restoration for fisheries ecosystem | - Technologies to make fishing gear more selective and environmentally respectful |
|  | **Topic 5.4**: biodiversity restoration for forestry ecosystem | - Preserve the protected and restored forestry areas, as well as continuing to restore the remaining degraded forests |

## 3.5.6 Synergy with other themes

The IoT system technologies and related activities prioritised in this Chapter are pillars to addressing the specific challenges of food, agriculture and natural resources. The Major Challenges of food safety and security, environmental protection and sustainable production, water resource management and biodiversity restoration are significant to leverage the future of agriculture through agrifood innovation and interdisciplinary collaboration. They are aligned with the European missions on "*adaptation to climate change including societal transformation*", "*healthy oceans, seas, coastal and inland waters*", "*climate-neutral and smart cities*", "*soil health and food*", and "*decarbonization*". The application needs under those missions can be addressed through the integration of robust smart IoT systems together with innovative technological solutions, as well as holistic approaches in processes covering the whole supply chain, from resource utilisation and production to food packaging, waste management and remediation. As such, there are potential synergies with the Health, Energy, Mobility and Digital Industry application Chapters.

Destination Earth (DestinE)[47] is an EU flagship initiative that aims to build a digital model of the Earth "*to monitor and predict the interaction between natural phenomena and human activities*", as part of the global Green Deal strategy. Two of the three main components of the DestinE system, namely the Data Lake and the Digital Twin, can benefit from the advances in IoT technologies proposed in this Chapter. The data lakes will need to be fed from a large variety of data sources, including of course the data captured in the field by IoT sensors. Likewise, the digital twins will need to integrate comprehensive IoT data from farms, forests and oceans. On the technology side, the envisaged IoT system solutions will require significant advances in terms of functionality. Synergetic topics include advanced multi-sensing and data fusion capabilities, energy autonomy (harvesting, storage, and power management), connectivity, interoperability at all levels, lifecycle properties, reliability, privacy and security. There are also great challenges to make these heterogeneous systems manufacturable at the right cost for market entry while simultaneously achieving miniaturisation, ultra-low-power consumption, adequate packaging considering the environmental conditions and other constraints. To this end, significant collaborative effort will be required in materials integration and process technologies, architecture and embedded software for individual components, devices, systems and systems-of-systems. New designs at different abstraction levels (component, devices, network) and computing (edge, cloud) paradigms, new and interoperable models (e.g. AI/ML/DL and digital twin), design flows and methodologies and their associated tools are also needed. This is required to cross boundaries between domains, e.g. for verification and automated design space exploration, as well as data analytics and decision-making through AI/ML/DL and digital twin-based solutions. Overall, an orchestrated synergetic approach in the areas of advanced materials, circular industries, manufacturing technologies, ICT, AI, digital twin, edge and cloud computing, robotics, electronics, photonics, and electrical, as well as other key technologies such as new advanced HMI like virtual, augmented and mixed reality, will facilitate technology- push/demand-pull advances in the development and exploitation of smart IoT agriculture and natural resources.

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# 3.6

*ECS Key Application Areas*

# DIGITAL SOCIETY

## 3.6

# Digital Society

## 3.6.1 Scope

**Supporting the digital transformation throughout society**

This Chapter describes the type of digital innovations that are essential to stimulate an inclusive and healthy society, and which will in turn contribute to solutions for European challenges in the fields of health, mobility, security, energy, and the climate, and consequently to European economic prosperity.

Europe needs digital solutions that support the individual, and at the collective level to empower society as a whole. These (smart) digital solutions will be driven by upcoming technologies such as 5G, Artificial Intelligence (AI), virtual reality (VR) and augmented reality (AR), brain–computer interfaces (BCIs) and robotics. They will shape new ways of how people use and interact with these technological solutions, with each other, and with society and the environment. Digital innovations should facilitate individual self-fulfilment, empowerment and resilience, collective "inclusion" and safety, as well as supportive infrastructure and environment.

However, such a transformation will also introduce a wide range of ethical considerations. Future digital innovations will therefore need to address societal concerns in a sustainable way, guaranteeing participation and reducing inequality. A human-centred approach is therefore a key aspect of the EU's approach to technology development. It is part of European social and ethical values, (social) inclusiveness, and the creation of sustainable, high-quality jobs through social innovation.

## 3.6.2 Application trends and societal benefits

### 3.6.2.1 External requirements

To guarantee economic and societal growth in Europe, digital inclusion requires tools and infrastructures in application domain roadmaps as described in the other chapters. Technology permeates every aspect of society and is an important instrument of change (as can be seen in Figure 3.6.1, where two distinct rows are shown: current status and future expansion).

People's expectations of the future impact of technology are broadly positive, but also involve specific concerns around employment, income, safety, equality and trust. By 2035 the impact of science and technological innovation will be enormous on prosperity, individual well-being, sustainability, fairness, and trust (see Figure 3.6.2). This underlines the importance of investing in our digital strategy today.

In striving to guarantee European sovereignty to support European digital societal goals (for instance, through the GAIA-X140 project), safety, equality and trust are key requirements. What does this mean for electronic components and systems (ECS) for our society? Ubiquitous connectivity ("everywhere and always on"), online services and social media ("always online") drive people to rely on intelligent applications and the services they offer. Public and private infrastructures will increasingly be connected, observed and controlled via digital infrastructures ("continuous monitoring").

Two important further drivers for European society and economy – from a human-centred approach on AI perspective – are lifelong learning and training, as well as being able to work anywhere, anyplace. The trend to work from home whenever possible, earlier triggered by the Covid pandemic, will continue, and people will endeavour to combine work and private life in a better way. In rural areas, as well as in cities, it should be easy to work either from home or remotely in distributed groups/workforces. This can be achieved through living labs and learning factories at both a personal and collective level.

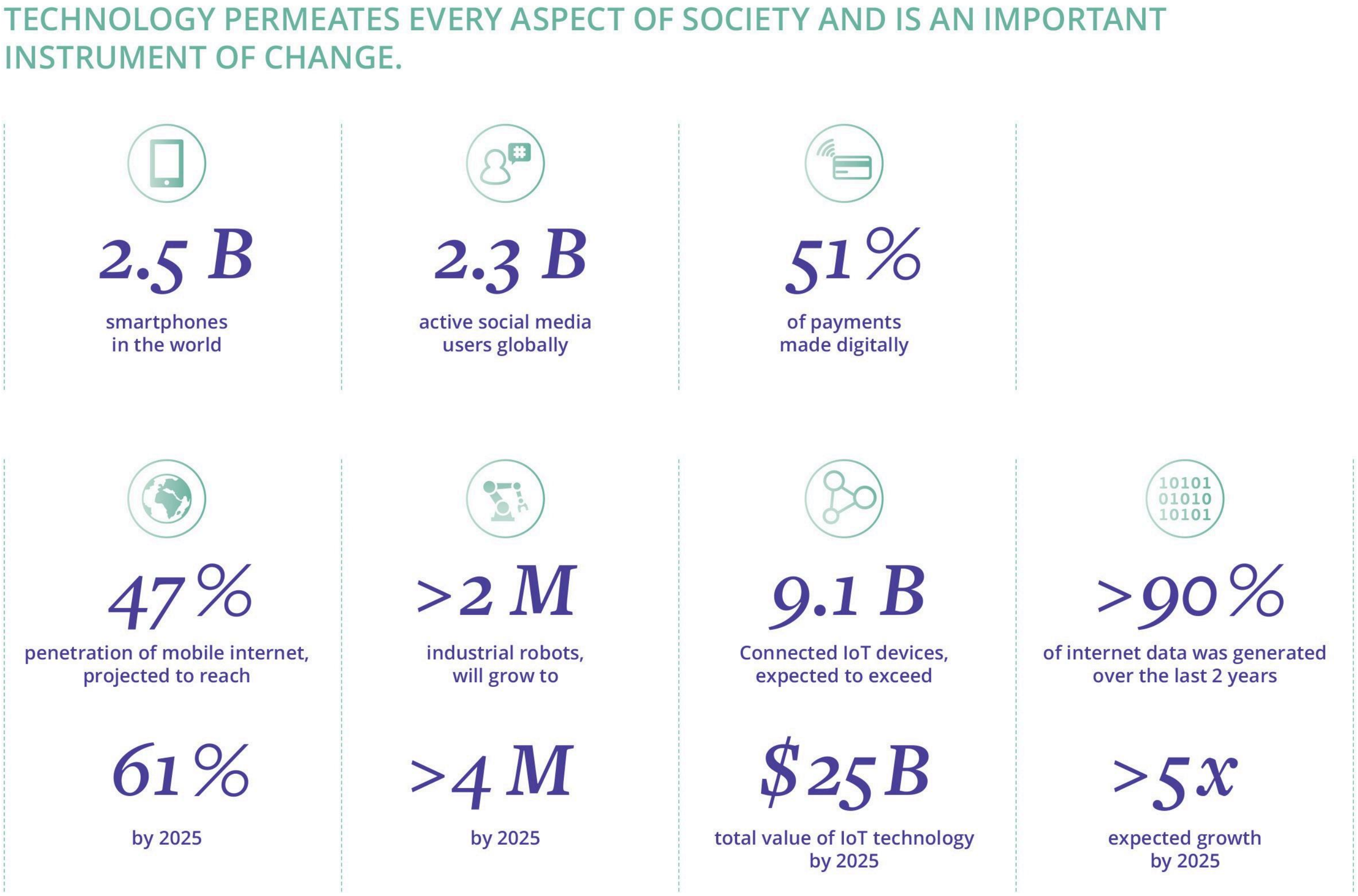


*Figure 3.6.1 - Technology permeates every aspect of society (Source: Why digital strategies fail, McKinsey & Company, March 2018; GSMA 2019; Domo; IDC; McKinsey Global Institute analysis)*

### 3.6.2.2 **Societal benefits**

All of European society will benefit from a major (AI-based) evolution in intelligent systems, on both the individual and collective levels:

- The benefit of digital inclusion for all individuals will involve employability through lifelong learning and training, and the personal well-being of individuals. To achieve these, the key ambition is to maximise the individual development of citizens.
    - How? By ensuring personal resilience, enabling lifelong learning and development, and stimulating employability. Human-centred solutions will optimise services to the needs and capacity of each individual, for applications in areas such as healthcare, lifestyle, coaching, training, and working from home or remotely collaborating in a "distributed" workforce. This will boost employee productivity, improve their work/life balance, and foster better mental health, and reduce pollution from commuters.
- The overall individual benefit is "well-being". A factor such as "prosperity" means job security, material living standards and the right to have the optimum education, any time, any place. On an individual level, well-being means health for every one of every age, and also adequate housing, ensured safety, protected privacy, reliable and ubiquitous digital infrastructures, in addition to social connectedness and more intense social cohesion. Our key objective is to empower and protect the individual.
    - How? By ensuring acceptable and trustable AI technologies to increase inclusion and prevent exclusion, protecting citizens against identity theft, and providing a protective environment against new virus infections; in addition, through lifestyle monitoring and coaching, to enable and support healthier lifestyles.
- The benefits of digital inclusion. A society resilient against setbacks, and the societal acceptance of novel technologies will achieve the key ambition of safeguarding a collective society and well-being for all.
    - How? By societal and digital inclusion, providing societal access for all, and ensuring collective resilience against setbacks. Also, the elderly will be supported to continue their social participation, which will reduce feelings of loneliness, improve their well-being and health, but provide reassurance that their precious experience can still be used.
- On an environmental level, the benefits are a physical and digital sustainable environment, intelligent Infrastructure management, stability and resilience against threats, and agreement on fall-back solutions in times of crises. The main aim is to contribute to a supportive infrastructure and environment.

- How? By providing reliable and resilient infrastructures, protecting society against destabilising forces, establishing a sustainable environment, and securing controlled climate change. Monitoring and intelligent control of infrastructures will also contribute to a sustainable environment by solutions that address, for example, optimal use of natural resources, reduction of pollution and crisis management.

"Sustainability" means environmental as well as economic sustainability, and equal opportunities for all people. It is related to fairness and trust in our societies. It must be ensured that AI-based systems will take European-style human values into account by design. A human-centred approach will therefore be a key requirement. As such, "FAIRness" (findability, accessibility, interoperability and re-use) will help shape future applications.

## 3.6.3 Strategic Advantage for the EU

Overall, a strategic advantage for the EU lies in digital solutions and people with high-developed digital skills who can contribute more efficient solutions for European challenges in the fields of health, mobility, security, energy and the climate. A digital "healthy" society will contribute to European economic prosperity. Digital tools, infrastructures, applications and digital skills will offer the following:

- Ensure companies that their labour force will work efficiently, whether they work at the head office or from their homes (i.e. to prevent virus spread, or for other reasons). An advantage here is the widespread empowerment of citizens to work from different locations, taking into account that some jobs will need to be undertaken in the office or factory, but that knowledge workers with computer-based jobs can work remotely.
- Provide people with greater employability and better protection against social or economic exclusion (the possibility of ubiquitous connectivity).
- Support citizens instead of replacing them with robots, as EU technical solutions will be based on human-centred AI systems that have a focus on human values. AI solutions applied should be trustworthy (responsible, transparent and explainable).
- Help European governments, companies and citizens to cooperate more easily, and develop reliable societal emergency infrastructures. This will make European societies better prepared to deal with emergency and crisis situations.

Widespread empowerment to work from different locations will require optimal use of (but also drive) the growth of interconnection bandwidth. Remote working will also require further use of cloud applications, using AI software as a service (SaaS) (possibly based on Large Language Models) to automate processes and support employees in decision- making, resulting in a spectacular growth of AI (as shown in Figure 3.6.2).

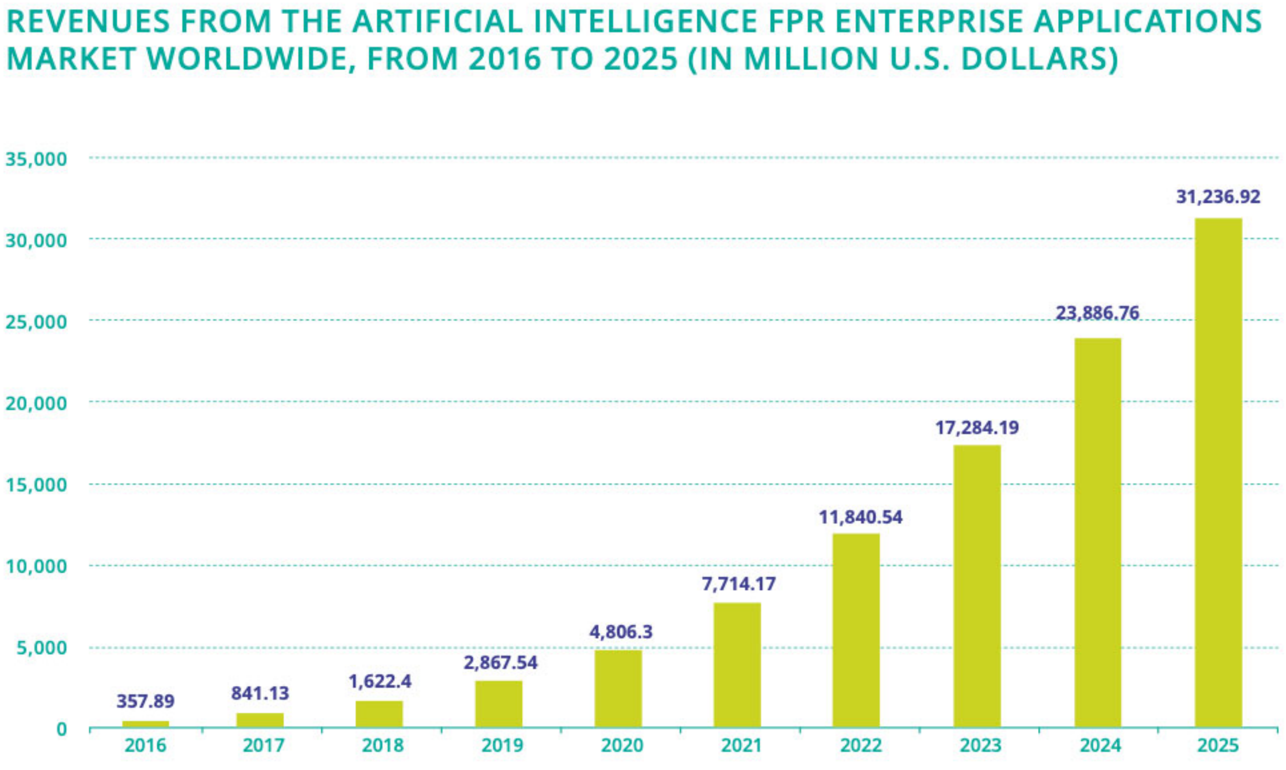


*Figure 3.6.2 - Enterprise AI market revenue growth worldwide (2016–25)*[1]

## 3.6.4 Major Challenges

Enabling and ensuring a digital society implies various aspects will be facilitated by ECS products and services. To structure these aspects, we distinguish between the individual or collective context and the internal or external scope. This leads to the matrix shown in Figure 3.6.3.

Each of these four areas relates to one of the following Major Challenges:

- **Major Challenge 1**: Facilitate individual self-fulfilment.
- **Major Challenge 2**: Facilitate empowerment and resilience.
- **Major Challenge 3**: Facilitate inclusion and collective safety.
- **Major Challenge 4**: Facilitate supportive infrastructures and sustainable environments.

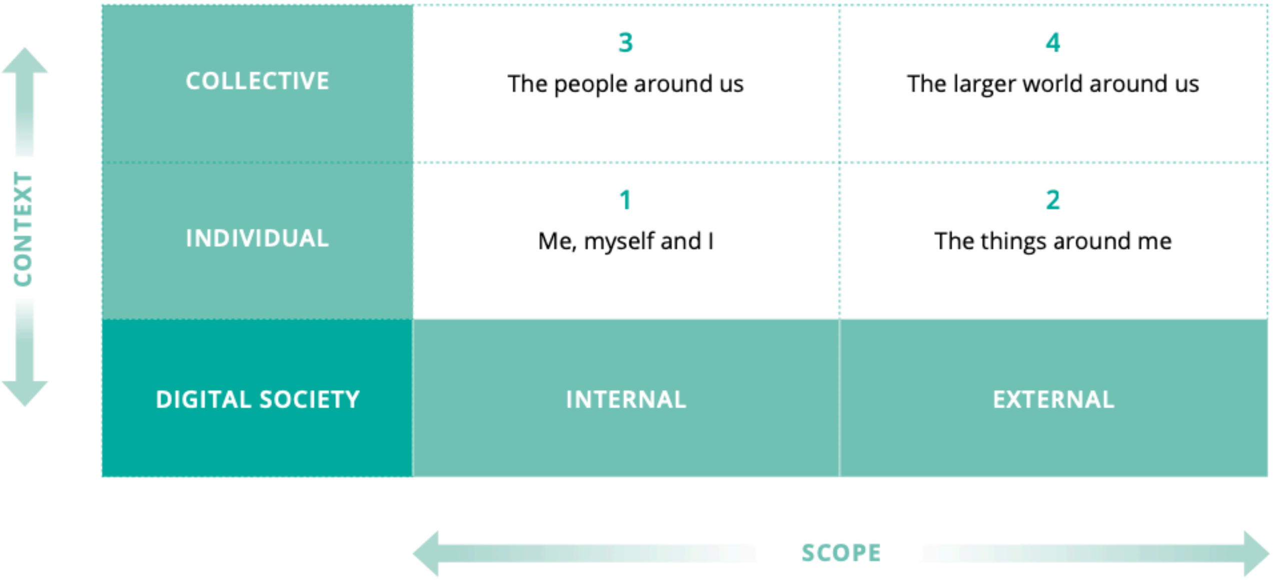


*Figure 3.6.3 - Structuring the Major Challenges in scope and context*

### 3.6.4.1 Major Challenge 1: Facilitate individual self-fulfillment

#### 3.6.4.1.1 Status, vision and expected outcome

Ambition: to maximise the individual development of citizens.

- Provide empowerment to citizens.
- Ensure personal resilience.
- Enable lifelong learning for both children and adults (serious gaming, including AR/VR).
- Give citizen more freedom to do their work wherever they want/need.
- Stimulate employability.
- Well-being (e.g. by gamification[2], connection to others, leisure).
- Improved human–machine interaction solutions for perception, reasoning and autonomy, with interaction being adaptive to the user's abilities.

To maximise the empowerment and self-fulfilment of citizens, Europe has to strive for lifelong learning, employability and the freedom to work wherever one resides, as well as optimal well-being in the context of an independent and pluralistic media. These enable lifelong empowerment by keeping citizens informed and facilitate the flow of educational content. Educating through the media is an important means to develop valuable skills that will help to end violence and eradicate forms of discrimination (such as sexism and racism). More fundamentally, the media encourages the acquisition of civic knowledge and facilitates discussion concerning current issues, while at the same time entering new frontiers of engagement using on-demand and interactive paradigms, and in employing AR/ VR technologies backed by 5G/6G connectivity.

The 30-year career has become a thing of the past. Education does not end after school; individuals need to keep on learning throughout their careers to stay up to date and adapt their skills as the world changes at an unprecedented rate. To better support lifelong learning, technologies are needed that encourage collaboration, foster autonomy and responsibility, and implement learning initiatives. Technological advancements such as cloud computing, mobile devices and web 2.0 technologies are still relatively new additions to the workplace that must be further explored[3].

To provide the citizen with more freedom to do their work wherever they want or need, Europe must ensure the availability of high bandwidth secure connections (wired and wireless) at all possible locations one could use to work from. This should be reinforced by easy and secure access to cloud applications, and novel AI-based solutions to automate processes, analyse data, guide the user in decision-making, and to minimise repetitive work.

Advanced technologies, including smart automation and AI, have the potential to not only raise productivity and GDP growth, but also to improve well-being more broadly, as well as offer a healthier life and longevity, and greater leisure time. Studies have shown that, besides income, the following factors contribute to individuals' well-being and self-reported life satisfaction: social life, use of leisure, health, spouse/partner, job, flat/house and the amount of leisure[4]. New technologies in the digital society can, and will, influence all these factors.

An example of the relevant tools is Coursera, which utilises gamification to offer the lifelong free and open learning of languages and brings massive open online course (MOOC) platforms to the public. Additionally, AI-tools that are based on Large Language Models (such as ChatGPT) can be beneficial for the individual development of citizens in several ways (access to knowledge, skill development, critical thinking, etc.). However, no tool can replace the richness of human interactions and experiences in personal development.

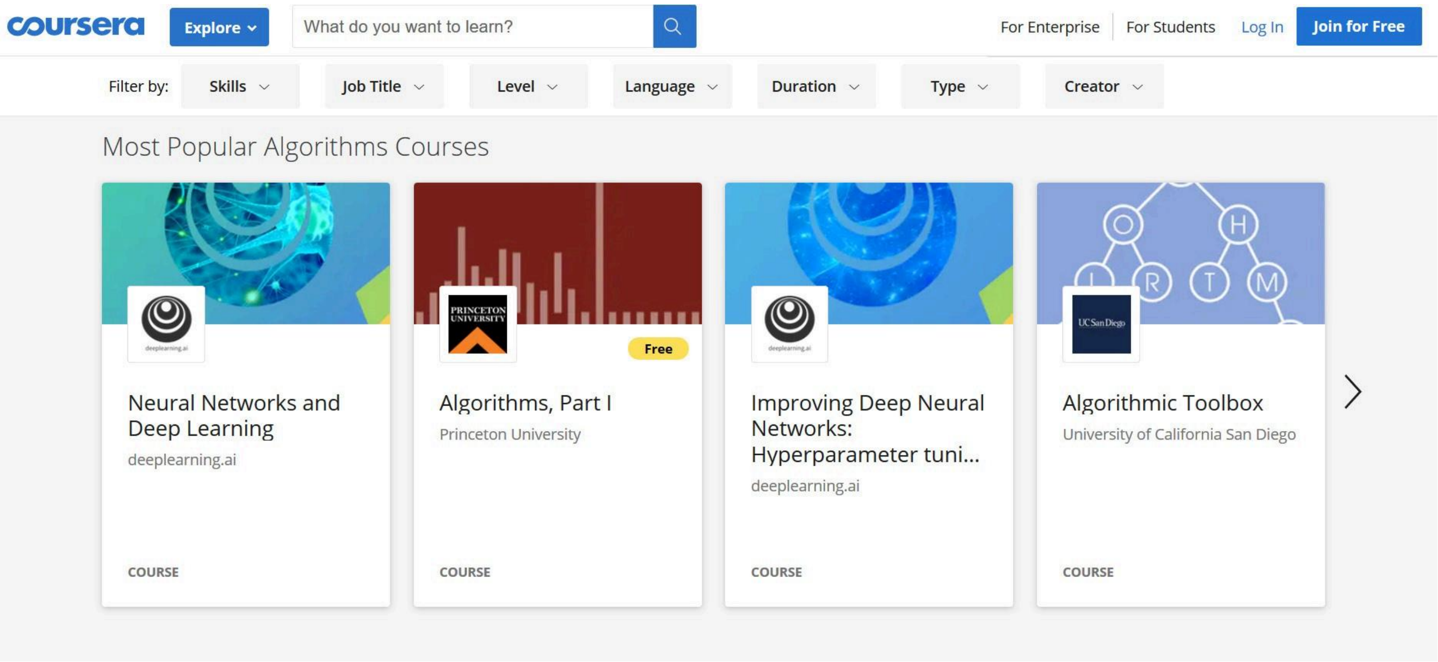


*Figure 3.6.4 - Coursera (Source: Coursera, Inc.)*

## 3.6.4.1.2 Key focus areas

High-priority research and development and innovation (R&D&I) areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Online education and examination: VR/AR training and support.
- Improved human–machine interaction (HCI) solutions.
- Support devices: wearables, robots, cobots, etc.
- Nudging and serious gaming: for personal development and healthier lifestyles.

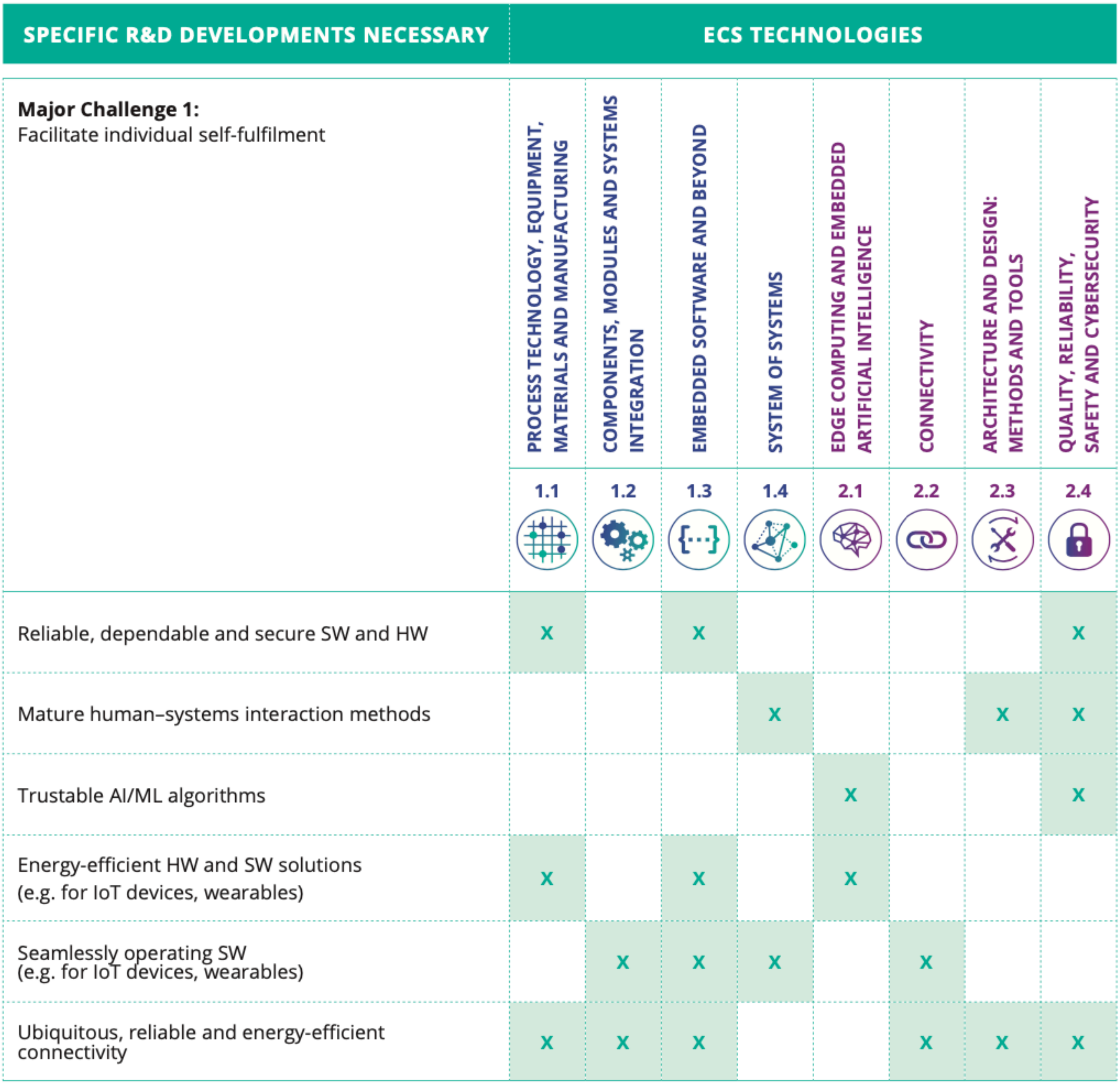
To improve the awareness of our body's condition to external or internal stimuli, smart systems can provide support for disabilities, or a personal coach and trainer to identify behaviour to be avoided (wrong body position and other bad habits), as well as possible future injuries or disorders. Smart systems can also offer an immersive experience through vision, gaming and sensory interaction by way of VR or AR. Consumers can be offered the immediacy, individualisation, interactivity and immersion they expect from media content consumption ("even better than being there").

A healthier and more comfortable environment can be offered based on personal preferences (control of temperature, humidity, air flux, etc.), in the context of running activities and clothing, and by adapting lighting and acoustic quality to one's own sense of well-being. It also provides the capability to comfortably communicate and interact remotely with people, institutions and sellers, possibly without leaving home, saving time for self- development and leisure.

Selective automation, AR at work and a range of feedback tools can help boost satisfaction and give more meaning to work. This is a particularly important element for the millennial generation, which -according to surveys- tends to place more emphasis on work satisfaction than on income (above a certain income level). During the Covid pandemic, large events have been difficult to organise, and many people could then only take part in events while not being physically present. Technological advances will make it possible to place audiences in the middle of the action and to offer them immediacy, individualisation, interaction and immersion without the need for them to actually be there in person. This will further change consumption patterns and create new business opportunities.

**Required R&D&I developments within ECS**

Taking the above into account, specific R&D developments are necessary within ECS technology, as shown in Figure 3.6.5.



| SPECIFIC R&D DEVELOPMENTS NECESSARY | ECS TECHNOLOGIES | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Major Challenge 1:** Facilitate individual self-fulfilment | PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1 | COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2 | EMBEDDED SOFTWARE AND BEYOND 1.3 | SYSTEM OF SYSTEMS 1.4 | EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE 2.1 | CONNECTIVITY 2.2 | ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3 | QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4 |
| Reliable, dependable and secure SW and HW | X | | X | | | | | X |
| Mature human–systems interaction methods | | | | X | | | X | X |
| Trustable AI/ML algorithms | | | | | X | | | X |
| Energy-efficient HW and SW solutions (e.g. for IoT devices, wearables) | X | | X | | X | | | |
| Seamlessly operating SW (e.g. for IoT devices, wearables) | | X | X | X | | X | | |
| Ubiquitous, reliable and energy-efficient connectivity | X | X | X | | | X | X | X |

*Figure 3.6.5 - Required R&D&I developments within ECS –Major Challenge 1*

### 3.6.4.2 Major Challenge 2: Facilitate empowerment and resilience

#### 3.6.4.2.1 Status, vision and expected outcome

Ambition: empower and protect the individual citizen.

- Increase inclusion and prevent exclusion.

- Protect citizens against cyber-fraud (scams) and identity thefts; provide privacy.
- Enable smart homes with ubiquitous connectivity.
- Ensure acceptable AI technologies.

Diversity and inclusion within societies are increasingly recognised as crucial for equality at work and economic development. Research has established a strong link between gender equality in society, attitudes and beliefs about the role of women, and gender equality in work[5]. Technology can improve equality at work – for instance, by revealing pay gaps and biases, and helping de-bias recruitment. It can also improve equal access to essential services – for example, biometrics and cloud technology can contribute to increasing the diffusion of microfinance to women and underserved populations. Technology can also help enforce inclusive legal rights, policies and social norms. While e-voting still poses a number of cybersecurity challenges, it can support diversity by facilitating the vote for vulnerable and marginalised parts of society. Finally, technology can help with physical security and autonomy for minority groups through objects and digital communications tools that reduce or mitigate exposure to risk – for example, connected devices such as smart bracelets can enable women to signal an assault and call for help.

Reliance on technology comes with many benefits, but also brings new risks[6]. The radical nature of the ongoing technology transition could result in risks that are not just an extension of the previous challenges, but require fundamental changes to core aspects of our society, including how we think about our identity, security and rights. Concerns about technology are justified by recent events, such as security breaches in prominent companies, data theft and information misuse. In addition, AI provides more powerful examples of potential risks. Its full potential can be utilised only if we fully rely on it for decision-making, allowing it to process data beyond the human ability to cross-check and verify. This depends on a high level of trust, raising questions about, and requiring, new technical solutions that take into account explainability, accountability, trustworthiness and ethics.

In the early ‘20’s we have experienced the necessity of a connected smart home and an adequate home office during the pandemic. However, the availability of high bandwidth connectivity is not evenly distributed geographically across Europe.

Machine learning is essential for a resilient future. AI will have a far greater chance of successful implementation if there is a focus on four key areas: augmented intelligence; intelligent automation; assessed intelligence; and adaptive intelligence. Augmented intelligence concerns augmenting and thus improving the productivity of humans. Intelligent automation is about building systems that integrate humans and machines in productive ways (instead of just replacing humans entirely with machines). Assessed intelligence is all about making models robust by evaluating them rigorously and continuously. Finally, adaptive intelligence involves developing more resilient systems that can adapt to changing circumstances by shifting to a causal inference paradigm.

### 3.6.4.2.2 Key focus areas

High-priority R&D&I areas:

- Reliable and ubiquitous digital infrastructures.
- Access control/intrusion detection/surveillance.
- Provide protective environment and tools against virus infections.
- Protect individual citizens against cyber-fraud (scams) and identity theft.
- Off-grid living and emergency survival.

Since the Covid pandemic, working from home has become an integral part of how knowledge workers do their work. To further enable working from home (or wherever and whenever one wants), wireless and wired infrastructures will have to be further improved (through increased reliable bandwidth, lower cost, better geographical coverage and finer granularity), security of connections will have to improve to protect the worker at home (as will the company using a distributed workforce with many internet connections) against cyber-attacks, and the theft of personal and/or company information. New functionality running in the private/public cloud will be needed to support real-time actions that may suffer from latency issues over the internet, as well as to support the worker in decision-making. Examples here are control of robotic surgical devices, remote control of robots in industrial processes, remote control of cameras in security applications and live television productions, and so on. Other professions, such as translation services, voice recognition and all kind of analytical algorithms for data analysis, also come to mind.

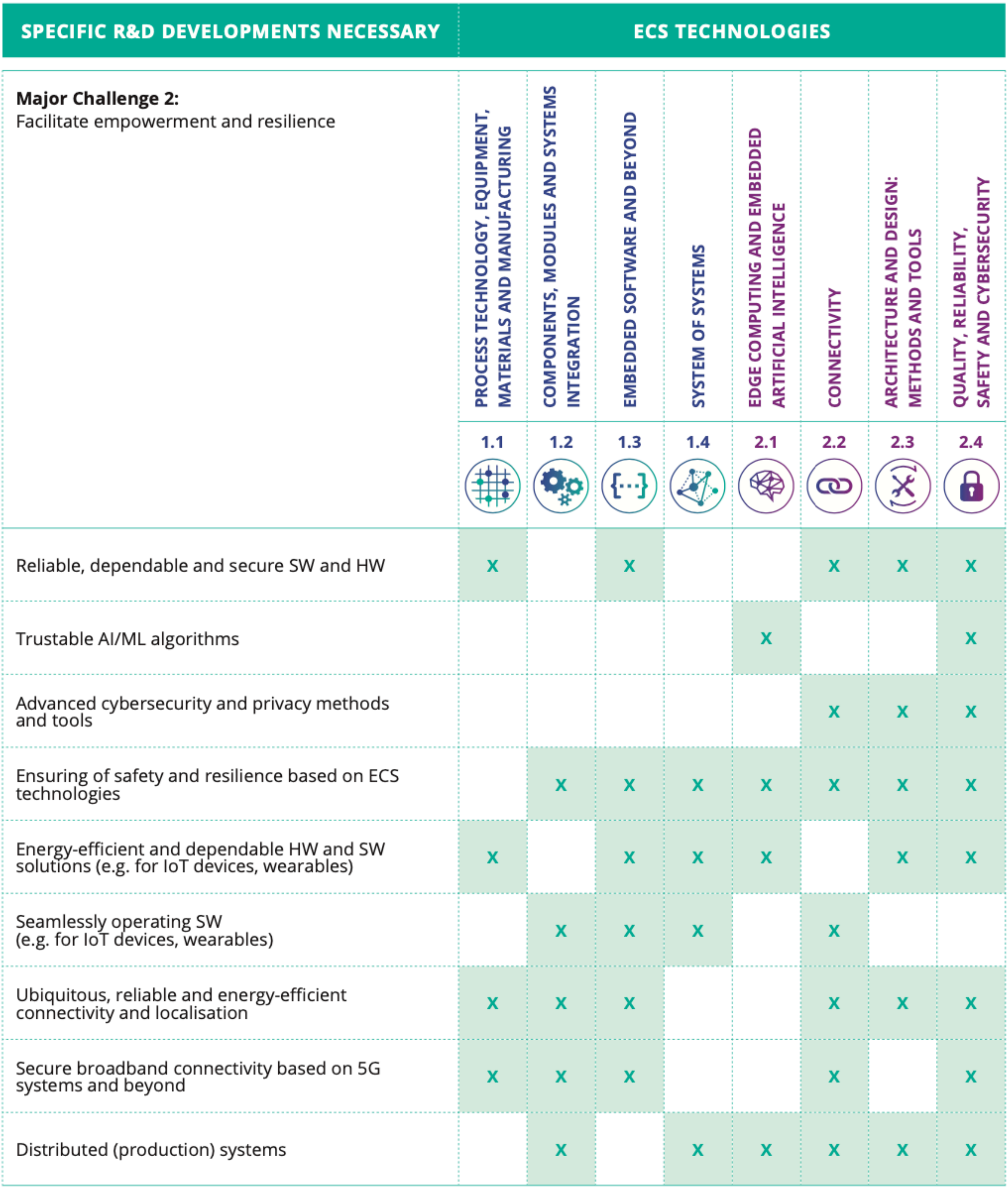
To create equal opportunities, innovative research should include: speech-generating devices (SGD) to help people with speech disorders; exoskeletons that empower disabled people in their everyday life; semi-autonomous vehicles that increase mobility for people with deafness and blindness; smart objects linked to geospatial information to improve women’s security (e.g. invisible SOS buttons); augmentative and alternative communication tablets that help paralysed patients; VR solutions that provide realistic experiences for people with physical disabilities; and smart glasses that can be used to help people with autism on cognitive, social and emotional skills.

Given the experience of the past pandemic, we learned that Europe needs better technologies: (i) to fight and contain the rapid spread of highly contiguous diseases (such as Covid-19); and (ii) to ensure that public health institutions can maintain their capacity to meet the ever-increasing needs caused by such a pandemic[7]. The in-depth analysis provided by the European Parliamentary Research Service’s “Ten Technologies to Fight Coronavirus” identifies the importance of AI, blockchain, open-source-, telehealth- and gene-editing technologies, 3D printing, nanotechnology, synthetic biology, and drones and robots for fighting pandemics.

Intrinsically, technology is neither good nor bad – it is the use to which it is put that makes the difference. Malicious uses of technology include mass disinformation campaigns and cyber-attacks that seek to jeopardise national security, and cyber-fraud that targets consumers. This duality has always existed. Over the coming years, technologies such as the IoT, smart robotics, automation and AI are likely to follow the same pattern. It is up to European technology specialists to ensure that the technologies developed not only support diversity and inclusion, but also protect both the individual and groups against cyber-attacks, theft of personal information and unwanted intrusion into the personal environment.

**Required R&D&I developments within ECS**

To facilitate empowerment and resilience, specific R&D developments are necessary within ECS technology, as shown in Figure 3.6.6.



| SPECIFIC R&D DEVELOPMENTS NECESSARY | ECS TECHNOLOGIES | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Major Challenge 2:**<br>Facilitate empowerment and resilience | PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1 | COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2 | EMBEDDED SOFTWARE AND BEYOND 1.3 | SYSTEM OF SYSTEMS 1.4 | EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE 2.1 | CONNECTIVITY 2.2 | ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3 | QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4 |
| Reliable, dependable and secure SW and HW | X | | X | | | X | X | X |
| Trustable AI/ML algorithms | | | | | X | | | X |
| Advanced cybersecurity and privacy methods and tools | | | | | | X | X | X |
| Ensuring of safety and resilience based on ECS technologies | | X | X | X | X | X | X | X |
| Energy-efficient and dependable HW and SW solutions (e.g. for IoT devices, wearables) | X | | X | X | X | | X | X |
| Seamlessly operating SW (e.g. for IoT devices, wearables) | | X | X | X | | X | | |
| Ubiquitous, reliable and energy-efficient connectivity and localisation | X | X | X | | | X | X | X |
| Secure broadband connectivity based on 5G systems and beyond | X | X | X | | | X | | X |
| Distributed (production) systems | | X | | X | X | X | X | X |

*Figure 3.6.6 - Required R&D&I developments within ECS – Major Challenge 2*

### 3.6.4.3 **Major Challenge 3: Facilitate inclusion and collective safety**

#### 3.6.4.3.1 Status, vision and expected outcome

Ambition: safeguard collective society and well-being for all.

- Societal and digital inclusion.
- Provide societal access for all.
- Ensure collective resilience against setbacks.

Although European countries have different types of welfare models, they also share a history of robust social protection and a focus on inclusive growth, which has been under stress in recent years[8]. There could be cracks in the sustainability of the EU social contract over the next decade caused by six trends: ageing; digital technology, automation and AI; increased global competition; migration; climate change and pollution; and shifting geopolitics. Based on these trends, inequality may rise again, and divergence within Europe could increase.

Inequality at work may emerge through a combination of: (i) automation and the substitution of labour; and (ii) corporate diffusion dynamics, leading to a competitive disadvantage among non-adopting firms. To prevent reduced employment and secure real wage growth, automation using AI, robotics and other innovative technologies should lead to significant productivity gains. In general, occupations based on more repetitive and non-digital tasks will be taken by workers with low education and skills, who will therefore be the first to experience pressure on wages.

Collective growth and well-being are not only determined by equality at work, but also by individual development supported by collective interactions. Studies have shown that active social relationships increase health and longevity by improving key biomarkers of physical health. A lack of interaction causes a subtle decline in mental health by reducing attention, learning, memory and decision-making skills. In short, our bodies reward us for social interaction and punish us for isolation by negatively impacting mental and physical health. Direct interactions with family and friends, participating in team sports and, for instance, visiting an event with friends are very important. No technology can fully replace direct contact. However, during the recent Covid pandemic, direct social interactions were often not possible in the way we were used to. Thus, we had to rethink our social interactions, and adapt existing and new technologies to increase and improve social interactions – not just between individuals but also between individuals and groups, as well as between different groups. How can improved technologies support existing social interactions, and secure healthy digital social interactions in cases of setbacks?

In addition, collective safety can be enhanced by solutions that directly address specific communities or groups of people the individual is a member of, such as family, friends, neighbourhood, region, (sports)club or association. These solutions can either have a warning or alerting function (e.g. contamination, local fire, local air pollution, incident of violence), but can also be of a supporting nature – for instance, alerts or instructions in combination with collective supporting devices (e.g. automated external defibrillator (AED), diagnostics, measurement).

#### 3.6.4.3.2 Key focus areas

High-priority R&D&I areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Collective safety: secure access control, surveillance, pandemic control, prevention of misinformation without limiting freedom of expression.
- Safe environment for living, working and transport: buildings and bridges resilient against earthquakes through continuous monitoring (e.g. fibre-based stress sensors).
- Emergency/crisis response solutions and services.
- Dynamics of society: systemic change.

As Europe wants to play a major role in digital inclusiveness, it is important to ensure availability and accessibility of solutions to enable remote education, learning, training and assessment of professionals, students and consumers in all regions (both cities and rural areas). Also, solutions to support social inclusiveness for people of all age should become available.

The EU has stated, in their document on orientations towards the first strategic plan for implementing Horizon Europe[9], that the interaction of science, technology, social sciences and humanities will be crucial in this respect, as will be the input of the creative sector and artists to sustainable inclusive innovation and human- oriented technologies.

To facilitate inclusion, more research will be needed on education, simple human–machine interfaces and digital technology interfaces that avoid the digital split between high- and low-educated citizens. In addition, remote presence and remote connectivity to keep people connected even if they are not in the same location, trustworthy social media, serious gaming, media consumption and AR/VR will be key.

To safeguard digital inclusion, education is one of the most important research areas. Examples here are the use of AI to build personalised journeys and enhance learning outcomes, to adapt curriculum to individual student needs, digital support and nudging systems to reduce the administrative burden on teachers, tablet-based learning to improve results and decrease distress for students with dyslexia, automation of administrative tasks to free up time and resources for educational professionals, wearable devices that provide real-time support to pupils, eye-tracking solutions to adapt students' learning experiences, and use of AR/VR to provide immersive experiences to civilians in less well-served areas.

AR may improve connectedness for remote places, reducing the need for commuting or business travel. It could also enable consumers to enjoy an event together even if they are not physically at the event.

There are still several challenges to effectively take full advantage of AI in video creation and consumption. One is the size of video data. Results are only accurate when algorithms are fed with millions of observations. Technologies therefore have to be deployed and strategies have to be implemented to gather data at scale to harness the full power of AI techniques. However, size creates another challenge: datasets need to be manually labelled by humans to train the model, making the process expensive and cumbersome. New techniques that are becoming available to overcome the challenge of (expensive) data categorisation are reinforcement learning, generative adversarial networks, transfer learning and "one- shot learning". In consumer-facing applications, such as marketing and recommendation algorithms, AI models may need to be refreshed continuously due to changes in the environment that drives them. Continuous updates to AI models are expensive. Other challenges relate to data management and data gathering: to create accurate results with AI, and thus value, different types of data have to be managed in a unified manner. This includes audience data, operational data and content data (metadata). Also, "selection bias" (i.e. the data gathered is not representative of the population studied) has to be prevented to exclude wrong conclusions in a perfectly working model.

To facilitate collective safety, further research is required on secure access control, intrusion detection, (video) surveillance of security sensitive areas, and individual and collective activity tracking.

Secure access control as a service (ACaaS) is growing in relevance. This combines biometric readers and identity access management and can be integrated with other physical security systems (e.g. video surveillance) and building automation systems. Combined with building occupancy management systems, it can deliver valuable information on the location of staff and visitors, and in the event of an emergency to rapidly clear the building.

Both the Covid pandemic and the military conflicts on our continent has brought new physical security requirements. In addition to regular cameras, thermal cameras could be added at the entrance of buildings and venues to measure people's temperature as they enter premises. Physical access control, enriched with video security evidence, can provide important insights on where an infected individual has been, which doors they have used and who else may have come into contact with those doors and that individual. It can also provide these insights for more general security purposes.

More research on AI security solutions will ease the work of security operators. AI software can analyse images and audio from video surveillance live streams and recordings, and use image recognition algorithms to recognise faces, objects, and events, more than a hundred times faster than human operators. AI algorithms can also be used to carry out event detection, scene reconstruction, video tracking, object recognition, and (re)-identification, 3D pose estimation, motion estimation and image restoration. Video surveillance may be extended with freely moving cameras mounted under drones to recognise unusual behaviour in crowds from a high altitude, to monitor hazards such as fires, floods or erupting volcanoes, and to recognise criminal faces and follow targets. Since drones are airborne, they need fast mobile and wireless communications. Low-latency broadband technologies such as 5G can improve the precision and speed of their response times and enable high-speed communication to a nearby edge computing device.

Video quality should be further improved to support deep-learning algorithms, and to improve the video experience in media consumption: the spectral range and colour gamut can be extended, sensitivity must increase for low light use and dynamic range for better performance under all (and changing) lighting conditions.

AI video and audio algorithms will have to be transparent and explainable. Dedicated video and audio technologies will be required to prevent and trace fake video and audio used to create misinformation in (social) media.

#### Required R&D&I developments within ECS

To facilitate inclusion and collective safety, specific R&D developments within ECS technology are necessary, as shown in Figure 3.6.7.

| SPECIFIC R&D DEVELOPMENTS NECESSARY | ECS TECHNOLOGIES | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Major Challenge 3:** Facilitate inclusion and collective safety | PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1 | COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2 | EMBEDDED SOFTWARE AND BEYOND 1.3 | SYSTEM OF SYSTEMS 1.4 | EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE 2.1 | CONNECTIVITY 2.2 | ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3 | QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4 |
| ECS technologies for AR/VR and high-quality video/videoconferencing | X | X | X | | X | X | X | |
| Tools, methods, SW and HW technologies for extensive and ubiquitous use of AI/ML | X | | X | | X | X | X | |
| Advanced cybersecurity and privacy methods and tools | | | | | | X | X | X |
| Intelligent connected IoT devices using new sensors for safety and resilience of EU societies | X | X | X | X | X | X | X | X |
| Ubiquitous, reliable and energy-efficient connectivity and localisation | X | X | X | | | X | X | X |
| Secure broadband connectivity based on 5G systems and beyond | X | X | X | | | X | | X |

*Figure 3.6.7 - Required R&D&I developments within ECS – Major Challenge 3*

### 3.6.4.4 Major Challenge 4: Facilitate supportive infrastructure and a sustainable environments

#### 3.6.4.4.1 Status, vision and expected outcome

Ambition: contribute to a collective supportive infrastructure and environment.

- Provide reliable and resilient infrastructure.
- Protect society against destabilising forces.
- Establish a sustainable environment.
- Secure controlled climate change.

To fully benefit from the power of digitisation, Europe must enable a supportive infrastructure and environment. Given the rapid pace of change, this requires companies to get their technology, people and culture ready to join the digital transformation. This should be achieved by providing a reliable and resilient digital infrastructure (with ubiquitous and continuous connectivity), protecting society against destabilising forces and establishing a sustainable environment. The former includes preventing harmful use of the internet (e.g. manipulation of elections, misinformation such as “deepfakes” and “cheapfakes”, but also identity theft and phishing), which are covered by Major Challenge 3. The latter includes securing controlled climate change (as stipulated in the Green Deal). Furthermore, monitoring and intelligent control of infrastructures and essential resources (especially in the urban environment) will contribute to a sustainable environment.

The vision is to introduce new digital products and services that contribute to a sustainable lifestyle in all areas of human life, including cradle-to-cradle and circular economy aspects. We are addressing the following aspects:

- Comprehensive assessment of resource usage to identify largest areas of consumption. As well as air quality monitoring systems, they need to offer solutions for lighting, heating, computing with reduced usage of energy, and other resources. In addition, solar panels and batteries, home-grown vegetables and city farming systems are key.
- Providing IoT/smart systems that support the digital business life with the minimum amount of resources (energy, water, paper, travelling, etc.), ensuring a highly efficient, productive and sustainable working environment. Reduction of (food) waste in supermarkets and restaurants, as well as resource recycling.
- Smart water management to protect resources. Intelligent management of energy in public spaces such as football stadiums and railway stations, including smart street lighting. Promoting green areas in cities and enabling citizens to provide their own sustainable solutions.
- Sustainability and dealing with climate change.

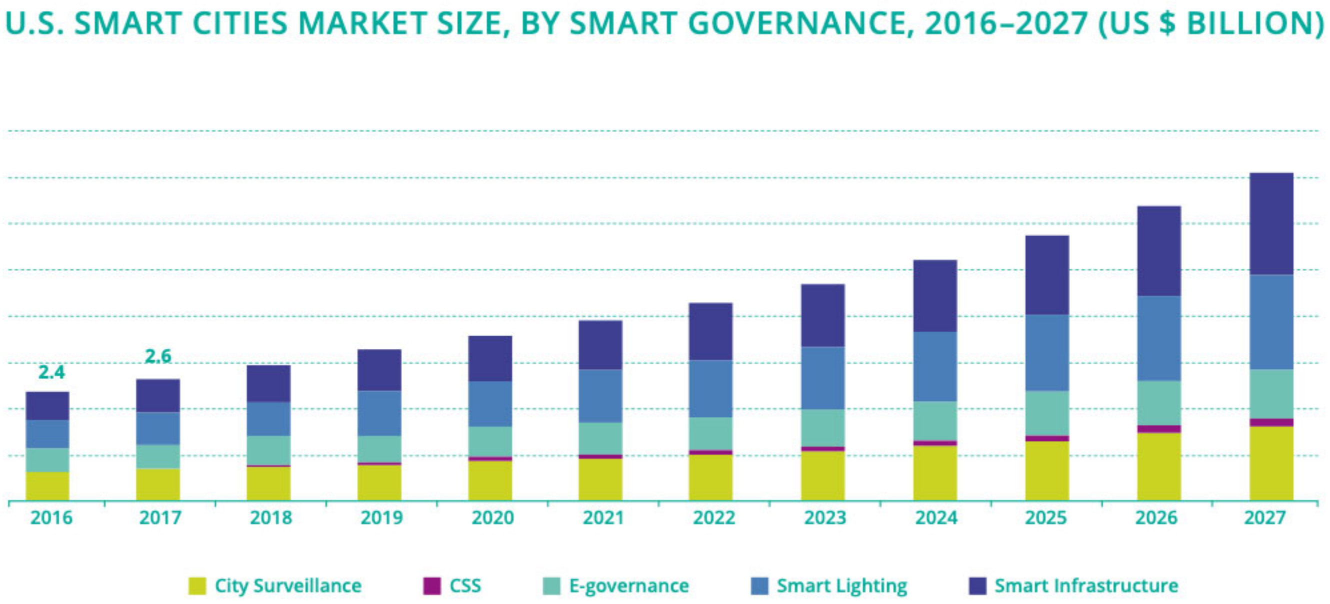


*Figure 3.6.8 - Growth of US smart cities market (Source: **www.grandviewresearch.com**)*[10]

The European approach to working with regard to digitalisation will be focused on the preservation of our democratic system, and on values such as trust and cooperation. Ethical requirements will include fairness, accuracy, confidentiality, transparency, accountability, explainability, trustworthiness and absence of bias. This involves offering AI capability maturity programs to companies that use AI in their designs, to coach them in the best ethical points of view. In this way products will become more resilient, accessible, reliable and trustworthy, and hence ready to take part in the new European digital society (with an effective AI act).

### 3.6.4.4.2 Key focus areas

High-priority R&D&I areas:

- Physical infrastructure management/physical resilience.
- Intelligent infrastructure management (intelligent buildings, city-owned infrastructure, synergies with industry, etc.).
- Digital infrastructure management/digital resilience.
- Smart cities: e-government/citizen support.
- Resource monitoring (air, water, etc.) and feedback to enable more effective management.

To further improve digital infrastructures, investments should be aimed at enhancing infrastructure coverage and quality – for example, with broadband rollout and public Wi-Fi. Also, outcomes have to be influenced through legal frameworks and by setting standards.

Intelligent buildings will require security, eco-friendship and building management. Security systems such as access control and cybersecurity were covered under Major Challenge 3, but the further development of smart lighting, air quality monitoring and control, and IoT-based real-time monitoring of electric, water and gas meters to increase the energy efficiency of buildings with the help of distributed energy systems will improve the well-being of occupants and reduce the carbon footprint of buildings. Smart technology (e.g. sensors placed around radiators, boilers, pumps and other machinery to detect critical levels of noise, vibration or heat) will enable facility managers to save maintenance costs by switching from a reactive to a predictive maintenance model.

Cities are very complex organisms. They combine a variety of means allowing for mobility, city infrastructure providing different types of media (gas, water, energy, etc.), and citizen-oriented services that increase their quality of life. It is predicted that by 2050 between 68% and 90% of the global population might live in cities, from small municipalities right up to megacities[11]. This means that, in the near future, technical means will be required to enable digital solutions for more sustainable development in cities of all size and wealth. Available technologies from tech giants such as IBM, Microsoft, Amazon, Google and Cisco raise concerns from city managers about data privacy policies, and the very high maintenance costs caused by licence fees and the potential for vendor lock-ins[12]. Available open-source solutions – such as the Red Hat integration platform, which could be used in smart city applications – can also easily be acquired by large companies such as IBM[13] to be integrated with their company product portfolio offered commercially. This means that, in such a dynamically changing world, open-source solutions that are widely available, promoted and deployed within EU (such as FiWARE[14]) have to be developed to protect European sovereignty and values. Additionally, due to the rich industrial heritage in many EU countries, opportunities for re-using or integrating available well- developed open-source industry platforms, such as the Eclipse Arrowhead Framework[15], have to be thoroughly investigated. This is especially the case since industry sites are often integrated within city areas, and therefore naturally create synergies that can influence each other. These smart city applications create natural synergies with the System of Systems, Mobility and Digital Industry sections.

The impact of technology on environmental sustainability is likely to be highly significant. In retail, where shifting customer habits will be key (for example, for new products such as plant- or insect-based food), IoT sensors and devices will also yield a positive impact – for example, by reducing waste through improved food temperature or expiry date management. In the manufacturing sector, smart building applications related to energy and wastewater management, as well as applications such as carbon capture and biofuel generation on industrial sites, will have a significant impact.

**Required R&D&I developments within ECS**

Development of supportive infrastructure and a sustainable environment within EU needs the following specific R&D developments within ECS technology:

| SPECIFIC R&D DEVELOPMENTS NECESSARY | ECS TECHNOLOGIES | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Major Challenge 4:** Facilitate supportive infrastructure and a sustainable environment | PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1 | COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2 | EMBEDDED SOFTWARE AND BEYOND 1.3 | SYSTEM OF SYSTEMS 1.4 | EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE 2.1 | CONNECTIVITY 2.2 | ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3 | QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4 |
| Open systems and platforms for managing complex cross-connected physical infrastructure and associated processes | | X | X | X | | | X | |
| Energy-efficiency oriented HW technologies and embedded SW | X | | X | | X | X | X | |
| Advanced cybersecurity and privacy methods and tools | | | | | | X | X | X |
| Intelligent connected IoT devices using new sensors for safety and resilience of EU societies | X | X | X | X | X | X | X | X |
| Ubiquitous, reliable and energy-efficient connectivity and localisation | X | X | X | | | X | X | X |
| Secure broadband low-latency connectivity based on 5G systems and beyond | X | X | X | | | X | | X |
| Distributed (production) systems | | X | | X | X | X | X | X |

*Figure 3.6.9 Required R&D&I developments within ECS – Major Challenge 4*

## 3.6.5 Key Enabling Methodologies

Key Enabling Methodologies[16] support in bridging the opportunities of the Key Enabling Technologies in ECS (electronic components and systems) with the four Major Challenges for the Digital Society. Key Enabling Methodologies (KEMs) are the ‘instruments’ that direct and structure the way of working in multi-collaborative settings, give direction and realise impact with useful applications and meaningful interventions.

KEMs contribute to the integration of the technological opportunities of ECS with the knowledge from design, social sciences and the humanities about the Digital Society.

Several categories cover the main areas of the KEMs: Vision & Imagination, Participation & Co-creation, Behaviour & Empowerment, Value Creation & Upscaling, Institutional & System Change. KEMs can support in answering questions such as how technological tools, infrastructure and training can empower citizens towards digital inclusion. How to imagine and anticipate for setbacks and build collective resilience? How to include the relevant societal stakeholders into the R&D&I developments within ECS?

## 3.6.6 Timeline

The following table illustrates the roadmaps for Digital Society.

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| **Major Challenge 1:**<br>**Facilitate individual self-fulfilment** | **Topic 1.1:** improved human– machine interaction solutions | Intensive research on human–machine interaction solutions | Improved human–machine interaction solutions in pilot phase | Improved human–machine interaction solutions in the commercial phase |
| | **Topic 1.2:** online education and examination | Developments of methods and solutions for online education and examination | Online education and examination used in most EU universities, also for education of adults | Online education and examination widely used across the EU |
| | **Topic 1.3:** VR/AR training and support | VR/AR pilots, including remote training, support and work | VR/AR training, support, and remote work is mature | VR/AR training widely used across the EU |
| | **Topic 1.4:** support devices (wearables, robots, cobots, etc) | Wearables and used for commonly used devices | Support devices (wearables, robots, cobots, etc) gain more intelligence and interaction | Support devices (wearables, robots, cobots, etc) used in daily life |
| | **Topic 1.5:** nudging, gamification (for development or health reasons) | New nudging, gamification systems developed for education and health | Nudging, gamification pilots in education and health | Nudging, gamification (for development or health reasons) is widely used across the EU |
| **Major Challenge 2:**<br>**Facilitate empowerment and resilience** | **Topic 2.1:** access control/ intrusion detection/surveillance | Classic surveillance systems | Smart surveillance with rudimentary intrusion detection | Smart surveillance with AI-based intrusion detection |
| | **Topic 2.2:** reliable and ubiquitous digital infrastructures | Increased quality of service (QoS) and available bandwidth with 5G, less time-critical functions moving to the cloud | Bandwidth and QoS increase especially for video-based applications<br>Time-critical functions moved to cloud | Bandwidth and QoS no longer an issue for video applications.<br>AI algorithms support supervision |
| | **Topic 2.3:** social media/serious gaming/AR/VR | AR on social media moves from photos to video >80% on social media in video by 2024; in-game systems that self-adapt to guide human learning | Apart from, AR also VR for videos on social media<br>Multimodal and multi-sensory interfaces in serious gaming<br>Application beyond single game.<br>Personal learning | Real-time emotion state sensing<br>Cognitive learning |
| **Major Challenge 3:**<br>**Facilitate inclusion and collective safety** | **Topic 3.1:** digital inclusion: tools, infrastructure, training, connectivity | Development of technologies (AR/VR, hearables, haptics, etc) for digital inclusion | Pilot deployments of hybrid systems for collective interactions | Technologies for immersive collective interactions |
| | **Topic 3.2:** resilient society against setbacks | Emergency/crisis response solutions and services with ubiquitous localisation | Trustable solutions for collective activity tracking, access control and intrusion detection | Trustable AI-supported hybrid solutions for resilient society |
| | **Topic 3.3:** societal acceptance of novel technologies | Technologies (serious gaming, nudging, etc) for societal acceptance and adaptation | Human-oriented trustable AI systems and technologies | Trustable AI for collective growth and well-being |
| **Major Challenge 4:**<br>**Facilitate supportive infrastructure and environment** | **Topic 4.1:** physical infrastructure management/ physical resilience | Development of IoT and dedicated robot-based inspection systems supported by AI algorithms | Pilot deployments of trustable AI-based systems relying on dependable edge/cloud IoT | Intelligent, affordable and trustable IoT and robot-based systems are available |
| | **Topic 4.2:** intelligent infrastructure management | Development of systems for intelligent management of infrastructure (water, street lighting, heat, etc) | Pilot deployments of trustable AI-based orchestration systems to create synergies in infrastructure management | Smart systems for multi-domain infrastructure orchestration and management available |

| MAJOR CHALLENGE | TOPIC | SHORT TERM (2024–2028) | MEDIUM TERM (2029–2033) | LONG TERM (2034 and beyond) |
|---|---|---|---|---|
| | **Topic 4.3:** digital infrastructure management/digital resilience and cybersecurity | Acceleration of initiatives to create open, secure privacy- oriented systems; development of AI-based algorithms for increased cybersecurity | Adaptation and pilot deployments of available interoperable open and reliable systems supported by trustable AI algorithms for increased cybersecurity | Open, secure, interoperable and reliable privacy-oriented systems empowered by trustable AI-based IoT solutions available |
| | **Topic 4.4:** surveillance, homeland security and emergency response systems | Edge/cloud solutions, IoT systems and robot-based inspection platforms, increased multimodal situational awareness, ubiquitous localisation | Deployment of trustable AI-based edge-cloud solutions, IoT systems and robot-based inspection platforms for surveillance and emergency response support | Trustable and dependable AI-based IoT systems and robot-based inspection platforms for increased situational awareness widely available |

## 3.6.7 Synergy with other themes

There is synergy with several other ECS key application areas, which has been delineated as follows:

- **Mobility**: where the Mobility Chapter mainly addresses infrastructure-related aspects, Digital Society implies "being on the move" from time to time. The aspects addressed by the Major Challenges for Digital Society in general therefore also apply when being on the move.
- **Digital Industry**: while sustainability is an important aspect of life in the digital society, it is also addressed in the Chapter on Digital Industry.
- **Energy**: electrical energy is a prerequisite of a digital society, as smart devices are based on it. Although -in general- energy generation and distribution are a different area, energy scavenging of IoT sensors and actuators, energy storage and wireless charging of smartphones and other wearables can be essential elements of a digital society.
- **Health and Well-being**: where healthcare aims to cure people of diseases, well-being implies measures to keep healthy people healthy. The Major Challenge "Ensuring individual empowerment and well-being" will contribute to the aim of keeping healthy people healthy by supportive products and services in the Digital Society.
- **AgriFood and Natural Resources**: the protection of natural resources can be considered part of ensuring environmental sustainability; for the rural, this is addressed in the Chapter on AgriFood and Natural Resources, while the urban lies more in the scope of Digital Society.

There is also synergy with some other ECS technology chapters:

- **Quality, Reliability, Safety and Cybersecurity**: there are relevant Major Challenges in that Chapter that link to this Chapter on Digital Society: quality and reliability, ensuring dependability in connected SW, privacy and cybersecurity, safety and resilience, and human–systems integration.
- **Connectivity**: homeland security and cybersecurity of the digital society needs reliable connectivity infrastructure.
- **System of Systems**: smart city topics require reliable digital solutions that can handle a variety of many interconnected systems within cities.

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# 4

*Strategic Research and Innovation Agenda 2024*

# LONG-TERM VISION

# 4 Long Term Vision

## 4.1 Introduction

In this Chapter, we present research subjects that need to be addressed by European organizations to enable and support effective development of European industry in about a decade from today. The previous chapters have presented status, trends, and plans for the near future, including challenges that are foreseen to require special attention within the coming decade. We build upon these identified challenges and specify long-term industrial needs. These needs are the basis for research programs for effective research and development in appropriate technological and/or application domains, so that European technological strength increases continuously in time and at the appropriate rate. Since lead-time from a first scientific breakthrough (TRL1) to market presence of related products (TRL9) is typically 10 years or more, the effective identification of the future industrial needs is a determining factor for the success and speed of innovation.

The long-term vision is shaped by three main factors: technology, application domains and policies. Clearly, all factors are drivers of innovation, because (i) anticipated technological advances lead to innovative applications of these advances and (ii) user needs lead to technological innovations that enable applications and services. At the same time, policies and politically established goals and processes lead technologies and applications towards common goals and targets.

Regarding policies, which lead many technologies and applications on a pan-European scale, the ECS community has specified its common objectives that influence and shape long-term innovation and must be considered in future research directions. As anticipated in the Introduction, these four high-level common objectives are:

- Boosting industrial competitiveness through interdisciplinary technology innovations;
- Ensuring EU digital transition through secure, safe and reliable ECS supporting key European application domains;
- Establishing and strengthening sustainable and resilient ECS value chains that support the Green Deal, gaining technological sovereignty in the process, and
- Unleashing the full potential of intelligent and autonomous ECS-based systems for the European digital era.

These objectives, which are aligned with policies and European political priorities, address the need to establish unrestricted access to goods and services, free exchange of know-how and information, under trusted, protected and regulated multilateral agreements in the emerging international political and economic landscape. European Union’s policies to protect its strategic autonomy, and sustain its competitiveness are shaping and continuously advancing, especially for the ECS industry, which constitutes the backbone of the digital society. European digital strategic autonomy – European Union’s ability to maintain control and security of its products, overcoming disruptions and vulnerabilities – is one of the major challenges when considering that its major economic drivers, i.e., digitisation and connectivity, are strongly dependent on the supply of hardware and software from countries outside Europe. This challenge needs to be addressed immediately, for the short term as well as for the long term, by research programs on the following topics:

- Safety and security: development of rigorous methodologies, supported by evidence, that a system is secure and safe; safety and security are requirements for trustworthiness. These methodologies should enable certification through appropriate methods, such as testing and/or formal methods to prove trustworthiness guarantees.
- Artificial intelligence and machine learning (AI/ML): AI/ML-based techniques will contribute significantly to the development of robust ECS components, systems, and applications, with short development cycles. AI/ML will influence all major technologies in ECS development, from model-based engineering and embedded software to fabrication, and will constitute a major link between quality, reliability, safety, and security.
- Trustworthiness: development of methodologies that integrate traditional ECS technologies with AI/ML, from device level up to applications and human interface. Trustworthiness is key to the acceptance of such emerging systems. Advances in explainable AI models for human/ system interaction, safety, security, risk analysis and management, liability and certification are necessary for the necessary trustworthiness that will lead to the acceptance of the new generation of innovative products.

The European Green Deal is another policy that combines wide civilian acceptance with high political priority and shapes innovation strongly. As climate change and environmental degradation pose an existential threat to Europe and the world, the European Green Deal is the European strategy to make the economy of the European Union sustainable in the long term[1]. By 2050, a modern resource-efficient and competitive economy must be in place, characterized by:

- Zero net emissions of greenhouse gases;
- Economic growth decoupled form resource use;
- Inclusion (no person and no place are left behind).

The ECS community is instrumental to the realization of the European Green Deal. The many challenges associated with energy management can be tackled only with ECS-based solutions, leading to energy-efficient ECS devices as well.

The first three high-level common objectives of the ECS community (competitiveness, robustness of ECS products and establishing value chains) can be achieved only by reaching the fourth one as well. The “unleashing” of intelligent and autonomous ECS-based systems requires the interdisciplinary effort and coordination of all stakeholders; academic, institutional, and industrial. In the effort to ensure effective and timely identification of effective exploitation of opportunities, a close cooperation of all stakeholders along the value chain is a prerequisite. This cooperation is traditionally strong in Europe and constitutes a valuable European strategic asset. This strength is based on the availability of many research facilities with excellent competence and extensive experience in the ECS domain. This comprehensive ecosystem of universities, RTOs, and industrial research organizations distributed across many countries in Europe forms a leading incubator for pioneering technologies that enable the creation of hyper-smart, safe, secure, and resource-efficient electronic components and systems. This ecosystem enables increasingly networked scientific work and is the base for maintaining the competitiveness of the European ECS industry now and in the future. Cooperation also offers the best opportunities for coping with the growing interdependencies and interdisciplinarity through strong coupling of basic and applied research within the European Research Framework Programme. This, in turn, creates the fertile soil, from which industry can receive substantial impulses to achieve breakthrough solutions with minimal time to market, leading to maintenance of

European technological excellence and leadership, which is the cornerstone of long-term European technological leadership and a basis for prosperity and peace in our continent.

Additionally, and independently of policies, long-term vision is shaped by technological and application evolution and revolution. Many future applications will be enabled by enhanced functional and non- functional properties provided by new technologies (both hardware and software), as projected in technology-application roadmaps such as the one shown in ***Figure 4.1***. Typically, the advances that are foreseen through roadmaps are considered evolutionary. However, there have been several occurrences of revolutionary or disruptive developments in technology. These are not projected in roadmaps; they exploit and establish innovative technological models and have tremendous technological and societal impact. Often, they lead to paradigm shifts with significant impact to business and society. The World Wide Web is a typical example of disruptive technology.

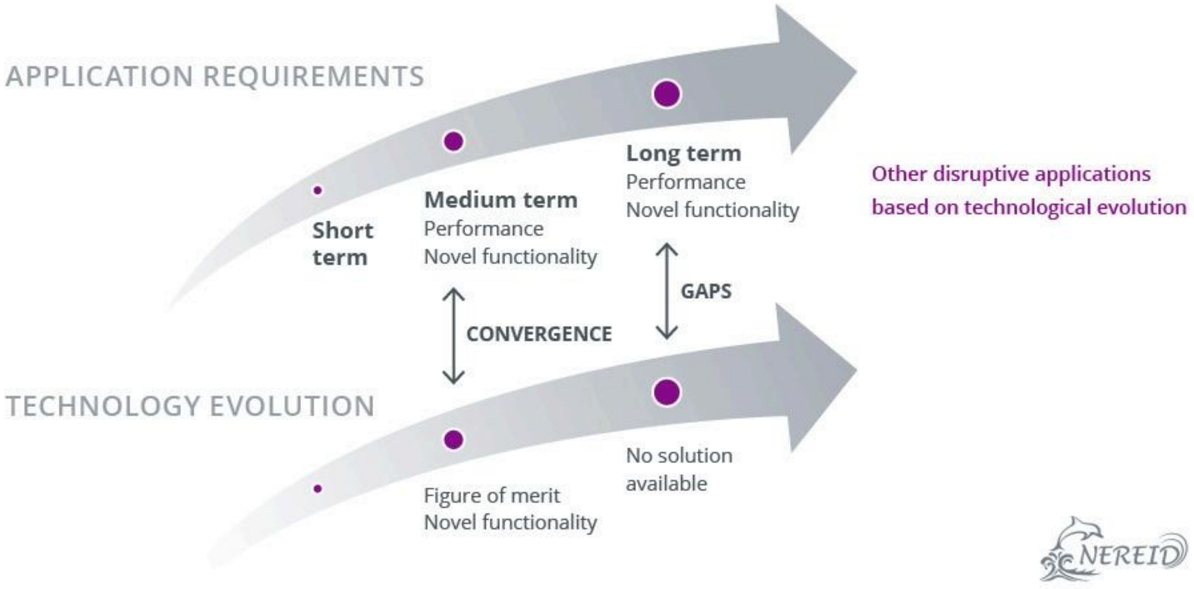


*Figure 4.1 - Technology evolution and application requirements.*

Over the last decades, the ECS domain has evolved from a technology-driven field to an environment where societal needs and application requirements guide the research agendas of the centers of expertise. However, technology-driven research goals need to be a part of the research agendas, considering that novel technologies often create and enable new classes of applications. The European competences in “Beyond CMOS”, ‘More Moore’ and ‘More than Moore’ have been instrumental in bringing about this change, resulting in a strong European position in markets that require complex multifunctional smart systems. Clearly, maintaining and extending these competences is fundamental to the continuous offering of disruptive technologies that will preserve the European competitive position.

In this Chapter, we present the main research trends that are of particular importance to the European strategic research and innovation agenda. Clearly, presenting a complete list of anticipated evolutionary and revolutionary, or disruptive, technologies and challenges is infeasible, by its very nature. Considering the three factors that shape the long-term vision - technology, application domains and policy - in the following section we present a model that enables us to present challenges in a systematic way. We consider policies to provide the framework as well as parameters for technologies and applications and then, we present technological challenges and needs to be met in application domains.

## 4.2 Model

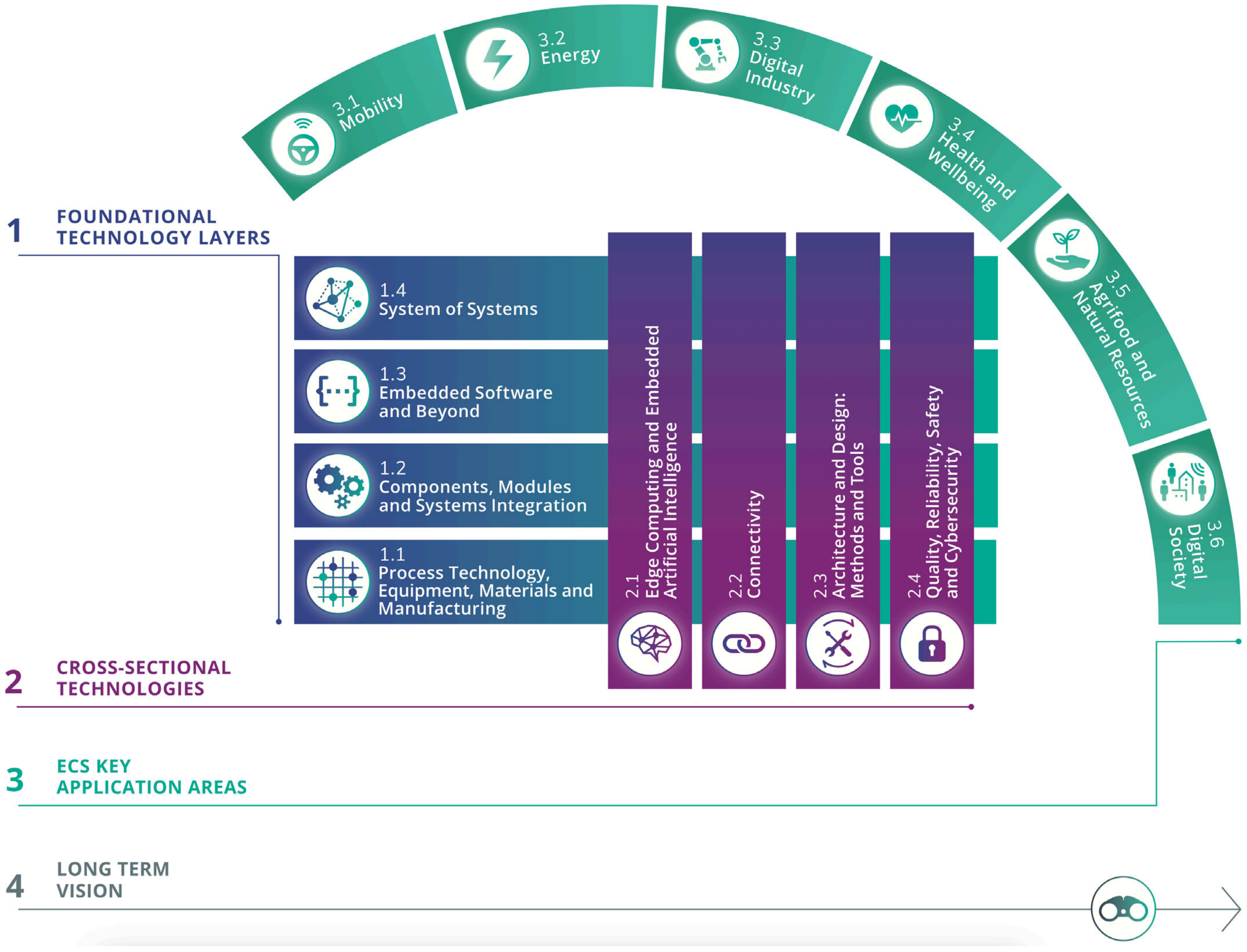


*Figure 4.2 - Technology domains evolution and application requirements.*

As explained in the introductory chapter of this SRIA (Chapter 0), we consider a layered model for the technological and application challenges for ECS, as shown in ***Figure 4.2***.

In the remaining sections of this Chapter, we present challenges in technologies, fundamental and cross-sectional, as well as in the application domains that are enumerated in ***Figure 4.2***, with the understanding that our presentation addresses evolutionary and revolutionary technologies based on conventional technological and societal understanding. Independently, our expectation is that disruptive innovations will be readily integrated in our long-term view, since they will affect part or parts of the layered model which we exploit for abstraction, understanding, presentation and openness.

## 4.3 Technology Long-term Challenges/Vision

### 4.3.1 Process technology, equipment, materials, and manufacturing

Europe has a strong competence in ECS process technology, enabled by the presence of an industrial, institutional, and academic ecosystem with a long tradition in multidisciplinary collaborative research in regional, transnational and European cooperative projects. With the growing complexity of ECS-based devices and systems, this multidisciplinary collaborative approach along the value chain is one of the major assets for Europe in maintaining its competitiveness.

In the More Moore field, there are strong interests in Europe for specific activities that involve very low power devices, leading to possible disruptive applications – for instance, for future IoT systems, embedded memories, 3D sequential integration or application-driven performance (e.g. high temperature operations in the automotive industry).

New materials, including 1D and 2D structures, ultimate processing technologies and novel nanodevice structures for logic and memories are mandatory for different applications, as well as new circuit architectures, design techniques and embedded software. Some of these nanostructures are also very interesting for advanced sensors, energy harvesters and photonics. All of these are key for future high performance/ultra- low power tera-scale integration and autonomous nanosystems.

These promising technologies that could underpin numerous future applications will allow us to overcome a range of challenges being faced for future ICs – in particular, high performance, low/very low static and dynamic power consumption, device scaling, low variability, and affordable cost. Many long-term challenges must be addressed to ensure successful application of these nanotechnologies. A number of these are described briefly in the following:

- Nanowires and nanosheets, for high performance and very low-power nanoscale devices, the best material and geometry options for logic (high speed as well as low power) need to be identified.
- Millimetre-wave front ends with III-V MOSFETs have to be developed (with applications in communications, radar, etc.), including 3D aspects of processing.
- Non-conventional switching devices, like negative capacitance field-effect transistors (NCFETs), tunnel effect transistors (TFET), 1D (CNT) or 2D (graphene and others), which could be suitable for very low power devices, need development in basic material, extended characterization of optimal architectures and design strategies.
- For nano-electro-mechanical FETs (NEMS-FET), low-voltage reliable devices have to be developed.
- Spin-based devices also for switching and sensing.

In the field of alternative memories, resistive RAM, magnetic RAM and ferroelectric RAM/FeFET will be key for driving the limits of integration and performance beyond that afforded by existing non-volatile, DRAM and SRAM memories. Research should address:

- Widening the material screening and programming schemes.
- Variability and reliability, especially data retention.
- Trade-off between programming speed and programming power/data retention.
- Compatibility with standard logic processes.
- Architectures for memory embedding in logic, for novel computing schemes.

In the long-term beyond CMOS domain, the challenges to be addressed are in the field of beyond-conventional CMOS technologies, non-Boolean logic, and beyond-von Neumann architectures, including novel state variables, new materials and device, and innovative device-architecture interaction.

Integrated photonics evolving from silicon photonics is required to interface conventional electronics with photonic-based communications and sensors, and, in a longer perspective, with photonics-based quantum computing and communications.

The emerging field of Quantum computing poses its own challenges in process technology, equipment, and materials:

- As there are still several candidates for becoming the standard quantum computing technology (such as semiconductor quantum dots, semiconducting junctions, photonic circuits, ion-traps, etc.), a wide range of materials is relevant, together with innovations in process technology.
- New metrology capabilities are required, especially the measurement of electrical properties, such as local carrier mobility, is needed.
- To achieve practical applications, reliable fabrication, connection, and read-out of qubits need to be developed. The low temperatures at which most quantum systems are operated requires the development of cryogenic devices, to interface conventional electronics.

Importantly, all quantum technologies related to sensing, communications and computing, including software, present significant challenges today.

#### Reducing the environmental impact of semiconductor manufacturing

While the chip advancements are contributing to the industries across verticals, and are crucial to achieve the Green Deal objectives, significant efforts must be made to tackle the direct environmental impact of chips and more generally ECS manufacturing. Issues to be addressed include waste generation, resource usage, $CO_2$ and GHG emissions, hazardous materials use, including PFAS, and scarce materials use.

*Waste generation*

Fabricating a small 2g microchip (≈ 14-10nm technology node) requires 32-35 kilograms of water, 1.6kg of petroleum and 72g of chemicals. Since advanced technology nodes will require more metal layers and lithography steps, and, as the chip production could nearly double to satisfy chip demand in the coming years, the environmental impact of the semiconductor industry on power/energy and water consumption, and on $CO_2$ and GHG emission, will strongly increase. This consumption and emission can reach unacceptable levels to cope with the Green Deal sustainability objectives.

*Natural resource consumption*

Regarding water, each chip needs to be rinsed with ultrapure water (UPW) to remove various debris (ions, particles, silica, etc.) from the manufacturing process and prevent the chips from becoming contaminated. The semiconductor industry has been working for more than twenty years to reduce the amount of water needed to manufacture a chip for economic reasons as well. Nowadays, due to the most frequent occurrence of droughts, the water issue is a high priority in the sustainable development plans of major semiconductor companies. Semiconductor manufacturers must focus their efforts on new ways to recycle, reduce, and reuse the water used in their production. Nevertheless, new advancements in water treatment must emerge to allow semiconductor manufacturers to recover and reuse wastewater, remove targeted contaminants, and even reclaim valuable products from waste streams. New long-term approaches will deserve more R&D efforts for improving the effluent segregation systems and hence increasing the use of recycled water in semiconductor manufacturing lines.

The main European semiconductor manufacturing should use 100% of renewable energy sources in 2030. Likewise, the water and carbon footprints of the semiconductor industry must be strongly reduced to achieve near-zero $CO_2$ and GHG emission, for instance.

*$CO_2$ and Green House Gas (GHG) emission*

In the semiconductor industry, $CO_2$ and Green House Gas (GHG) emission arise from process gases used during wafer etching, chamber cleaning, and other tasks. Furthermore, they rise as node size shrinks. These gases, which include PFCs, HFCs, $NF_3$, and $N_20$, have high global-warming potential. Gas recycling of unutilized process gases and by-products through various means, such as membrane separation, cryogenic recovery, adsorption, and desorption can be a long-term approach to reducing GHG emission. In collaboration with equipment suppliers, semiconductor fabs could refine them into pure process gases that can be used again, potentially reducing process-gas emissions. For this lever to become economically viable, collaboration between semiconductor companies, equipment suppliers and researchers will be compulsory to address these major challenges related to the separation of process-gas outflows and purification.

Another long-term approach could consist of lowering GHG emissions by switching chemicals that have a lower environmental impact than the aforementioned fluoride gases, such as on-site generation of molecular $F_2$ for replacing $NF_3$, since molecular $F_2$ has no global warming potential. Developing new solutions will require strong R&D efforts and will be both costly and time- consuming, as is the process for qualifying new chemicals on existing processes and tools.

Since most of the aforementioned fluoride compounds are used for etching, another long-term approach could concern the replacement of some non-critical etching processes by additive manufacturing process steps. Such a replacement will require strong R&D efforts to develop highly selective deposition processes and/or self-assembled molecules that can prohibit the deposition of metal and dielectrics.

*Sustainability issues in semiconductor manufacturing induced by PFAs*

PFAS is a class of thousands of synthetic substances known as ‘forever chemicals’ since they do not break down in the environment. Most of which are either persistent themselves or are transformed into persistent compounds in the environment. These substances are hazardous for human health as they accumulate in the body, but also in water, ground, and then the seas and oceans.

PFAS are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–). Due to the C-F bond strength compared to C-C bond, PFAS offer a unique set of technical characteristics, which include exceptional heat and chemical resistance, high electrical insulation resistance, high purity, low-outgassing and low coefficient of friction.

Those intrinsic properties are the basis of many of the technical benefits of fluorinated materials in semiconductor processing, but this also leads to their chemical stability and environmental persistence. Fluorination brings unique physicochemical properties and consequent qualitative improvements that are the enablers of semiconductor, performance and manufacturing advancements.

PFAS are used in the semiconductor manufacturing industry in the lithography process, as a component added to the photoresist to generate photo-acid generators (PAG), improve its adhesion to the silicon wafer, increase its durability, and enhance its resistance to harsh chemicals and high temperatures. In addition to their use in photolithography, PFAS are crucial in producing other semiconductor components. They are used in wet chemistries as surfactants (cleaning, stripping and etching, and metal plating), dry etching, chamber plasma cleaning, CVD and ALD. PFAS are paramount in packaging materials to improve thermal stability and moisture resistance. They are also used as a coolant in the chip etching process, as working fluids for vacuum pumps…

Besides their application in chipmaking, PFAS are also essential for semiconductor manufacturing equipment and factory infrastructure. Their exceptional properties, such as heat resistance and chemical inertness, make them useful in equipment components (tubing, gaskets, containers, filters, etc.) and lubrication (such as various oils and greases).

Up to now, unless for some dedicated applications, there is no PFAS-free alternative for most of the aforementioned applications.

As of today, 1485 tonnes of PFAS are used every year for producing semiconductors in the European Economic Area. Since the European Chips Act aims at doubling the EU’s current manufacturing capacity from 9-10% to 20% by 2030, it will require a four-fold expansion of the semiconductor manufacturing capacity in the EU, and consequently a four-fold use of PFAS.

Accordingly, it will be crucial to conduct research to, where possible, identify alternative chemistries that are preferable from an environmental point of view and to develop measurement, recycling, treatment, and efficient abatement technologies to prevent environmental releases for uses to which no PFAS alternative can be found.

*Scarce materials use*

Finally, to secure their whole supply chain and for not wasting mineral resources, in view of the limited extractable quantities of metals in the earth’s crust, chipmakers will be increasingly concerned with the potential scarcity of some ores that are compulsory for producing ultra-pure metals for the high-volume manufacturing of devices. One approach to resolve this issue is to use recycled metals instead of premium metals. Another one is to recover the metals from the electronic waste (e-waste), thus, preventing the use of natural resources. The recovery of scarce metals from microelectronic devices opens a wide research domain for material scientists, ensuring sustainable metal sources for chipmakers.

### 4.3.2 Components, modules, and systems integration

The interaction among people and other information agents and their environment usually features a trade of data, which is curated into information that either results in a gain of knowledge and/or the enabling of purposeful action or reaction to a given situation.

The width and breadth of such data trading is expected to increase in the future in terms of space and time density. Seamless integration / interaction with the environment and agents involved, based on evolved human-machine interaction (e.g. haptic and brain-computer interfaces) or machine-to-machine interaction, is expected in scenarios that either empower or substitute humans in decision loops.

ECS conform to the HW and SW ensembles that at different levels of integration and organization complexity, mediate the different elements of such information trading: acquisition, management, and exploitation. Indeed, HW and SW integration schemes are the ones ultimately responsible for substantiating the expected increasing number of systems functions and applications that are to emerge from the reunion of:

- New sensitive and structural materials.
- Physical-to-digital (and vice versa) transducers architectures.
- Local (on-system) intelligence.
- Communication/interaction interfaces with users or higher instances of the decision chain.

In addition to the continuous improvement of semiconductor processes and materials, increasing the level of proficiency of elements managing information, integration of more diverse components will be essential to make systems aimed at monitoring the condition of people, assets, processes, and environments less dependable on the use of energy and on external supervision. Making these devices and systems faster, more sensitive, efficient, robust, functional, and apt to different application scenarios will demand higher levels of heterogeneity of materials and fabrication and assembling processes.

Self-powering, energy harvesting and storage will become more and more important and significant advances are expected in solid-state devices to cover the needs of edge and IoT devices. Integration of intelligence to these inherently power-restricted devices requires novel power-efficient computational platforms, such as neural networks and analog computing approaches in parallel with CMOS and other traditional semiconductor devices as commented in the previous chapter.

Next generation computing devices, using physics to make computation, pose challenges in integration as well as in development. In such approaches, envisaged in Chapter 3.1, and made possible in the frame of processes of Chapter 2.1, other modes of coding information besides bits will be used, e.g. using qubits or encoding in time, like for neuromorphic architectures where information is coded in a succession of spikes, or their coincidence in time. Another massively parallel approach using biological technology (based on proteins, DNA construction, etc.) can also emerge for niche applications, or for storage[2]. Most of these technologies will be used first in servers for very specialized acceleration but will slowly improve to be integrated into edge devices.

Moreover, ECS are pivotal elements of the digital transition that supports the current and future quest for making our civilization sustainable, maximizing performance and minimizing e-waste, and particularly for slowing down, reverting or making human environments resilient to climate change.

In addition to the sustainability of the ECS fabrication processes themselves, the scarcity of materials and the increasing demand for ECS imply that approaches and architectures that improve the chances of ECS modules to be repaired and/or reused, and of their material constituents to be reclaimed, need to be addressed. Single-use or disposable devices need to be designed with minimal, and minimally invasive, electronics. The same applies to install-and-forget systems to be deployed in natural remote locations. For example, organic and printed electronics can lead to biocompatible electronics and more effectively recyclable systems. Although there are widespread efforts to recycle computing systems, we are far from the goal of effectively recycling because of the lack of processes to support an appropriate circular economic and business model. Component and system level challenges range from homogenizing component and subsystem lifecycles to computing models and materials used. In a wide range of application domains, a significant challenge is the ability for global reconfiguration of system resources to satisfy diverse applications' functional and non-functional requirements, such as latency and energy, including re-training in AI/ML subsystems. Significant effort needs to be made to develop systems that are scalable linearly or functionally.

In terms of global resilience to climate change, multifunctional smart information systems will be in demand to react faster to such upcoming challenges and risks. For instance, globalization of human activity and large-scale weather changing patterns will ease the spread of known diseases beyond their usual geographical boundaries as well as spur the appearance of new ones. Swinging weather conditions will affect application fields directly exposed to climate conditions such as mobility, energy, or agrifood/ environmental applications. ECS helping these applications to react to those abrupt changes need to be integrated and packaged themselves in a way that can cope with these harsher environmental conditions.

Integration, as the art of recursively combining physical devices, components, and systems together to form a new entity with increased functionality in the minimum volume possible, will be key to leverage the different positive aspects of diverse technologies and their reference materials. It has been already appraised that a combination of nanoelectronics, photonics (optoelectronics), electronic smart systems, including AI/ML subsystems, and flexible, organic and printed electronics is setting the path for future enabling functional electronics[3], which will be characterized by aspects such as:

- A shift from physical to functional integration.
- The use of novel substrates and structural systems.
- Seamless integration in everyday objects for a broad spectrum of new applications.
- Real-time capture and management of multi-physics data and contextual information.
- Safe and secure operation.

- Networked, autonomous operations complemented by software solutions (including AI).
- Eco-design approaches at product, process, and business model levels.

The distinction of monolithic and heterogeneous integration, and what can be achieved with them, is subjected to boundaries that will evolve with time. Particularly, monolithic integration at chip, chiplet, and SoC levels is progressing through the development and maximum exploitation of 3D sequential integration, a technology with important research activities in the EU that will impact applications with very high-density interconnections (IoT, neuromorphic computing, etc.). Heterogeneous integration, from non-CMOS materials and device processing on top of CMOS wafers to customized application platforms, is also progressing thanks to the evolution of scalable wafer-level or package-level integration schemes nurturing compact System-in-Package (SiP). Still, maximum versatility comes with integration of technologically dissimilar components (e.g. MEMS/MOEMS- NEMS and ICs, electronic and photonic elements, etc.) onto application-oriented platforms, which could be board-like or built on flexible/conformal substrates. To serve such versatility, 3D place-and-route tools with extended ranges of speed, precision, and gentleness for handling components that on occasions are fragile, will be needed. Modelling/simulation, characterization and reliability evaluation tools, which are also strong European domains, will be required to take all the new materials, technologies, device architectures and operation conditions into account, so that cost of development is reduced, and technology optimization is speeded up. All those encompassing schemes are expected to be beneficial for the integration of future high-performance sustainable, secure, ubiquitous, and pervasive systems, which will be of great added value for many applications in the field of detection and communication of health problems, environmental quality, secure transport, building and industrial monitoring, entertainment, education, etc.

### 4.3.3 Embedded software and beyond

The next generation cyber physical systems will play a key role in the future AI, IoT, SoS realisations, while they will need to be sustainable and easy to maintain, update and upgrade in a cost-effective way, across their complete lifecycle. Mature software platforms running on them will ensure safety and security by design and be available as a part of the European digital infrastructure to a wide audience for building services and business.

We envision an open marketplace for software frameworks, middleware and digital twins with a seamless integration and ubiquitous presence that will represent a backbone for the future development of one-of-a-kind products. While such artefacts need to exploit the existing software stacks and hardware, they also need to support correct and high-quality software by design.

Thus, the envisioned long-term achievements in embedded software will drive the digital industry, while enabling collaborative product-service engineering, and making sure to be inclusive.

For overcoming challenges related to efficient engineering of software, new programming languages and tools for developing large-scale applications for embedded SoS will emerge. Software engineering will address hybrid distributed computing platforms, including efficient software portability, and the development of new software architectures involving edge computing will follow. Model-based testing will contribute to handle uncontrolled SoS.

Short-delivery cycles, maintenance, and extension of software systems are goals that require continuous integration and deployment. Autonomous embedded systems and autonomous processes for IoT & edge embedded HW/SW co-design, and integration & orchestration platforms for IoT and SoS will contribute to achieving those goals. Model-based engineering, based on multi-dimensional, complex and of scale digital twins in the edge, as well as their deployment along with systems, will contribute to a continuous integration. Next generation hybrid digital twins, based on big data-driven and classical physics principles, will be developed and integrated in embedded hardware, while supporting enhanced cognition and intelligence that will demonstrate enhanced capabilities to encapsulate the real word, e.g. power modules, while enabling unseen capabilities for supporting high-level missions as the Green Deal.

As anticipated, software in cyber physical systems must support sustainability: approaches for lifecycle management will enable this by supporting distinction between core systems capabilities and applications and services, and by enabling interplay with legacy subsystems. Interoperability must be built-in and ensured by integration platforms, and will enable features such as easy SW updates, device management, and data management. Composability of systems will be a property supported by properties contracts and orchestration systems, and will be directed towards “write once, run anywhere” for optimal execution on the cloud-for-edge computing continuum.

The modularity of future cyber physical systems, which will dynamically compose in large SoS, will require a high-level of trust, both at the level of the constituent components of SoS and considering how they connect and compose. To this regard, the evolution towards stronger protocols and interfaces (including well-defined pre-compilation connections), supporting security, privacy, and dependability aspects, represents a key factor.

Use of safe, trustworthy & explainable AI will be dominant in autonomous systems and will enable embedded intelligence. AI will play several key unconventional roles in innovation, e.g. as a tool for SW development/ engineering. These innovations will be supported by the European Processor Initiative and its integration in cloud servers, open-source hardware, and software.

Finally, use of quantum computing and IoT digital twin simulation will support software reliability and trust.

### 4.3.4 System of Systems

System of Systems (SoS) is projected to become an area of exceptional economic growth, both short term and over the coming decades[4]. This will create a strong market pull for the complete ECS value network upstream of the SoS area.

Strategic investments addressing open platforms, engineering, and deployment efficiency, SoS management and control represent key factors to propel Europe towards very large scale of digitalization and automation solutions across integrated and optimised operations of engineering, production, logistics, infrastructures, etc. The inherent heterogeneity of SoS is expanded with the new, emerging computational models that include accelerators, AI/ML subsystems, approximate computing, organic systems, and others, pose significant challenges at all levels. Interoperability and adaptation to diverse physical interfaces and communicated data structures constitute clear examples of challenges. The management of heterogeneity at all levels, including dynamic instantiation of multi-paradigm computing resources considering application requirements and specifications, auto-configuration of distributed resources (locally or globally) to satisfy application functional and non-functional requirements, require significant advances in the field. Success in this direction requires additional activities towards standardization for HW/SW functions as well as scalability specifications to achieve wide and cost-effective use in applications and use case with variable performance requirements.

Large scale usage of SoS technology is further expected to be a significant contributor to the Green Deal through distributed and intelligent solutions that provide significant reduction of environmental footprint in terms of energy consumption, material consumption, waste and, in general, through a more rational and controlled use of all types of resources. This strengthens the ECS value network through energy efficient and robust electronics hardware, connectivity, and embedded software.

The future evolution of SoS will further require cooperation between domains, enabling a wider shared understanding of the context and situation, more useful services, richer functionality, better user experience and value proposition. This evolution will introduce the concept of connected and interacting domains (potentially both physical and virtual), where application and services run transversally on top of connected vertical domains.

In the medium/long term, many technologies will allow the evolution of SoS towards the scenarios previously described, including:

- Distributed AI, to control the inherent and quickly increasing complexity of SoS, making them secure, reliable, easier to maintain, etc.
- Connected and interacting domains, supported by:
    - Open and robust integration platforms.
    - AI method adopted to address conflicting functional and non-functional requirements.
- Engineering support for emerging behaviors in complex SoS:
    - Model based engineering.
    - Predictability, controllability, monitoring and diagnoses.
- Automated and autonomous engineering.
- Machine interpretable content.

### 4.3.5 Edge Computing and embedded artificial intelligence

Artificial intelligence will be the enabling foundation for the digital society, ensuring that the systems that make up its framework function in an effective, efficient, secure, and safe manner. Most of the ambitions that are to be realised in the digital society, such as a zero-emission economy, affordable healthcare for everyone, safe and secure transactions, etc., can be achieved only if an underlying AI infrastructure is in place. This implies that the Internet of Things will gradually transform into the Artificial Intelligence of Things (AIoT), where AI constitutes the interface between the digital world (e.g. edge and cloud computing, cognitive and autonomous cyber-physical systems, embedded systems) and the analogue real world.

Artificial intelligence and machine learning (AI/ML) methods enable efficient and effective automated decision making in domains ranging from system design, design space exploration and manufacturing to application and business processes. As computing models distribute functionality at all systems from the cloud to the edge, AI/ML methods need to be distributed and coordinated, leading to efficient smart systems at all levels of the computing hierarchy. In addition to the ongoing research in AI/ML for applications in increasing application domains, efficient and effective methods for distributed intelligence and federated learning become increasingly important. Advanced AI approaches, like composite AI, require heterogeneous technologies to be addressed altogether, such as vision and natural language processing. The accelerating adoption of AI/ML, in its various approaches, results in high demand of subsystems and accelerators, creating a significant set of challenges analogous only to the growth of the respective market. Importantly, considering the known social questions regarding the adoption of AI, significant effort needs to be spent on certifiable and explainable AI, which will lead to the necessary social acceptance of AI-related technologies at all fronts.

AI technology is becoming increasingly demanding for computational power, especially for the learning phase. As ***Figure 4.3*** shows, the need for increased accuracy in AI techniques leads to methods that employ increasing numbers of parameters (for deep learning techniques, specifically, in ***Figure 4.3***), which, in turn, lead to dramatic increase of need for computational power to implement these techniques. This will imply new progress in energy efficiency to keep the Cost of Ownership affordable. Mainly the GAFAM and BAITX will be able to afford the computing infrastructure that will require a large number of servers.

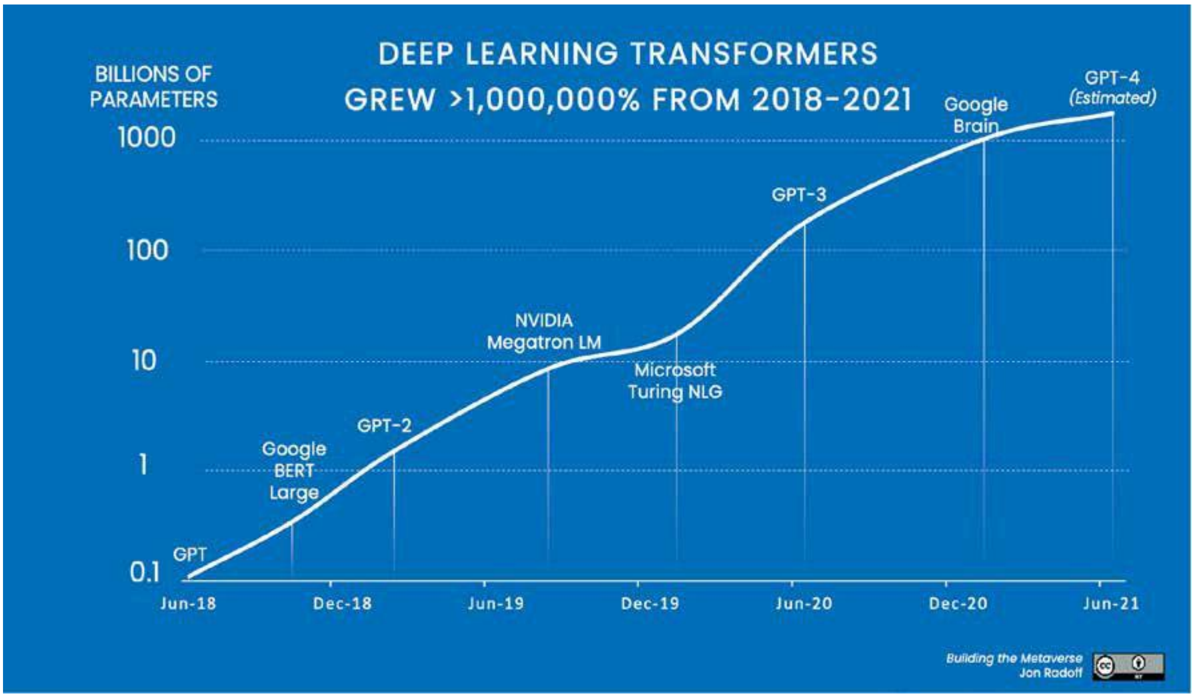


*Figure 4.3 - The increase of parameters employed for deep learning systems (2018-2021)*

IA accelerators will appear in many devices from the deep edge to home servers, allowing to process all kind of data and changing the way we interact with computers. ***Figure 4.4*** demonstrates this, showing the dramatic increase of deep learning chiplets that have been shipped worldwide in the last years. Computing systems will disappear in the environments and will allow natural interactions.

To be able to cope with the diversity of requirements and the Cambrian explosion of designs, AI techniques will be used to select the best architecture (automatic design space exploration) and to generate the code from high-level specifications (no-code) with guarantees of correctness. AI/ML application in the ECS domain include the automated design of SoCs, the respective design space exploration, the integration and orchestration of multiple computing paradigms into embedded systems (including AI-based ones) as well as the design and evaluation of cyber-physical systems overall, which include physical components for operation or computation.

New AI paradigms will emerge, including self-supervised approaches, that can be highly efficient at the edge and decreasing the need for a large database and computing power like for deep learning. Quantum computing, in addition to other computational models, needs to be explored for efficiency and effectiveness in AI methods.

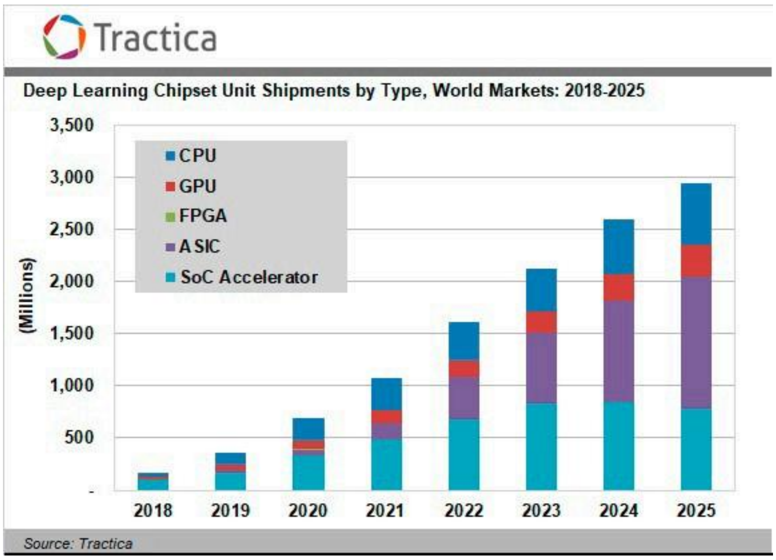


*Figure 4.4 - The growth of deep learning chip shipments (2018-2025)*

The mass market for smart systems will still be fulfilled by very advanced foundries, but “small” foundries will also appear (assuming that they become sufficiently cheap and efficient) to make the very diversified deep edge devices that most of the time don’t need the latest technology. Some low-cost applications will be made with non-silicon technologies, e.g. using printing or 3D printing technologies[5]. This will allow enterprise level organizations to have their own “device manufacturing” that don’t need high quality clean rooms. AI/ML technologies will play an important role in this direction, towards high automation that leverages AI/ML for the exploration of architectures and code generation.

### 4.3.6 Connectivity

Today, connectivity is a key enabler to support the development of innovative applications in several markets, such as consumer, automotive, digital manufacturing, network infrastructure (to name a few). This is also pushed by the need of being connected anywhere+anyhow+anytime. The availability of innovative connectivity technologies, both wireless (e.g. low-power wide area networks (LPWAN), cellular (5/6G)) and wired (e.g. new bus-oriented communication protocols), will enable and enhance a wide range of new business opportunities for the European industry in the context of Systems of Systems (SoS), Cyber-Physical Systems (CPS), and Internet of Things (IoT). Long-term roadmaps for connectivity and interoperability will guide a seamless integration of heterogeneous technologies (hardware and software) for the design and implementation of complex connected systems in effective ways.

Connectivity is a critical asset to any digitalization and automation activity to strengthen Europe’s position and enable the European industry to capture new business opportunities associated with the connected world we live in. It is vital to support European technological leadership in connectivity, fostering digitization based on Internet of Things (IoT) and System of Systems (SoS) technologies; for example, this can be achieved by being at the forefront of new standard development for the current 5G initiative, the emerging SoS market, and the upcoming 6G initiative. Furthermore, to bring added value and differentiation with respect to US and Asian competitors, The European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report[6]). For instance, connectivity (e.g. in terms of wireless infrastructure market, led by Ericsson and Nokia) will be supported by the European leadership position in the traditional IT environments as well as the embedded segments, guaranteed by companies such as STMicroelectronics, Infineon and NXP. Connectivity from device, over the edge, and to the cloud will need to be virtualized, relying on run-time design, deployment, and management of integrated edge and cloud network architectures. This will enable the connectivity from cloud to far edge, shifting the perspective from point-to-point connectivity to application-to-application connectivity.

Connectivity engineering and management must be significantly improved to support simplified and inexpensive deployment and integration of new applications into SoS, CPS and IoT solutions.

Connectivity will provide the basis for a data layer supporting instant and seamless data and information exchange between producers (supply below the data layer) and consumers (demand above the data layer) within and between domains. This layer will enable large-scale integration of SoS, CPS and IoT solutions. Targeting systems and applications, we should consider the interconnection between sub-systems and focus on individual component technology development, according to needs identified at system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key. To fully leverage this heterogeneous integration at hardware level, software interoperability is a parallel challenge to provide connectivity that will allow for SoS integration. Thus, an alternative major challenge is to enable SoS integration through nearly lossless interoperability across protocols, encodings, and semantics. To do so, dedicated software tools, reference architecture and standardization are key to supporting SoS integration, thus enabling the provision of a scalable and evolvable SoS. As it remains very difficult to assume that highly customized embedded systems will be built based on a single, unified, high-level modelling principle and toolset, there is a quest for consolidation, or even the standardization of basic runtime frameworks, component libraries and subsystem interfaces that will ease the deployment of interoperable components into generic, domain-specific solutions and architectural frameworks in a bottom- up fashion. Such an approach is also expected to provide for better traceability of requirement validation, and formal verification of distributed system compositions and their emerging functional and non-functional properties.

Finally, data protection must be ensured at an appropriate level for each user and each functionality, regardless of the technology. One major challenge is to ensure security interoperability across any connectivity. This foresees the utilization of different connectivity technologies, and these differences create security incompatibilities leading to increased engineering costs. Therefore, the development of innovative hardware and software security solutions, that will support and provide correctness and safety, is of fundamental importance. Such a solution will have to be linked with the previous challenges to ease SoS engineering, deployment, and operation in a seamless manner. Security assessment is a significant issue here considering the criticality of applications. Standards and directives are required not only for technology transfer and system evaluation, but for legal purposes as well, considering the existing GDPR legal framework and the emerging laws regarding European and national cybersecurity requirements.

Thus, the following major challenges need to be addressed in the connectivity roadmap until 2050:

- Keeping European leadership in connectivity.
- Providing virtualized connectivity.
- Introducing data-oriented connectivity.
- Developing connectivity engineering.
- Meeting future connectivity requirements leveraging heterogeneous technologies.
- Enabling nearly lossless interoperability across protocols, encodings, and semantics.
- Ensuring secure connectivity and interoperability.

### 4.3.7 Architecture and design: methods and tools

The European ECS industry has been strong in systems engineering, integration, validation and verification, test and simulation, and certification of innovative ECS-based products. The produced systems are characterized by high quality in such terms as functionality, safety, security, reliability, trustworthiness, and certifiability.

Considering the need to maintain and increase this strength, we need to invest in extending existing, and developing new processes, methods and tools that will ensure European leadership in the field. Emerging ECS components and systems are characterized by new functionalities, increased complexity, and diversity on all fronts, ranging from methods and paradigms to modeling and analysis. As the competition by US and Asian ECS companies is fierce, significant effort and investment is necessary to enable European leadership in the technologies for integration, validation, verification, testing and certifiability. A significant parameter in the establishment of leadership and effective technologies is the support of the European Green Deal, by enabling green development and green ECS-based products. Tools and methods for managing the complete ECS lifecycle are necessary, ranging from resource-considerate and climate-neutral design and operation to development, production and maintenance of ECS-based products addressing issues that include even decommissioning and recycling.

To realize this vision and associated goals, the European efforts need to extend existing, and develop new, processes and methods that cover the whole lifecycle of products, from initial requirements elicitation through design, integration, verification, validation, test, certification, production to commissioning, operation, maintenance, and decommissioning. These processes and methods need to support data collection from production as well as from operation and maintenance to be analyzed and used for continued development and integration, updates in the field, validation, verification and test at the development phase, as well as in the field, at run-time.

Novel architectures and development and analysis tools need to be developed which will enable:

- Seamless design, development, integration, verification, validation and test across all layers of the technology stack, from semiconductor up to systems of systems. These methods need to address individual ECS-based systems, groups of systems that form and dissolve statically or dynamically as well as systems that cooperate with other systems and with humans, at the cloud or at the edge. Furthermore, methods and tools need to support open platforms and integration of open systems.
- Verification, validation, and test of highly automated and autonomous systems, especially coping with open-world assumption and uncertainty.
- System development that includes AI methods, such as explainable and trusted AI.
- The use of AI-based methods in the design and development process, for example design space exploration and analysis, including certified products.
- Managing the increasing functionality, connectivity, and complexity of systems.
- Managing the increased diversity of tools, such as modeling and description languages and simulation and testing tools, in emerging components, modules, and systems.

### 4.3.8 Quality, reliability, safety, and cybersecurity

Quality, reliability, safety, and cybersecurity are fundamental components of any innovation in the digital economy. Especially in Europe these characteristics are particularly important since European products are well-known to be of high quality in almost every aspect. They are driven by high expectations of the European society demanding these features. Continuous evolution of our European society is driven by the development of electronic components and systems (ECS). By having now a mobile phone in our hands, we can buy a flight ticket, make a money transfer, or maintain social contacts. Even more services are available. ECS simply promises to make our lives more comfortable, safe, and efficient but this promise relies on user trust and acceptance concerning the perception of sufficient privacy, security, understandability, and usefulness in people’s daily lives. In the near future, highly automated and autonomous systems supported by AI will have a constant growing trend. We expect that in the next ten years such systems will be increasingly deployed, not only in controlled environments, such as in manufacturing industries, but massively spread in our personal, professional, and social spheres.

ECS of the future will not require an external environment control to work as wished. More generally, the ECS of the future will have to satisfy different constraints on different scientific and social disciplines and ought to meet both the founding principles of European society.

To maintain European leadership in electronic devices and systems we have to make our efforts to provide innovative products of the well-known high quality, reliability, safety and cybersecurity to our customers. From this perspective we expected the following challenges to be considered in a long term:

- Development and integration of new materials for advanced packaging and interfaces, new characterization techniques, and new failure modes caused by new use-case scenarios.
- AI/ML methods, including digital twins, to be a cornerstone of keep leadership regarding quality and reliability of ECS made in Europe and be an enabler for new data-driven business models.
- Model-based engineering (incl. standardization of data management and processing) to be a key instrument for virtual release of ECS through the supply chain and shortening time to market.
- Assuring user trust and acceptance of ECS through early inclusion of user requirements, explainability-by-design, and user education and training.
- Model-based engineering (incl. standardization of data management and processing) to be a key instrument for virtual pre-qualification of ECS and shortening time-to-market.

- Data transmission methods and protocols that are so reliable that they can be used to transmit life-sustaining information over long distances (e.g. for robotic surgery).
- Reliable and certified software that can be kept even if the underlying hardware or hardware architecture is changed, including potential influence of SW updates on HW reliability.
- Software that can adapt to a degrading underlying hardware to achieve a long-lasting and reliable HW/SW combination.
- Liability of trusted AI-driven systems (it is based on trustworthiness of (AI-driven) systems, included safety and certification of AI-driven CPS, which is a main challenge in 2021).
- Safely manage /design for human interactions in complex systems, SoS and application scenarios
- Ensuring sustainability, cybersecurity, safety, and privacy, for AI-driven and quantum-based systems (based on "ensuring safety, security and privacy and sustainability of (AI-driven) systems").
- The attention to the environment and privacy have increased significantly in the population. This implies that conceiving any safety solutions is not enough. Our vision on 2030 is an integration between disciplines, which have nothing to do with safety or computer science in stricto sensu, such as privacy, social trust, liability, and sustainability.

Importantly, all properties of quality, reliability, trustworthiness and safety are heavily dependent on the integrity of the supply chain that is employed to develop ECS and ECS-based systems. The business models that are employed within Europe and abroad, lead to dependence of organizations on suppliers and contractors for provisioning of hardware as well as software components and systems. Trust among them is not a given. Actually, many cybersecurity incidents that have hit headlines originate from exploited vulnerabilities in the supply chain. Conventional verification and testing methods are not sufficient to address these problems, which range from insertion of hardware trojans at fabrication plants and implanting malicious hardware components in systems to compromised system and application software. Addressing these problems requires significant research effort for new methods to validate systems at all levels of hardware and software.

## 4.3.9 Machine Learning & Artificial Intelligence

The recent advances in machine learning (ML) and artificial intelligence (AI) have opened several opportunities in hardware design and design tools, especially in embedded computing and design of cyber-physical systems. The major directions are: (i) exploitation of AI/ML techniques in component and system design, (ii) architectures and designs for efficient AI/ML processing in emerging solutions, and (iii) effective AI/ML methods for embedded and cyber-physical application domains. Thus, AI/ML is increasingly becoming a fundamental technology that influences all foundational technology layers and cross-sectional technologies depicted in the model shown in Figure 2.

The increasing complexity of integrated circuits (IC), still following Moore's Law, leads to a (still) exponentially increasing design space that needs to be explored for IC designs at all levels of design abstraction. The problem of design space exploration is not new and has been addressed with various methods in the past, in the context of design synthesis. The problem includes identification of designs that meet design specifications as well as optimization of desired parameters, such as delay, area, power, etc. Heuristic algorithms have been employed extensively to identify appropriate designs, since exhaustive search of design spaces for modern IC's is infeasible. AI/ML methods are increasingly adopted in design space exploration in place or complementing heuristic algorithms at several stages of circuit design, from manufacturing and physical design to RTL design and high-level synthesis. Importantly, AI/ML are increasingly exploited in design testing and verification.

AI/ML methods are used in several approaches to address different problems in the system design process. A comprehensive review of the problems and approaches is given by M. Rapp et al.[7], which classifies the problem types solved with ML with 3 parameters: (i) development of predictions, actions and/or data, (ii) the design stage and (iii) the exploited AI/ML algorithm. In terms of predictions, currently, AI/ML methods are used and proposed for predicting design properties after explored decisions, while for actions, they are used in place of existing techniques at various stages of design, such as RTL design, placement and routing, etc., with the purpose to optimize an appropriate criterion. As most of the employed algorithms are supervised learning ones, data constitute a significant component of effective employment of AI/ML techniques. As such data do not exist or may differ significantly in practice, because of the different existing tool chains, AI/ML methods are used to produce or collect training data within and from the design process itself. Employed algorithms range from regression to neural networks, mostly for supervised learning, based on models that range from graphs to images at the various stages of the design process.

Despite the large and increasing research work in employing AI/ML in embedded system design, there are several challenges that need to be addressed for the penetration of research results in practical design frameworks. The biggest problem is that of appropriate data for training the models; this is a well-known problem in most application domains of AI/ML. The need for large amounts of appropriate data, considering the exponential space of design alternatives that need to be evaluated, will lead to long delays until the appropriate models are built. Alternative methods for generating appropriate date will also need to be developed.

Machine Learning (ML) and, more generally, Artificial Intelligence (AI) algorithms are essential to extract relevant information from massive data amounts. As the computational capabilities of edge- and end-devices (also indicated as "far edge") is ever increasing, ML-based inference processing is no longer carried out in the cloud, but is distributed across the device-edge-cloud continuum. This requires the identification of a proper architecture to efficiently distribute the computational load, with dynamic methods for model compression or model splitting among the architecture tiers. Edge AI or, more generally, edge intelligence has emerged as crucial in multiple applications. Likewise, the possibility of implementing tiny ML (TinyML) algorithms in constrained devices opens new perspective in the Internet of Things (IoT). Distributed ML will involve several aspects, including latency, bandwidth utilization, data safety, data quantization, privacy, cost.

AI/ML accelerators constitute innovative components in new generation computing systems of all scales, from large and core to edge. Research in this area is continuously growing with accelerators that target application domains, from low-power embedded systems for inference to back-end high- performance accelerators for model training. Several surveys exist presenting methodologies for AI/ML accelerations, especially for neural networks[8,9,10] , while there also exist surveys of commercial accelerators[11]. The wide range of application domains of accelerators poses significant challenges to designs, from performance to power to cost. Especially for embedded systems, accelerators are effectively targeted for edge systems, from automotive to medical, from industry to consumer. From the surveys it becomes alarmingly clear that most technologies are developed and commercialized by organisations outside Europe. European efforts exist, such as AnIA[12] , Axelera AI's AI Edge accelerator, Infineon's Parallel Processing Unit (PPU) AI accelerator[13] and others. However, market penetration, even in the start-up domain, is limited when compared to the US and Asia. Efforts focus on specific application domains, such as computer vision, automotive, etc. Strengthening of these efforts is necessary, to address challenges for cost-effective accelerators in a wide range of domains. The challenges include development of effective architectures and exploration of the trade-offs among memory design, power consumption, high performance and arithmetic calculation precision that dominate AI/ML neural network accelerators, in conjunction with specialized algorithms.

Significant challenges also exist in adopting AI/ML in embedded and cyber-physical application domains. AI/ML methods are already used and are continuously being developed for effective operation of embedded and cyber-physical systems in various environments, through predicting operational parameters, including input, and/or environmental parameters. However, often, the unpredictability of parameters combined with the lack of effective training data leads to suboptimal operation and creates a significant challenge to develop effective solutions that are application dependent.

### 4.3.10 Quantum Technologies

Quantum technologies are promising to provide effective solutions to a wide range of application domains. Some application-specific systems are at the first steps of commercialisation, such as quantum sensors for gravitometers and neuroimaging and quantum communication devices specifically for quantum key distribution. At the other end, quantum computing requires significant research and advanced development effort to produce large scale, fault tolerant and general-purpose systems. Considering the challenges and the characteristics of quantum systems, the expectation is that quantum computing will complement conventional computing and digital systems, focusing on specific complex problems such as fractioning large numbers, optimizations requiring multiple variables, solving quantum problems as in quantum chemistry and physics, data analysis and sorting, and data encryption.

Quantum systems have been developed exploiting the wave-particle duality at the physics level and their ability to achieve discrete states. Their power originates from the exploitation of their superposition and entanglement properties. Superposition refers to their ability to exist in two or more states at once, while entanglement refers to their ability to create interdependencies among particles even when separated by large distances.

Superposition and entanglement enable powerful operations in terms of computing and communications, considering that entanglement promises high speed and secure communications while superposition coupled with entanglement enables effective parallel processing. Quantum networks and a Quantum Internet are the targets of several research efforts, including a test site in Chicago in the USA. Quantum computers are the focus of several efforts around the world, from large companies, such as IBM, Google and Intel, and small companies, like Rigetti, IonQ and Oxford Quantum Circuits, to universities such as TU Delft in Europe and the University of Science and Technology of China.

Quantum operations in computing and communication systems are based on quantum bits, named qubits, where a qubit constitutes the smallest unit in which quantum information is generated, transduced, processed, stored, and transmitted. A qubit is a superposition of the classical binary states (0,1). Analogously to classical computers, quantum computers perform a series of operations (a quantum algorithm) to modify qubit superpositions (probability of being in a particular state) and entanglements to increase some probabilities and to reduce others. Measurement of a qubit causes its state, and the states of entangled qubits, to collapse to either '0' or '1' with a probability dependent on the state of the qubit at the time of measurement. The goal is to maximize the probability of measuring the correct answer.

There are two main quantum computing models today:

- Analog or adiabatic quantum computing, and
- Gate-based quantum computation.

Analog quantum computing is typically based on quantum annealing, which performs processing by initialisation of the system followed by slow, global control of the qubits towards a final state and readout. In this computational model, the energy state of a quantum system encodes or models a problem and the energy landscape, which starts flat, changes slowly and continuously to a final state with the energy peaks and valleys representing the problem to be solved. Analog computers constitute some of the most developed quantum systems to date, but their functionality is limited to simple and very specific problems, because they have limited ability to reduce noise, which impairs qubit quality.

Gate-based quantum computation is analogous to traditional gate-based computers, using a sequence of quantum gates, each composed of a few qubits, that perform logical operations, followed by measurement. Unlike many classical logic gates, quantum logic gates are reversible. A universal set of quantum gates is still needed to achieve the full capability of quantum computation.

Gate-based quantum computing is error prone, due to noise. High gate and qubit error rates limit the scalability of quantum systems, leading to the challenging requirement for fault-tolerant quantum computation (FTQC) that would enable system scalability. In this direction, gate error rates as well as qubit and gate fidelity are metrics for the robustness of gate operations; qubit fidelity measures the loss of qubit coherence due to its interaction with its environment and due to shifts of its quantum states over time. These metrics essentially measure how closely actual gate operations match -on average- ideal versions of these operations. Analogously to classical computing error correction methods, quantum error correction (QEC) dramatically lowers effective error rates by encoding the quantum state using redundant "physical" qubits and using a QEC code to emulate stable qubits with very low error rates, often called "fault-tolerant" or "logical" qubits. Importantly, logical qubits currently require a large number of physical qubits and many quantum gates to maintain their state, incurring significant resource overhead in terms of both additional qubits for each “logical” qubit, and additional quantum gates for each logical operation. As an example, for simulating a chemical structure, a FTQC computer based on 111 “logical” qubits would require $10^8$ and $10^5$ “physical” qubits when the physical qubit error rate decreases from $10^{-3}$ to $10^{-9}$[14]. The development of an accurate and general-purpose quantum computer would need between $10^4$-$10^6$ “logical” qubits (Fig. 1) and a quantum and gate fidelity around ($1-10^{-15}$) for industrial applications[15]. Since QEC leads to considerable overhead with conventional technology, Noisy Intermediate Scale Quantum (NISQ) computers are an intermediate step towards large scale error corrected fault-tolerant quantum computers (FTQC). NISQ computers use qubits without QEC, and although not fully fault-tolerant, they are expected to be practical in the near term for some applications. NISQ computers will require around $10^2$ to $10^4$ logical qubits (Fig. 1) and a very high qubit fidelity, improving the mean error rate of current quantum computers which reaches 4%. To reduce the impact of environmental noise, and of the unwanted interactions on qubit fidelity, quantum error mitigation (QEM) algorithms are used to mitigate these errors rather than completely remove them.

Quantum computers are expected to find their first use cases in combination with classical computers, so that the QC will serve as an accelerator, that solves the one part of the computation that is computationally expensive for a classical computer, and the classical computer runs other tasks. In this way, even a relatively small and noisy quantum computer can provide benefit in a larger problem.

Figure 5 shows the expected evolution of the number of “logical” qubits for both FTQC and NISQ approaches.

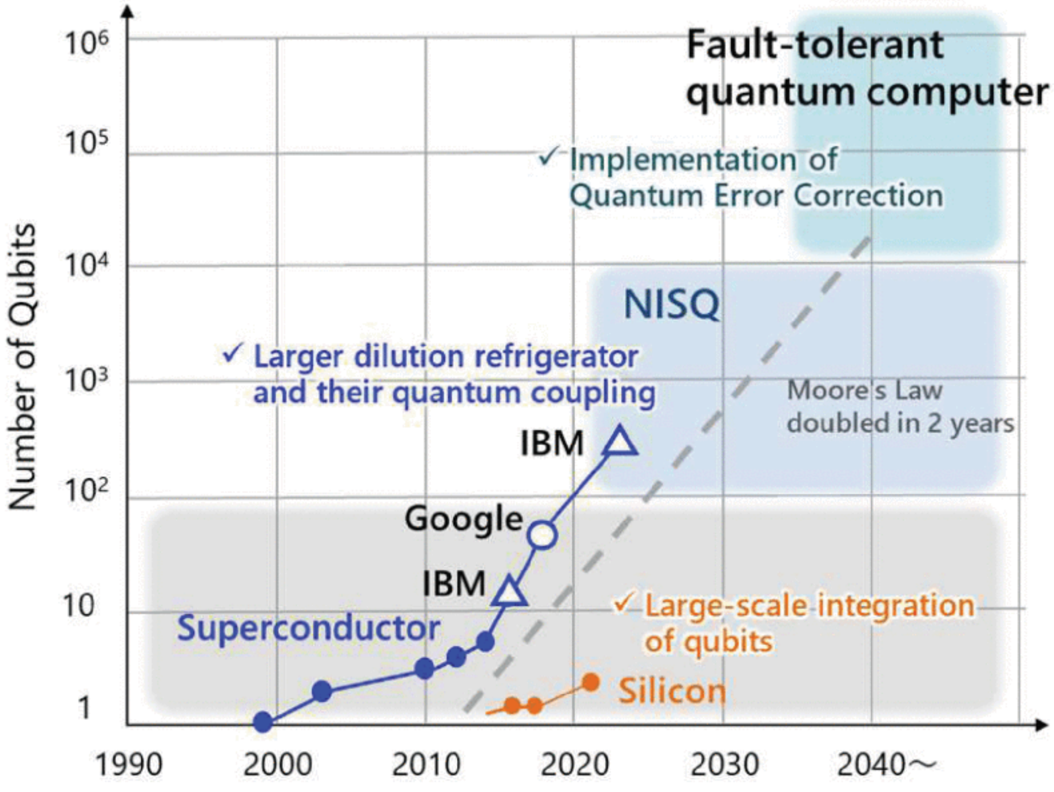


*Figure 4.5 - The trend of the number of “logical” qubits and the goal for NISQ and FTQC approaches*[16]

The number of qubits, and qubit and quantum gate fidelity in a system are the defining parameter for effective quantum computing. For this reason, significant research and development effort is spent on investigating alternative technologies for qubit manufacturing. Current efforts focus on superconducting qubits, semiconductor gate-defined quantum dots, color centers, trapped ions, cold atoms, photons and topologically protected Majorana modes. These alternative qubit technologies differ significantly in physical aspects, operational and miniaturization challenges. Neutral atoms in vacuum are entirely different from superconducting and electron spin qubits, and photon-based qubits, also named “flying qubits”, are also quite different from other types of qubits which are static in location; in contrast to solid-state qubits, photons do not have significant decoherence problems but are harder to generate, control and detect in a deterministic way. Figure 6 provides a mapping of current qubit technologies in terms of maturity and research intensity, while Table 1 presents the properties of the alternative qubit manufacturing technologies.

**Table 1: Properties of various qubit manufacturing technologies for quantum computing**

| **Qubit technology** | **Superconductor** | **Trapped ion** | **Si e- spin** | **Cold atom** | **Photon** | **Color centers** |
|---|---|---|---|---|---|---|
| **Qubit size** | 100µm$^2$ | 1mm$^2$ | 100nm$^2$ | 1-10µm$^2$ | 5-25µm$^2$ | 100nm$^2$ |
| **Quantum gate** | Microwave Magnetic field | Laser Microwave | Magnetic field | Laser Microwave | Interference | Microwave |
| **1-qubit fidelity** | 99.96% | 99.999% | 99.93% | 99.9% |  | 99.9952% |
| **2-qubit fidelity** | 99.3% | 99.9% | > 99% | 99.5% | 98% | 99.2% |
| **Gate speed** | 12-400ns | 100µs | 1µs | 0.4-2µs | 1ns | 20-50ns |
| **Coherence time T2** | 150µs | 50s | 20ms | 40s | 150µs | 0.6s |
| **Variability** | 3% | 0.01% | 0.1-0.5% | - | 0.5% | large |
| **Operation Temperature** | 15mK | 10K | 1K | 4K | 4-10K | ≈ 273K |
| **Entangled qubits** | 433 | 32 | 6 | 256 | ≈ 20 | 5 |

*Figure 4.6 - Core qubit technologies mapped by maturity, intensity, and disruption potential*[17]

The different quantum computing approaches lead to challenges in problem-solving aspects of quantum computers, in addition to the manufacturing issues. Quantum algorithms and software for quantum computing are in their first steps and present significant challenges. The goals of user-friendly quantum computers that are programmed effectively and efficiently require significant advances in terms of algorithms and software tools. Recent advances in specialized application domains such as localisation, optimisation and machine learning exploit quantum computers effectively but require very specialised knowledge. Popular current environments and tools, such as Qiskit, demonstrate the ability of tools to make quantum computing more attractive to new generations of engineers, but the challenge of producing tools such as appropriate compilers and interpreters, needs to be met in order to enable a sufficiently wide adoption and evolution of quantum computing.

## 4.4 Application Evolution And Long-term Challenges

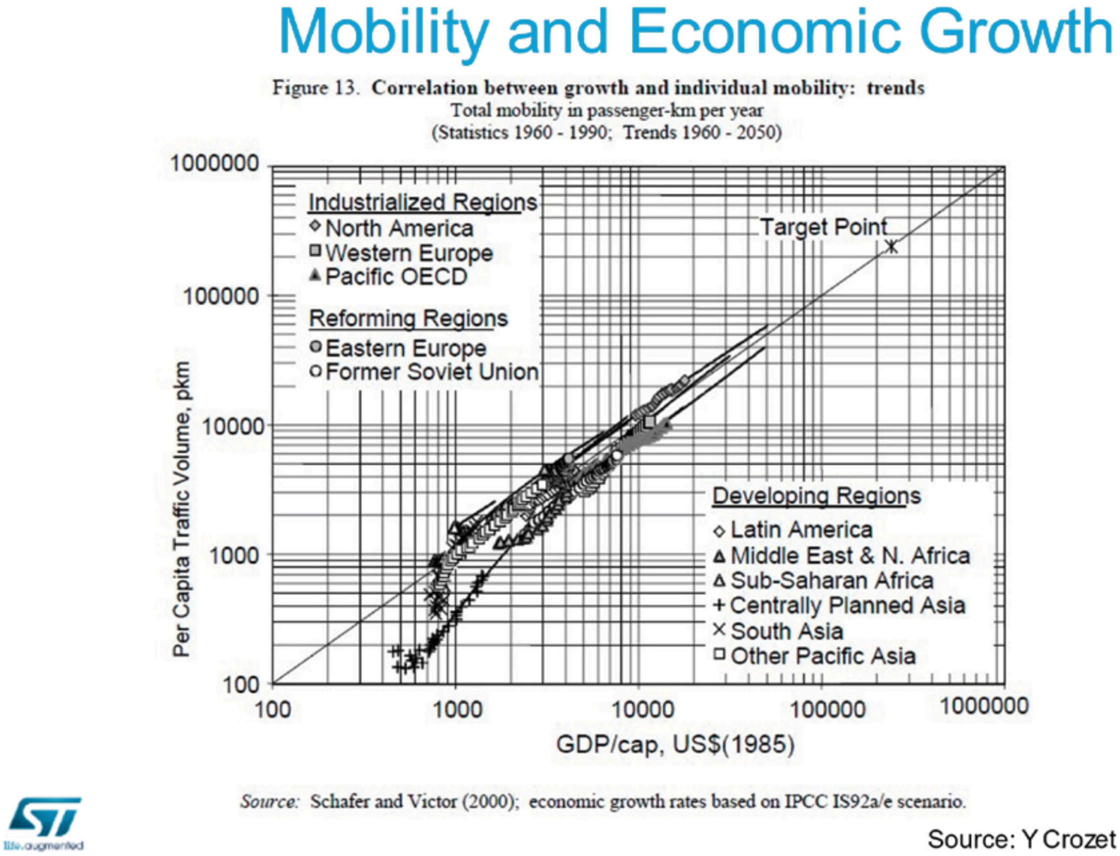
### 4.4.1 Mobility

The European Union has issued ambitious policy statements regarding transport and smart mobility:

- Emissions from transport could be reduced to more than 60% below 1990 levels by 2050.
- The EU has adopted the Vision Zero and Safe System approach, to eliminate deaths and serious injuries on European roads.
- Sustainable Mobility for Europe: safe, connected, and clean.

To realise this vision, possible scenarios include the projection that mainly autonomous and electrically driven vehicles (FEVs) will be on the road, and that all road users will be connected. It is envisaged that other road users (bicycles, pedestrians, public transport) will also participate in this connected, autonomous model, in addition to transportation network infrastructure (tolls, signals, etc.), creating an augmented Internet of Vehicles. Key networking technologies, such as the emerging 5G cellular connections with their very low latency (ms range) and the powerful edge nodes (Mobile Edge Computing, MEC), will enable highly effective vehicular communications for traffic management and safety applications. Railways and maritime transport will also become more autonomous. Fully integrated multimodal traffic will be applied, in which air, railways and maritime are fully integrated with road transport.

Until now, the rule was simple: more income equals more travel distance as ***Figure 7*** indicates. Will this very simple equation still work in the future?



Mobility and Economic Growth

Figure 13. Correlation between growth and individual mobility: trends
Total mobility in passenger-km per year
(Statistics 1960 - 1990; Trends 1960 - 2050)

Source: Schafer and Victor (2000); economic growth rates based on IPCC IS92a/e scenario.

Source: Y Crozet

*Figure 4.7 - The correlation between growth and individual mobility*

Many attempts have been made in the past to move people from individual to public transport. Huge investments have been made into infrastructure, fast trains have been deployed massively, bus lines installed. Nevertheless, this did not change the distribution of shares in the transport between planes, trains and cars. It could just allow to keep pace in an ever-increasing mobility. The most important means of transport is still, and will also very probably be in the next decade, the individual car.

If we want to reduce emissions and energy waste, then we need to focus on this means of transport, and make it more ecologically friendly. It must use less space and energy.

The global mobility is undergoing a significant change triggered by the increasing thread of global warming. The European Union started the Green Deal, which is radically changing the way mobility works. Classical fossil fuel-based transport and mobility will be completely replaced by CO2 neutral mobility. As all the alternative mobility systems, be it battery-based, H2 based or synthetic-fuel-based, have their individual challenges, all of them have in common that CO2 neutrality is only possible in using a connected, shared and energy-usage minimized mobility network. To reduce the space needed by cars, the best solution would be to use them better during the day by sharing their usage.

Owning cars should thus be replaced by shared mobility and intermodal transportation offering the most convenient and CO2 neutral way to move goods or persons from point A to point B. This will be only possible by a stable, everywhere available, user-friendly, secure, fast communication system connecting people, traffic operations, cars, trucks, busses, airplanes, ships, busses, etc. across the globe.

Today’s vehicles contain more software than any other embedded system and most compute applications. Tomorrow’s vehicles will multiply the software lines of code by a factor 6. Semiconductor value in the car will more than double through the next 10 years (from 600$ to 1200$). Some already talk about ‘’software- enabled vehicles” or “data-centers on wheels”. Besides the electronics and software to get the car rolling, there will also be a lot of complexity added in terms of performing safety & security checks and to monitor the health or lifetime of electronic components and batteries. Overall, the evolution of the car and mobility in general results in the rise of complexity in electronics and software that has almost become uncontrollable.

Additionally, the growing global population as well as the aging society will be supported by more and more automated transport means at all mobility variants taking the best advantage of the available resources as roads, parking space, airspace, and water space, and serving best the needs for mobility of the society. This will be supported by sensors combining different sensor principles in one sensor with significantly less power consumption, as well as new AI optimized edge computers in the transport vehicles. These systems will be part of completely new HW/SW systems spanning from sensors via embedded edge computers via predictable, fast, clean (also for the user), safe, secure, and failsafe communication to globally interconnected cloud systems.

## 4.4.2 Energy

Power electronics is the enabling technology for the efficient generation, conversion, distribution, and usage of electrical energy. It is a cross-functional technology covering very high gigawatt (GW) power (e.g. in energy transmission lines) down to the very low milliwatt (mW) power needed to operate a mobile phone, and even to microwatt (µW) to power autonomous sensor nodes. Many market segments, such as domestic and office appliances, computers and communication, ventilation, air conditioning and lighting, factory automation and drives, traction, automotive and renewable energy, can potentially benefit from the application of power electronics technology. The ambitious goals of the EU to reduce energy consumption and CO2 emissions can only be achieved through extensive application and use of power electronics, as this is the basic prerequisite for:

- Efficiently feeding wind and solar energy into the power grids.
- The stabilization of the power grids with an increased share of fluctuating renewable energy sources.
- Highly efficient, variable speed, motor drives.
- Energy-efficient and low-emission mobility with hybrid and full electric vehicles.
- Energy-saving lighting technology.
- Efficient recovery of braking energy.
- Energy management of batteries.
- Control appliances and building management systems via the grid interface (smart grids).

The estimated energy savings that can be achieved by introducing state-of-the-art and future power electronics components into systems is enormous, estimated at more than 25% of current electricity consumption in the EU. Since power electronics is a key technology in achieving a sustainable energy society, the demand for power electronics solutions will show significant growth over the coming decades. The European industry holds a strong position in the field of silicon-based power semiconductors and modules and is establishing a robust foundation for future progress in wide bandgap semiconductor technology. Europe also has high-quality power electronics research groups at universities and research institutes with well-established networks and associations across Europe to provide platforms for discussion, cooperation, and joint research.

A long-term roadmap for power technology needs to cover different sectors.

- New, highly-efficient power devices based on wide-bandgap semiconductor materials such as SiC and GaN-on-silicon, and possibly $Ga_2O_3$, AlN, diamond, diamond-on-silicon, or nanowire-based materials.
- New, cost-efficient, Si-based power devices to enable high efficiencies for mass-market applications such as super-junction MOSFETs.
- Power management for very low-power applications as required for IoT, including the development of energy harvesting technologies, covering the full range from GW to µW levels.
- High temperature-capable packages serving new materials and 3D technologies that offer the highest requirements and integration capabilities.

In the energy roadmap towards 2050, five major challenges were identified:

- Smart & Efficient – Managing Energy Generation, Conversion and Storage Systems, trying to fulfil the vision of loss-free energy conversion and generation.
- Energy management from On-Site to Distribution Systems.
- Transmission grids with the goal to achieve in 2020 solutions to cope with rising grid loads as a base for the carbon-free energy transition of Europe.
- Efficient Community and Regional Energy management.
- Cross-Sectional Tasks for Energy System Monitoring & Control, so that highly integrated monitoring and control of energy systems and grids, are achieved utilizing innovative ECS-based solutions.

These challenges need to be addressed to achieve the current EU policy target of 30% savings by 2030 by utilising innovative ECS-based solutions, as well as the milestones of (a) -55% GHG emissions until 2030 (getting closer to zero emissions due in 2050) and (b) grid integration. To realize this vision, we need to target the decentralisation of energy sources, opportunities with networked systems, limitations in peak electricity supply, oversupply times, new demand for electric energy supply for urban mobility, and the introduction of storage systems. This will lead to new challenges in energy management providing flexibility, stability and reliability in the grids and distribution for communities and cities. Furthermore, we need to develop components for HV transmission, of 1.2 MV or even higher voltages, to roll out an efficient energy transmission over Europe. Also, we need to combine local generation & demand site management with transmission & distribution grid operation & control technologies from sub-MW to GW scale, and we need to develop resilient solutions coping with adverse conditions resulting from the advancing climate change.

Additional technical solutions are needed to increasing share of renewable energy generation, self- consumption (mainly heating/cooling and EV) and building optimization, as well as introducing and managing new types of renewable energy carriers like hydrogen.

Relevant promising technologies, already under use and extension, include (a) artificial intelligence & advanced communication techniques for cyber-security increasing resilient energy system control, and (b) optimal control of distributed generation and dispersed energy-storage devices as well as robust, high power control devices.

### 4.4.3 Digital industry

Digital Industry is a must of European productive and commercial evolution on the next decade, following and empowering the EU policy related to digitalisation. Digital capabilities and functions will be the enabler for safer, greener, sustainable, lower cost and more productive, autonomous, and competitive EU industrial ecosystem.

EU planned, mostly after the Covid experience and lesson learnt, strategic investments addressing digitalisation including industrial productive arena, edge technological engineering studies, developments and deployment efficiency and services, addressing, in addition to industrial production, logistics, transportation, health, critical EU infrastructure etc.

The future evolution of EU Industry into Digital Industry will further require cooperation between multiple domains enabling a wider shared understanding of the context and situation, filling the gap towards EU industrial strategic autonomy and more useful services, richer functionalities, better user experience and value proposition introducing the concept of connected and interacting domains.

The manufacturing industry can essentially be classified into two main categories: process industry and discrete product manufacturing. The process industry transforms material resources (raw materials, feedstock) during a (typical) (semi)continuous conversion into a new material that has significantly different physical and chemical properties than the starting substance. Discrete manufacturing refers to the production of distinct items. Automobiles, furniture, toys, smartphones, and airplanes are examples of discrete manufacturing products. The resulting products are easily identifiable and differ greatly from process manufacturing where the products are undifferentiated, for example oil, natural gas, and salt. Another meaningful way to distinguish between manufacturing industries is by dissecting the domain by the end-product categories, such as energy industry, chemical industry, petrochemical (oil & gas), food industry, pharmaceutical industry, pulp & paper industry, steel industry (process industries), and furthermore car manufacturing, machine industry, robotics, and the semiconductor industry. Also, these subdomains constitute significant industrial domains for Europe. These industries are ever more demanding and voluminous consumers of ECS technologies such as sensors, big data, artificial intelligence, real-time system, digital twins, safety & security, computing systems, lifecycle engineering, human-system integration etc. ECS technologies are essential parts of most of the advances in these domains.

The perspective of industry is reflected in several efforts. The major ones are described in the following:

- The SPIRE[18] Roadmap 2030 and the SPIRE Vision 2050, which lists the following targets.
- Replacement of fossil-based materials by bio-based materials requiring completely new processes.
- Re-use of waste streams that require complete redesign of materials, products, and related production processes.
- New resource efficient applications that require completely new designed processes.
- Complete redesign of industrial parks to realize industrial symbiosis.
- The Factories of the Future (EFFRA[19]) roadmap summarizes its vision as follows:
    - Agile value networks: lot-size one – distributed manufacturing.
    - Excellence in manufacturing: advanced manufacturing processes and services for zero- defect and innovative processes and products.
    - The human factor: developing human competences in synergy with technological progress.
    - Sustainable value networks: manufacturing driving the circular economy.
    - Interoperable digital manufacturing platforms: supporting an eco-system of manufacturing services.
- The Connected Factories[20] project forecasts the emergence of new manufacturing concepts, such as:
    - Hyperconnected factories.
    - Autonomous factories.
    - Collaborative product-service factories.

Recently, a federation was set up of the three electronics ecosystems in Europe in nanoelectronics, electronic smart systems and flexible, organic & printed electronics (https://5e-project.eu/). Combinations of nanoelectronics and flexible organic & printed electronics that provide functionalities to electronic smart systems lead to novel solutions. This trend to functional electronics is characterized by the following aspects:

- A shift from physical to functional integration.
- The use of novel substrates and structural systems.
- Eco-design approaches at product, process, and business model levels.

- Real time capture & management of multi-physics data and contextual information.
- Networked, autonomous operations complemented by software solutions (incl. AI).
- Seamless integration in everyday objects in a broad spectrum of new applications.

All these efforts provide high-level targets, which translate into diverse and much more concrete targets in each domain, ending up also in a number of technology challenges in this ECS-SRIA, such as distributed AI along the edge-to-cloud continuum, computation and simulation capabilities, communications and interacting domains, engineering support for emerging behaviors in complex SoS, model-based engineering, predictability, controllability, monitoring and diagnosis, automation, autonomy and robotics, teleoperation, telepresence, simulation and training.

Clearly, ECS technologies that enable distributed Industrial IoT (IIoT) systems to monitor and control manufacturing systems and processes will enable disruptive industrial innovations and realise the vision of Industry 4.0 and the Industrial Internet that will lead manufacturing worldwide. Overall, these long-term trends translate into the need to invest in technology research and innovation projects in the following areas:

- The rise of artificial intelligence (AI), a powerful edge, and cloud computing networks; methods and algorithms need to evolve to more complex, reliable and explainable AI.
- Collection of measurement data, including image, video, and 3D animation, and, in general, large volumes of heterogeneous and unstructured data.
- New production schemes such as:
    - Modular factories, i.e., smaller standard units to be assembled according to needs, also mobile units.
    - More end-user driven agile production, i.e. end-users more connected to production and logistics chains.
    - Hyper-connected factories.
- New production technologies, e.g. 3D printing, and other novel emerging methods, leading to production that is closer to customers.
- Methods to extend closed-loop production lines to closed-loop regions (extensive recycling, net energy, zero-emission and waste, close to end-users).
- Autonomous to human-machine co-work, to enable flexibility and reduce excessive complexity.
- Recyclable electronics, since the digital industry will increasingly become a producer and enabler of “green electronics over the next decade”, leading to the need to recycle as many electronic components and systems as possible.

### 4.4.4 Health and wellbeing

The rising cost of healthcare, caused by an aging population, is one of the major challenges that present-day society must deal with. To keep healthcare accessible and affordable for everyone, it will change radically in the coming decades. Healthcare will become increasingly decentralised and personalised, as medical care will move from the hospital to people’s homes as much as possible. This transition in healthcare can only be achieved through the massive development of digital healthcare devices that can provide personalized monitoring, mentoring and treatment.

ECS will keep on being key enablers to realize the continuum of healthcare, notably in linking well-being, diagnostics, therapeutic approaches and rehabilitation issues. In addition to providing the tools for personal management of individual health and monitoring of health condition, ECS and smart systems will play an active role in assistive technologies with the goal to reduce inequalities linked to impairments originating in loss of physiological or anatomical structure or function after a disease or an accident. Ambient Assisted Living (AAL) is a high-priority direction for Europe, to support its increasing aging population.

In the long term, personalised and patient-tailored healthcare will be at the forefront of technology advancement. Further miniaturization of biomedical devices and integration of smart integrated systems (e.g. smart catheters, electroceuticals) will have significant impact on point of care diagnosis and treatment. Real-time localized detection of disease and minimally invasive targeted drug delivery will be a key priority. Achieving enhanced reliability and building stakeholder confidence in these technology advancements will be key to successful implementation. Data integrity and security around the use and storage of personal information will require new methods of application development and a robust system of operation, especially if moving towards a more connected healthcare approach with more focus on tailored patient diagnosis and treatment.

Beyond those technological challenges, aspects such as reliability, safety and privacy issues in terms of regulation and uptake by practitioners, especially when dealing with procurement policies, have to be tackled. A priority will be in bringing these stakeholders closer in the involvement phase of developing key enabling technologies (KETs) for healthcare applications with a customer pull and technology push approach.

Improvements in medicine over the ages greatly benefited from advancements in other disciplines. Medicine evolved over time from a “mechanical” medicine (surgery) toward “chemistry” medicine and more recently biotech medicine. Nowadays, the development in ICT and digitization has an important impact on the way healthcare is addressed. In ten years from now “digital medicine” will be deployed, and will complement, not necessarily replace, the tools offered to medicine to improve the benefits for patients and medical professionals.

These tools may include, for instance, human models also known as the “digital twin”. Here, ECS will have a crucial role in ensuring the necessary link between the digital and the real twins. Real time acquisition and processing of data and vital parameters collected from on-body IoT sensors, is a key technology that will advance existing wearables and will enable identification and prediction of a person's condition. The use of AI technologies, based on extended measurement data, will enable significant advances in this area.

Finally, progress in interfacing electronics components and systems with biological systems will offer seamless connection to the body for continuous monitoring but also for electrostimulation purposes. Results from the human brain flagship project will provide input for improved deep brain stimulation. Electroceuticals and nerve stimulation will enhance treatments of diseases and partially replace pharmaceutic treatments, thus avoiding side effects.

Some additional developments are presented in the following:

- Fully personalized medicine will be enabled by smart monitoring of health parameters, including factors from the molecular to the environmental levels. Developments in healthcare will benefit from the concept of "digital twins", so that prediction of health evolution and preventive treatment will become reality and standard procedures. Fully personalized and accurate health data will be available anywhere, anytime.
- Drug development will be assisted by emerging methodologies such as 'organ-on-chip'.
- 3D-bioprinting. Medicine is highly benefiting from advancement in other disciplines such as genomics or 3D printing. Combining 3D printing of living material and of electronic systems will develop a bottom-up approach to medicine, with advanced and personalized prosthetics and implants increasing biocompatibility, solving the problem of powering, and increasing quality of life.
- Cyborgisation. Future Brain-Computer Interface (BCI) technology will enable new ways of communication, e.g. for people with severe disabilities. By the 2040s wearable or implantable BCI technology will probably make smartphones obsolete. Due to the massive exposition of the physical and biological world in cyberspace, BCI systems will have to incorporate new means of protection of technology, data, and consciousness – like heartbeat, venous system, fMRI or 'Brainprints' as the top measures of security.

These innovations in the medical domain can be accelerated by the creation of an ECS-based technology platform for medical applications. The Health.E Lighthouse[21] initiative has compiled a list of emerging medical domains where further technical developments are required:

- Bioelectronic medicines.
- Organ-on-Chip.
- Personal ultrasound.
- X-ray free interventions.
- Smart minimally invasive instruments.
- Smart drug delivery.
- Intelligent wound care.
- Ambulatory monitoring.
- Point-of-care diagnostics.
- Remote sensing and monitoring.
- E-health.

Despite this urgent need and the enormous resources that are being invested in research, true innovation in terms of products reaching the market has been slow. One of the root causes identified is the lack of open technology platforms. This will release the power of Moore's Law, that has been the driving force in electronics for more than fifty years, to the healthcare domain: "Moore for Medical". It is the vision of the Health.E Lighthouse that innovation can be accelerated by stimulating the development of truly open technology platforms.

The list of challenges that ECS will face in the next decade is changing and new issues, linked to the developments described above, will have to be addressed. Security and reliability remain major issues to guarantee safety and integrity of medicine. Regulation will have to be developed to address these concerns. Furthermore, ethical issues may become more and more critical in the uptake of patients and may lead to fundamental decisions in the way medicine will evolve.

### 4.4.5 Agrifood and natural resources

Over the following decades the global population will increase, rising to an estimated peak of 9.78 billion by 2064. By the middle of the century, about two-thirds of the population will live in urban areas. This will require new digital approaches to supply the growing number of people with food, which will involve a great threat to food security for certain countries and especially for large cities. Digitalisation has already helped initiate open field farming through precision agriculture, but there are other ways of targeting this issue, especially by the emerging areas of "digital farming" and "vertical farming". In this form of farming, plants are grown in vertical arrays, inside buildings, where growing conditions can be optimized. Crops are supplied with nutrients via a monitored system under artificial lighting and can thus be grown year-round. This method makes it possible to grow plants without soil and natural sunlight, with optimal growth conditions being created artificially. The full potential of this approach can only be achieved with the help of information technology (IT) and IoT components and paradigms such as AI and Industry 4.0, which all still need to be adopted for this purpose. With these digital farming approaches, it will be possible to secure food supply autonomy and food safety for large parts of the EU. Furthermore, investigation into the provision of corresponding technologies and approaches will enhance the strategic autonomy of Europe.

On top of this, and considering the huge negative impact by the climate change, the European Green Deal is a response to these challenges. It includes two main programs “From farm to fork” and “Biodiversity 2030” having a strong impact in the goals of this Chapter, which should contribute to reach the targets defined by these two programs by the introduction of the adequate ECS technologies and solutions.

#### From Farm to Fork

European food is already a global standard for food that is safe, plentiful, nutritious and of high quality. Now European food should also become the global standard for sustainability. EU agriculture, the manufacturing, processing, retailing, packaging, and transportation of food make a major contribution to air, soil and water pollution and GHG emissions, and has a profound impact on biodiversity. As such, food systems remain one of the key drivers of climate change and environmental degradation. For this reason, the From Farm to Fork action targets to reduce dependency on pesticides and antimicrobials, reduce excess fertilisation, increase organic farming, improve animal welfare, and reverse biodiversity loss.

#### Biodiversity Strategy for 2030

Biodiversity is also crucial for safeguarding EU and global food security. Biodiversity loss threatens our food systems[22], putting our food security and nutrition at risk. Biodiversity also underpins healthy and nutritious diets and improves rural livelihoods and agricultural productivity[23]. For instance, more than 75% of global food crop types rely on animal pollination.

A sustainable food system will be essential to achieve the climate and environmental objectives of the Green Deal, while improving the incomes of primary producers and reinforcing EU’s competitiveness.

To contribute to reach the targets of these two programs, the long-term vision of this Chapter includes the following challenges:

- Food security:
    - Intelligent and adaptive food production should take advantage of smart (bio) sensing for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
    - Precision farming systems should require robots with advanced sensing and perception capabilities and drones with intelligent computer vision devices to provide a higher level of detail and on-demand images.
    - Farming Systems should have machine-to-machine interoperable communication (sensors, advanced farming machines and robotic collaborative systems) for cost-effectiveness.
- Food safety:
    - Plants and Animals control; AI should allow to monitor, quantify, and understand individual plants and animals and their variability to control the bio-physical processes (like growing conditions) and understand the biological environment (with plants and animals) to ensure food safety.
    - Plant precision breeding and plant phenotyping should apply large-scale and high-precision measurements of plant growth, architecture, and composition to optimize plant breeding.
    - Integrated pest management should provide smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts. They should include insect traps.
    - Livestock welfare and health should require smart sensor systems to monitor animal activity to provide useful information for the early detection of diseases and to increase animal wellbeing. They should be also needed for rapid verification of bacterial infection and behavioral observations to control disease spread.
    - Intelligent logistic systems for food chains should require sensing and monitoring of food quality during transport and storage. They should be efficient and interoperable among the logistics chain.
    - End-to-end food traceability should integrate blockchain into current technology to prevent fraud and counterfeiting and provide direct access to end-consumers.
- Environmental protection and sustainable production:
    - In-situ, real-time monitoring of soil nutrients and herbicides should be carried out through intelligent and miniaturized sensors with appropriate packaging. Furthermore, this type of systems should detect weeds, preserve the “good ones” and eradicate the ones that are competing with the crop in question.
    - Air quality monitoring (indoor, urban, and rural) should require the development and deployment of real-time intelligent multi-sensor technologies with high selectivity and embedded (re-)calibration techniques. Focus should be put in the GHG emission from animals by performing the analysis of the gathered data to support decision making for mitigation of main issues.
    - Smart waste management should provide smart monitoring, controlling waste treatment units in real time as well as gas emissions in landfills and anaerobic digestion monitoring. Data analytics including gamification for behavioral triggers.
- Water resource management:

    - Smart healthy-water systems should provide secure drinking water distribution by detecting in real-time compounds and contaminants through data analysis capabilities to take the adequate measures to mitigate these issues to secure water quality and its distribution over the network. This requires online information on the status of water sources at larger scales than before. For this, healthy water systems should require connected high-integrated multi-parameter diagnostic sensors for real-time chemical analysis to ensure freshwater.

    - Efficient and intelligent water distribution should require novel smart metering solutions based on various technologies, including electrochemical multi-parameter sensors with high stability, anti-fouling, high accuracy capabilities, and be cost effective. Furthermore, optical sensors based on different principles integrated into miniaturized systems, at a low cost, are also required.
- Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation:

    - Biodiversity restoration for Forestry Ecosystem should provide precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests as well as early detection and prevention of threats to the forests (wildfires, pests, diseases, etc.). Furthermore, smart systems are required for environment monitoring of forests and fields, as well as CO2 footprint monitoring. Remotely monitor wildlife behaviour and habitat changes, and provide timely warning upon illegal poaching activity, are also needed.

## 4.4.6 Digital society

Ubiquitous connectivity ("everywhere and always on(line)") drive people to rely on intelligent applications and the services they use and offer. Public and private infrastructures will increasingly be connected, monitored, and controlled via digital infrastructures ("always measuring") and devices.

Furthermore, the trend of combining of working at the office and from home (or other remote locations), which has been triggered by the Covid-19 pandemic, will continue, and people will endeavor to combine work and private life in other ways.

Digital infrastructures with increased quality of service (QoS) and available bandwidth, will support these trends and will be ubiquitous, both in rural areas as well as in cities. These networks will be open and secure and will support intelligent control management of critical infrastructures, such as water supply, street lighting and traffic. Edge/cloud solutions will arise which will enable increased multimodal situational awareness and ubiquitous localization.

Social inclusion and collective safety and privacy will be enhanced by improved access to public services and communities (as healthcare, education, friends, family, and colleagues), supported by technological innovations in several directions, such as tele-presence, serious gaming, chatbots, virtual reality, robots, and personal and social assistants.

More and more, these solutions will be human-centered, will have cognitive abilities, apply nudging techniques, and support personal development, health, and well-being.

## 4.5 Conclusions

The European ECS community, from academia to industry, is a world leader in research, development, and innovation for the past decades. The competition of US and Asian communities is strong and requires significant European effort and investment, so that Europe remains a leader in the coming years, considering the dramatic increase in need for ECS systems due to the emergence of IoT and the corresponding embedded and cyber-physical systems.

In this Chapter, we have presented research and innovation directions for ECS in the long-term, considering the European priorities, such as the Green Deal, and the main objectives of the European ECS community. Considering the interdependence of emerging technologies, application domains and policies that drive innovation, and considering the corresponding trends of European industry in the next few years, we identified long-term challenges for technologies and applications, to provide direction for the community to meet the expected needs of the future. Clearly, the list of challenges and directions that we provide is neither complete nor restricting. Innovation is a continuous process that adapts to new technological capabilities as they progress, application needs and, even, new application domains that are not foreseen. However, the current review indicates a clear path to establishing European leadership considering current trends and constraints.

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## 5

*Strategic Research and Innovation Agenda 2024*

# APPENDIX A

## Recommendations and Roadmap for European Sovereignty in Open Source Hardware, Software, and RISC-V Technologies

Report from the Open Source Hardware & Software
Working Group August 2022

# 5 APPENDIX A: RECOMMENDATIONS AND ROADMAP FOR EUROPEAN SOVEREIGNTY IN OPEN SOURCE HARDWARE, SOFTWARE, AND RISC-V TECHNOLOGIES

## 5.1 Executive Summary

The use of open source hardware and software drastically lowers the barrier to design innovative System-On-Chips (SoCs), which is an area that Europe excels in today. Open source is a disruptive approach and strong competences in this field are being developed worldwide, for example in China, the US and India. In order for Europe to become a global player in the field and ensure sovereignty, it is important to put in place a roadmap and initiatives that would permit to consolidate ongoing European activities and to develop new technology solutions for key markets such as automotive, industrial automation, communications, health and aeronautics/defence. Notably open source can be used as a sovereignty tool providing Europe with an alternative to licensing IPs from non-EU third parties. A key success criterion for this is for Europe to develop a fully blown open source **ecosystem** so that a European fork is possible (i.e., create a fully equivalent variant of a given technology), if necessary.

The realization of such an ecosystem requires a radical change in working across the board with leadership and contribution from major European industrial and research players and other value chain actors. An approach similar to the European Processor Initiative which brings together key technology providers and users in the supply chain is needed, but with the goal of producing open source IP. This report suggests the following way forward to foster the development of an open source ecosystem in Europe:

- **Build a critical mass of European open-source hardware/software** that will permit to drive competitiveness, enable greater and more agile innovation, and give greater economic efficiency. At the same time, it will remove reliance on non-EU developed technologies where there are increasing concerns over security and safety. In building this critical mass, it is important to do so strategically by encouraging the design of scalable and re-usable technology.
- **Develop both open source hardware and software as they are interdependent.** An open-source approach to software such as EDA and CAD[2] tools can serve as a catalyst for innovation in open-source hardware. To ensure a thriving ecosystem, it is necessary to have accessible software.
- **Address cross-cutting issues.** In order to enable verticalisation, it is important to address a number of cross-cutting issues such as scalability, certification for safety in different application domains, and security. This requires consideration at both the component level and system level.
- **Cultivate innovation** facilitated through funding from the public sector that is conditional on an open-source approach. The public sector can also have a role in aiding the dissemination of open-source hardware through the deployment of design platforms that would share available IP especially those that were supported through public funds.
- **Engage with the open-source community.** Links with initiatives such as OpenHW Group, CHIPS Alliance, RISC-V International etc. should be strengthened to get and maintain industrial-grade solutions whilst encouraging standardisation where appropriate and keeping links with global open source communities.

To this end, the Working Group that is at the origin of this report has defined a strategic roadmap considering short (2-5 years), medium (5-10 years) and long term (>10 years) goals. The success of the roadmap depends on European actors working closely together to create a critical mass of activities that enhance and expand the European open source community and its influence on the world stage. The Working Group advocates that this roadmap of activities is supported via coordinated European level actions to avoid fragmentation and ensure that Europe retains technological sovereignty in key sectors.

## 5.2 Introduction

Europe has a core competence in designing innovative System-On-Chips (SoC) for key application sectors such as automotive, industrial automation, communications, health and defense. The increasing adoption of open source, however, is potentially disruptive as it drastically lowers the barrier to design and to innovation. Already nations such as China, the US and India are investing heavily in open source HW and SW to remain competitive and maintain sovereignty in key sectors where there are increasing concerns over security and safety.

Europe needs to respond by creating a critical mass in open source. The development of a strong European open source ecosystem will also drive competitiveness as it enables greater and more agile innovation at much lower cost. However, to achieve this there is a need to align and coordinate activities to bring key European actors together.

This document proposes a high-level roadmap for Open Source HW/SW and RISC-V based Intellectual Property (IP) blocks which are of common interest to many European companies and organizations, considering design IP and supporting EDA tools. The aim of the roadmap is to consolidate ongoing European activities through the presentation of a number of concrete ideas, topics and priority areas for IP-blocks and future research in order to build sovereignty and competitive advantage in Europe towards future energy-efficient processor design and usage.

Chapter 2 presents an initial approach to open source, shows how sovereignty can be addressed via open source, and what Europe needs to do to create a strong and competitive critical mass in this area. This is followed by a roadmap for open-source hardware in Europe in Chapter 3, which also highlights the necessary toolbox of open-source IP for non-proprietary hardware to thrive. Chapter 4 presents the supporting software required for the ecosystem to flourish. Chapter 5 discusses some cross-cutting issues – such as scalability, safety and security – for a potential RISC-V processor in common use. Chapter 6 identifies gaps in the current European ecosystem for both hardware and software. In Chapter 7, some important elements of the proposed roadmap are discussed. In turn, Chapter 8 lists the short-, mid- and long-term needs for the different elements of the proposed roadmap. Chapter 9 presents a series of recommendations of both a global and specific nature. Chapter 10 lists a series of horizontal and vertical activities to address the needs of open-source development within Europe. Some concluding remarks and two annexes complete the report.

## 5.3 Views of an Open Source Strategy

### 5.3.1 Introduction

The interest in open source is rapidly rising as shown in **Figure 5.1** with the number of published academic papers exploding in the area of RISC-V. This presents a major discontinuity for SoC design. The use of open source drastically lowers the barrier to design innovative SoCs which is an area that Europe excels in and strongly depends on in key application sectors. Use of open source also allows a research center or company to focus its R&D effort on innovation, leveraging an ecosystem of pre-validated IP that can be freely assembled and modified. This is disruptive in a market where traditionally a set of IPs is designed in house at a cost that is only accessible to a few companies, or where alternatively 3rd party IPs are licensed by companies with constraints on innovation due to architecture. A key advantage of open source is that it provides a framework that allows academia and companies to cooperate seamlessly, leading to much faster industrialization of research work.

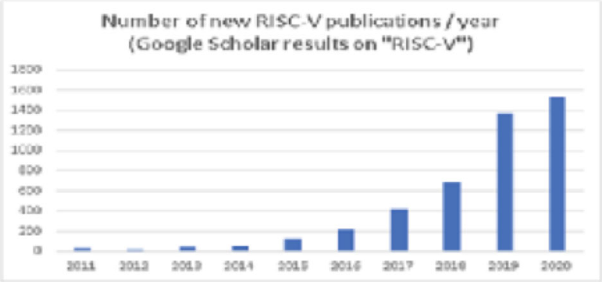


*Figure 5.1 - Google Scholar results on RISC-V (search performed 1 Sept 2021) showing growth of annual publications persisting even despite COVID-19 conference cancellations*

There are many parallels between open source hardware and open source software. There have been key exemplars in the software domain such as GNU and Linux. The latter started as an educational project in 1991 and has now become dominant in several verticals (High Performance Computing (HPC), embedded computing, servers, etc.) in synergy with open source infrastructure such as TCP/IP network stacks.

While there are a lot of commonalities in term of benefits, pitfalls and the transformative potential of the industry, there are also significant differences between open source hardware and open source software coming from the physical embodiment of any Integrated Circuit (IC) design via a costly and timely process.

The ecosystem is wide ranging and diverse including the semiconductor industry, verticals and system integrators, SMEs, service providers, CAD tools providers, open source communities, academics and research. It is an area with many opportunities to create innovative start-ups and service offers. The benefits and attraction of adoption of open source depends on the type of actor and their role within the value chain, and can include creating innovative products with lower costs and access barriers, and providing a faster path to innovation.

Annex A gives more details on open source, including potential benefits, the open source ecosystem, key players, business strategies, licensing models, and licensing approaches.

### 5.3.2 Current and growing market for RISC-V

Annex B presents an overview of the market trends in the global chips market. The value of this market in 2021 was around USD $550 billion and is expected to grow to USD $1 trillion in 2030.

RISC-based solutions are being used in a growing range of applications and the uptake of RISC-V is expected to grow rapidly.

Within these expanding markets RISC-based architectures have become important. RISC platforms have long enabled mobile phone and small-device consumer electronics vendors to deliver attractive price, performance and energy use compared to complex instruction set computing (CISC)-based solutions such as those of Intel and AMD. Also increasingly, RISC-based solutions are being used to power servers, moving beyond their small-device origins[3] as shown in **Figure 5.2** with a rapid growth in the uptake of RISC-V[4].

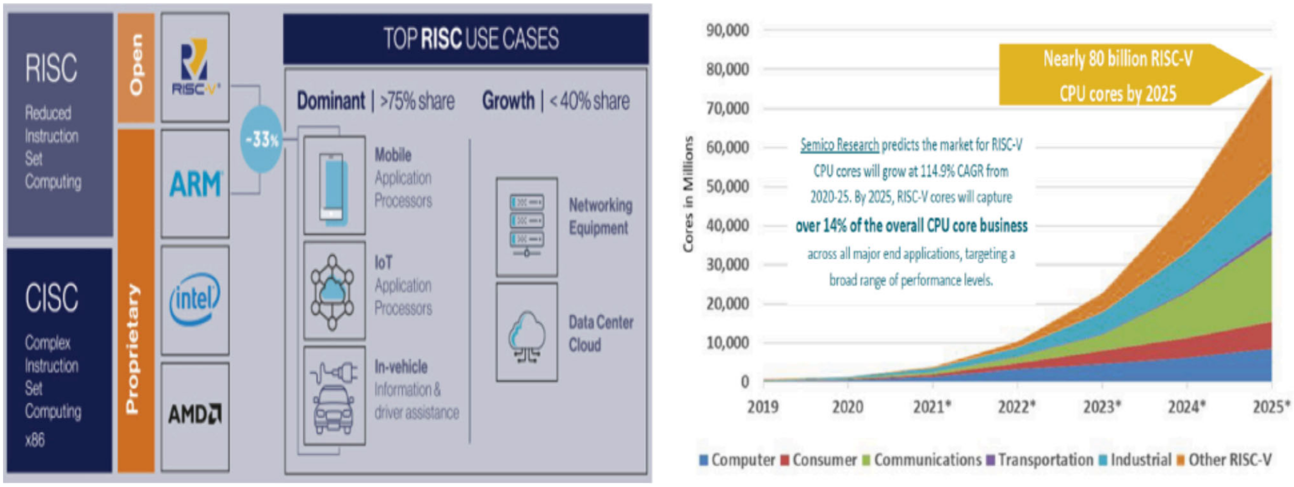


*Figure 5.2 - Growing RISC-based Architectures Usage (Source: Altman Solon and Semico Research Corp.)*

The compound annual growth rate for RISC-V from 2018-2025 is given in **Figure 5.2**[5]. In key European markets, the RISC-V penetration rate is expected to grow rapidly[6]. According to “Wilson Research Group Functional Verification” **in 2020**[7]**, 23% of projects in both the ASIC and FPGA spaces incorporated at least one RISC-V processor**.

The current RISC-V instruction set is very popular with RTOs and academics and is also attracting vertical companies that want to develop their own in-house semiconductors (Western Digital[8], Alibaba[9], ...). This has led to a number of start-up companies adopting RISC-V to develop specific processors or processor families to sell to the market. Some European examples of success stories, are:

- Greenwaves Technologies (founded in 2014): ultra-low power and AI-enabled GAP processor family for energy constrained products such as hearable, wearables, IoT and medical monitoring products.
- Codasip (founded in 2014): their processor core portfolio combines two complementary processor families, Codasip RISC-V Processors and SweRV Cores, to cover a wide range of design needs. Their business consists in selling of the standard cores that they have developed, as well as to customize the cores to the needs of the customer.
- Cobham Gaisler (founded in 2001): NOEL-V processor family based on 32-bit and 64-bit RISC-V including fault-tolerant implementation and Hypervisor extension, focusing on application of processors in harsh environments.

### 5.3.3 European Strategy

Open source shows lots of promise to boost the economy and welfare in our societies, but this is a non-trivial task. As illustrated with the RISC-V example, a generally agreed mechanism is to use open source to create or enlarge markets and to use proximity, prime-mover and other effects to benefit preferentially from those new markets, combining mostly publicly funded open source and privately funded proprietary offerings. This is well known already for software, and the aim is to replicate this for hardware, allowing the research and industry community to focus on new innovative points, rather than on re-developing a complex framework such as a processor and its ecosystem (compiler, interfaces, ...). There is no way to "protect IP" while still building real open source other than by providing adequate financing for Europe-based entities who work with open source as well as support for regional initiatives and leadership in identifying practical problems that can be solved. There is also a need to help connect open source vendors with customers in need of the innovation. **Speed from concept to product is also key to stay ahead of non-European competitors. This requires foundries and EU financing to build an ecosystem that can get from concept to products quickly in order to maintain European sovereignty.**

Europe is starting initiatives in terms of public adoption of Linux or Matrix in governmental institutions and other areas, and hardware presents a unique opportunity where the ecosystem is immature enough that it could really make a difference. Education is a key factor which could help. Talented and educated Europeans tend to stay in Europe, so significantly boosting open source hardware education could be a way to seed a strong ecosystem. RISC-V is already part of the curriculum in many universities and **Europe could further fund open source hardware education at an even earlier level and generally strongly encourage universities to produce open source.**

**The success of an open source project requires efforts going beyond putting some source code in a public repository.** The project needs to be attractive and give confidence to its potential users. It is said that the first 15 minutes are the most important. If a potential user cannot easily install the software (in case of open source software), or does not understand the structure, the code and the parameters, it is unlikely that the project will be used. Having good documentation and well written code is important. This requires time and effort to clean the code before it is made accessible. It is also necessary to support the code during its lifetime which requires a team to quickly answer comments or bug reports from users and provide updates and new releases. All modifications should be thoroughly checked and verified, preferably via automated tools. Without this level of support potential users will have little trust in the project. There is thus a need for support personnel and computing resources. This is a challenge for European Open Source projects as the code needs to be maintained after the official end of the project. Only if a project is attractive, provides innovation, is useful and is trusted, will it attract more and more users and backers who can contribute, correct bugs, etc. At this point it can be self-supported by the community with less effort from its initial contributors. The efforts and resources required to support an open source project should not be under-estimated. The project also needs to be easily accessible and hosted in a reliable industrial environment such as the Eclipse foundation, where the Open Hardware Group can provide support for ensuring the success of an open source project.

Success of open source depends not only on the IP blocks but also on the documentation, support and maintenance provided. This requires significant resources and personnel.

It is important to help steer Europe towards open source hardware and make sure that knowledge is shared, accessible, maintained and supported on a long-term basis. Barriers to collaboration need to be eliminated. Priorities should be discussed considering what is happening elsewhere in the world and **to maximize the value generated within Europe there is a need to build value chains, develop a good implementation plan and provide long-term maintenance and support**.

A more detailed economic view on the impact of Open Source HW and SW on technological independence, competitiveness and innovation in Europe has been documented in a report edited by Fraunhofer ISI and OpenForum Europe[17].

### 5.3.4 Maintaining Europe’s Sovereignty and Competitiveness

A key market challenge is that most of the current open source hardware technology resources are located outside of Europe, especially in the United States, in China (which has strongly endorsed RISC-V based open source cores) and India which has a national project. This raises the question: how can Europe maintain sovereignty and stay competitive in a rapidly developing open source market? The traditional value of the European landscape lies in its diversity and collaborative nature which reflects the nature of open source very well. EU funding looks favorably on open source solutions and there are well-established educational institutions which are of a less litigious / patent-heavy nature as compared to US private universities. The diversified industry within Europe is also a strength that can be leveraged to push the EU’s competitiveness in open hardware.

**To get sufficient return on investment for Europe, a focus should be given to application domains where there is stronger impact: automotive, industrial automation, communications, health, defense, critical systems, IoT, cybersecurity, etc.** These application domains convey specific requirements towards open source technologies: safety, security, reliability, power and communication efficiency.

**A key to sovereignty in the context of open source is the involvement of sufficient European actors in the governance of the various projects (CHIPS alliance, OpenHW group, etc.) and the achievement of a critical mass of EU contributors to these projects so that a fork could be pursued if this is forced onto EU contributing members.**

Competitiveness in the context of open source should be looked at in a reversed manner, that is, how much competitiveness European players would lose by not adopting open source. Open source is becoming a major contributor to innovation and economic efficiency of the players who broadly adopt the approach. The massive on-going adoption of open source in China, from leading companies to start-ups and public research centers, with strong support from both the central and regional authorities, is a very interesting trend in China’s strategy to catch up in semiconductors.

**Recommendation** – Calls by the Key Digital Technologies Joint Undertaking (KDT JU) should bring benefits to open hardware. Use of this hardware by proprietary demonstrations (including software, other hardware, mechanical systems, in key sectors automotive, industrial automation, etc.) would be beneficial for pushing acceptance of open hardware. Calls could formulate a maximum rate (e.g. 30% of volume) for such demonstrations. It should be required that proposals do not merely implement open interfaces (e.g. RISC-V) but also release implementations (e.g. at least 50% of volume). It is reasonable to demand that the open source licenses of such released implementations allow combination with proprietary blocks.

**While this document focuses on open source IC design IPs, the major control point from a sovereignty standpoint is EDA (Electronic Design Automation) tools, which are strictly controlled by the US**, even for process nodes for which Europe has sovereign foundries. Europe has significant capabilities in this area in research, which it regularly translates into start-ups for whom the only exit path currently is to be acquired by US controlled firms. Open source EDA suites exist but are limited to process nodes for which PDK is considered as a commodity (90nm and above). **A possible compromise approach, complementary to the development of open source EDA, is to emphasize compatibility of open source IP design with proprietary, closed source design tools and flows**. This objective can be achieved with efforts on two fronts: (I) promote licensing agreement templates for commercial EDA tools that explicitly allow the development of open hardware: this is especially important when open hardware is developed by academic partners in the context of EU-funded R&D actions, as current academic licenses (e.g., as negotiated by EUROPRACTICE) can often not be used for commercial industrial activities. And (II) even more importantly, emphasis should be put in promoting open standards for data exchange of input and outputs of commercial EDA tools (e.g., gate-level netlists, technology libraries). **Proprietary specifications and file exchange formats can hinder the use of industry-strength tools for the development of open source hardware**. This matter requires a specific in-depth analysis to propose an actionable solution.

### 5.3.5 Develop European Capability to Fork if Needed

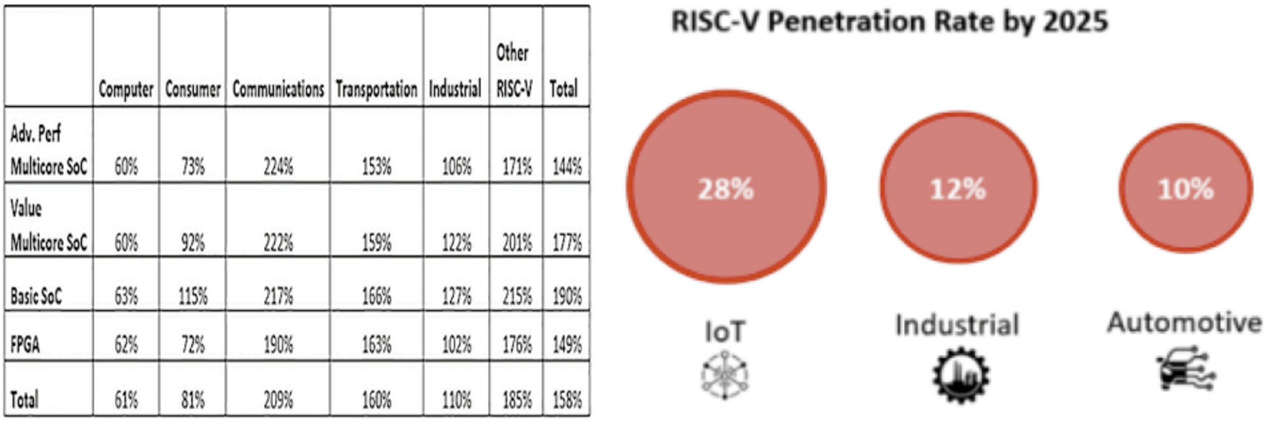
**Open source also brings more protection against export control restrictions and trade wars**, as was illustrated in 2019 when the US Administration banned Huawei from integrating Google proprietary apps in their Android devices. However, Huawei was not banned from integrating Android as it is open source released. Regarding US export rules, a thorough analysis is provided by the Linux Foundation[18].

Even for technologies developed in other parts of the world that have been open sourced and adopted in Europe at a later stage, **the ability to potentially “fork” i.e., create a fully equivalent variant of a given technology is a critical capability from a digital sovereignty perspective**. Should another geopolitical block decide to disrupt open source sharing by preventing the use of future open source IPs by EU players, the EU would need to carry on those developments with EU contributors only, or at least without the contribution of the adversary block. **For this there needs to be a critical mass of European contributors available to take on the job if necessary.**

The realization of such a critical mass will require an across-the-board change of working, with leadership and contribution from major European players (industrial and research) as well as a myriad other contributors. To achieve this there is a need to build or take part in sustainable open source communities (OpenHW Group, CHIPS Alliance, etc.) to get and maintain industrial-grade solutions. Care needs to be taken to avoid fragmentation (creating too many communities) or purely European communities with a disconnection from global innovation. A challenge is that current communities are young and essentially deliver processor cores and related SW toolchains. They need to extend their offer to richer catalogues including high-end processors, interconnects, peripherals, accelerators, Operating Systems and SW stacks, IDE and SDK, extensive documentation, etc.

Open source hardware targeting ASIC implementations requires software tools for implementation where licensing costs for a single implementation quickly amount to several hundred thousand Euro. **There is thus a need for high quality open source EDA tools supporting industrial-grade open source IP cores**. Europe also has a low footprint in the world of CAD tools, which are critical assets to design and deliver electronics solutions. Recent open source CAD tool initiatives are opportunities to bridge this gap.

Considering processors **involvement in RISC-V International should be encouraged** to influence and comply with the "root" specifications. RISC-V standardizes the instruction set, but additional fields will be needed in future for interoperability: SoC interconnect, chiplet interfaces, turnkey trust and cybersecurity, safety primitives, etc. **Europe should promote open source initiatives that would help maximize collaborations and reach a significant European critical mass. This is a key issue if Europe is to compete with China and the USA**. **A significant portion of the intellectual property produced in these European initiatives should be delivered as open source**, so that European actors can exploit these results.



| | Computer | Consumer | Communications | Transportation | Industrial | Other RISC-V | Total |
|---|---|---|---|---|---|---|---|
| Adv. Perf Multicore SoC | 60% | 73% | 224% | 153% | 106% | 171% | 144% |
| Value Multicore SoC | 60% | 92% | 222% | 159% | 122% | 201% | 177% |
| Basic SoC | 63% | 115% | 217% | 166% | 127% | 215% | 190% |
| FPGA | 62% | 72% | 190% | 163% | 102% | 176% | 149% |
| Total | 61% | 81% | 209% | 160% | 110% | 185% | 158% |

*Figure 5.3 -CAGR for RISC-V and Predicted Penetration Rates in key European sectors*

## 5.4 Towards an Open Source Hardware and Software Roadmap for Europe

### 5.4.1 Processors (RISC-V, beyond RISC-V, ultra-low power and high-end)

The Working Group has identified the strategic key needs for the development and support for:

1. a range of different domain focused processors,

2. the IP required to build complete SoCs and,

3. the corresponding software ecosystem(s) for both digital design tools and software development.

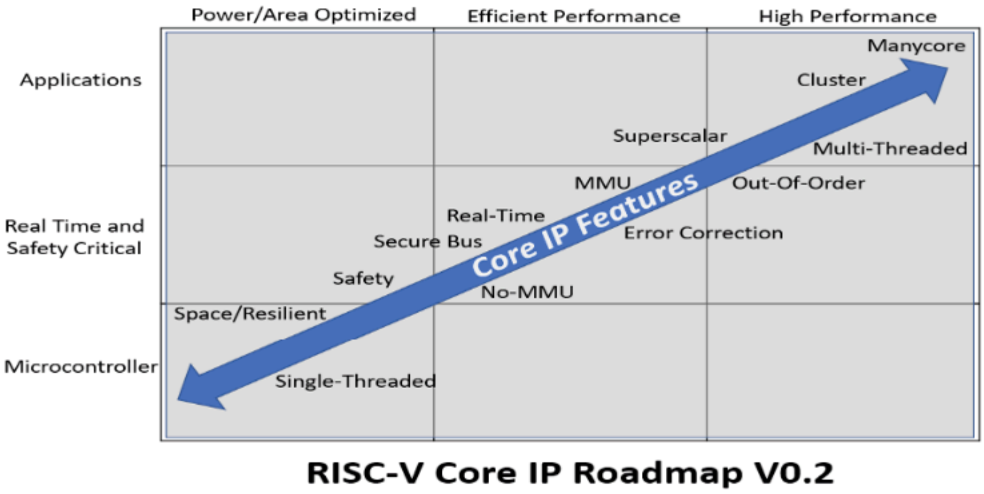


*Figure 5.4 -RISC-V Core IP Roadmap V0.2*

To align the software roadmap to the hardware IP core development roadmap, **efforts should be focused on supporting RISC-V implementations that correspond to the RV64GC and RV32GC set of extensions**. At the same time the creation/adoption of RISC-V profiles (microprocessor configurations) should be encouraged in the community. To scope this there is a need for an overall roadmap for RISC-V microprocessor core IP for specific market focus areas. A challenge is that microprocessor core IP comes in many shapes and sizes with differing requirements to meet the needs of applications ranging from 'toasters to supercomputers' as shown in **Figure 5.4**. In order to pursue this the Working Group has concentrated on a subset of this broader landscape whilst leveraging the underlying logic and thought process.

To be successful the IP roadmap must encompass attributes such as performance, scalability, software compatibility and deliver high levels of architectural reuse over many years of robust product creation. The focus has been on microprocessor core IP that drives system solutions ranging from edge IOT devices to manycore compute platforms which are key to many European applications. This needs to meet the challenges of scalability and must be sustainable in years to come. At the same time software and digital design tooling needs to be developed to support the foundational RISC-V IP. A key aim has been to leverage global open source hardware and software projects to maximize European reuse, avoid duplication and strategically direct investment.

### 5.4.2 Accelerators – Domain Specific Architectures

Accelerators are a key need and for many application domains, as meeting non-functional requirements (e.g., performance, energy efficiency, etc.) is often difficult or impossible using general-purpose processor instruction sets such as RV32IM or RV64GC. This is true, for example, in machine learning and cryptography, but it also applies to high-performance storage and communications applications. The use of extended instruction sets to enable more parallel processing, such as RISC-V “P” for Single Input Multiple Data (SIMD) processing and RISC-V “V” for full-scale vector processing, can provide significant performance and/or efficiency gains, however, even higher gains are achievable in many cases by adding application domain-specific features to a hardware architecture.

This has led to the concept of Domain-Specific Architectures (DSA) which was highlighted by computer architecture pioneers John Hennessy and David Patterson in their 2018 Turing Award Lecture[19] (the “Nobel Prize” of computer science and computer engineering). Here Domain-Specific Architectures were noted as one of the major opportunities for the further advances in computer architecture to meet future non-functional targets.

Accelerators are one approach to implement a DSA. They do not provide all of a system’s functionality, but instead assist more general-purpose processors by the improved execution of selected critical functions. In many cases, this “improvement” means “faster” execution, leading to the name “accelerator”, however, it can also mean “more energy efficient” or “more secure”, depending on the requirements. In order for the accelerator to exceed the capabilities of a general-purpose system on a similar semiconductor process node, the micro-architecture of the processor is highly specialized and very specific to the actual algorithm it implements. For example, machine-learning accelerators dealing with the efficient inference for Artificial Neural Networks will have very different micro-architectures depending on whether they aim to operate on dense or sparse networks. They, in turn, will have very different architectures from accelerators dealing, e.g., with 3D-Stereovision computations in computer vision for autonomous driving, or Quantum Computing-resistant cryptography for secure communications.

In most cases, accelerators rely on conventional digital logic and are designed/implemented/verified as is usual for the target technology (e.g., FPGA, ASIC). They would thus profit immediately from all open source advances in these areas, e.g., open source EDA tools. Open sourcing the accelerator designs themselves will benefit the ecosystem by encouraging reuse, standardization of testing and verification procedures and in inducing more academic interest and research. Some open sourced accelerators have seen widespread use. Successful cases include NVIDIA’s NVDLA[20] Machine Learning inference accelerator, or the 100G hardware-accelerated network stack from ETHZ[21].

**The opportunity for much higher impact when using open source for accelerators lies not so much in the accelerators themselves, but in the**

**hardware and software interfaces and infrastructures enabling their use.**

Accelerators are integrated into the surrounding computing system typically in one of three approaches (although others exist, e.g., network-attached accelerator appliance).

**Custom Instructions: At the lowest level, the accelerator functions can be tightly integrated with an existing processor pipeline and are accessed by issuing special instructions, sometimes called custom instructions or ISA eXtensions (ISAX).** This model is suitable for accelerator functions that require/produce only a limited amount of data when operating and thus easily source their operands and sink their result from/to one of the processor's existing register files (e.g., general-purpose, floating-point or SIMD). The key benefit of this approach is the generally very low overhead when interacting with the accelerator from software. This approach has been exploited for decades in processors such as the proprietary Tensilica and ARC cores and is also used, for example, in Intel's AES-NI instructions for accelerating Advanced Encryption Standard (AES) cryptography. In the RISC-V domain, companies such as Andes Technologies (Taiwan) emphasize the easy extensibility of their cores with custom functionality. In the open source area, ETHZ has implemented their Xpulp[22] instructions, showing significant performance gains and code-size reduction over the base RISC-V ISA.

Custom instructions generally require deep integration into a processor's base microarchitecture that is often difficult with many proprietary offerings, e.g., from Arm. In the open source RISC-V hardware ecosystem, though, custom instructions have become a very effective means towards Hennessy & Patterson's Domain-Specific Architectures. **Examples of custom functionality added in this manner include Finite-Field Arithmetic for Post-Quantum Cryptography [23], digital signal processing [24], or machine-learning[25].**

However, due to their need for deep integration into the base processor, such custom instructions are generally not portable between cores. What would be desirable is a lightweight, flexible interface for the interactions between base core and the accelerator logic realizing the custom functionality. This interface would need to be bidirectional as for example instruction decoding would still be performed by the base core, and only selected fields of the instruction would be communicated to the accelerator. The accelerator, in turn, would pass a result to the base core for write-back into the general-purpose register file. Additional functionality required includes access to the program counter computations, to realize custom control flow instructions (this is missing from UCB's RoCC interface), and the load/store-unit(s) for custom memory instructions. A key aspect of an efficient custom instruction interface will be that the unavoidable overhead (hardware area, delay, energy) is only paid for those features that are actually used. For example, a simple Arithmetic Logic Unit (ALU) compute operation should not require interaction with the program counter or memory access logic**. With a standard (de-facto or formal) interface in place, R&D work on tightly integrated accelerators could port across different base processors.**

**Loosely Coupled Accelerators: More complex accelerators that require or produce more data than can easily be provided/accepted by a base processor core are generally not integrated into the core pipeline itself but are coupled more loosely using industry-standard protocols** such as Arm AMBA. The communication requirements of the accelerator determine the specific flavour of interface used, which can range from Advanced Peripheral Bus (APB) for low-bandwidth interaction, or Advanced High-Performance Bus (AHB)/Advanced eXtensible Interface (AXI) for higher-performance accelerators. These loosely coupled accelerators accept commands from one or more base cores using memory-mapped interactions and are then capable of accessing their input and output data independently using Direct Memory Access (DMA) operations. Since these accelerators are integrated into a system using standard protocols, they are very portable. **For example, the open source NVIDIA machine-learning accelerator has been successfully integrated into a number of open source and proprietary Systems-on-Chips.**

However, for more complex accelerators, the open source ecosystem is much sparser when advanced capabilities are required. Two examples of this are shared-virtual memory and/or cache-coherent interactions between the accelerators and the software-programmable base cores. Both mechanisms can considerably simplify using the interaction between software on the base cores and accelerators, especially when more complex data structures (e.g., as used in databases) need to be operated on. To achieve shared-virtual memory, the accelerator and the base core(s) need to share address translations, invalidations, and fault-handling capabilities. The UCB RoCC interface achieves this by leveraging the capabilities of the underlying base core (Rocket, in most cases). However, for better scalability across multiple accelerators, it would be beneficial to have a dedicated Input-Output Memory Management Unit (IOMMU) serving just the accelerators, possibly supported by multiple accelerator-specific Translation-Lookaside Buffers (TLBs) to reduce contention for shared resources even further. However, no such infrastructure exists in an open source fashion. Currently, designers following Hennessy & Patterson's ideas towards accelerator-intensive systems do not just have to design the (potentially complex) accelerators themselves, but they also often have to start "from scratch" when implementing the supporting system-on-chip architecture allowing these accelerators to actually operate. **Portable, scalable and easily accessible open source solutions are sorely needed to lower this barrier of entry.**

**Recommendation** - Low-level generic and higher-level domain-specific frameworks should be made available in an easily accessible open source manner. For the lower-level frameworks, the goal should be portable and scalable solutions that support the selected model(s) of computation in a lightweight modular manner.

**High-Speed DRAM Interfaces: Accelerators are often employed for highly data-intensive problems (e.g., graphics, vision, machine-learning, cryptography) that need to store significant amounts of data themselves, and/or require high-performance access to data via a network**. Thus, the availability of high-speed interfaces to Dynamic Random Access Memory (DRAM), ideally even in the form of forward-looking 2.5D/3D memory technologies such as High Bandwidth Memory (HBM), and to a fast network or peripheral busses such as PCI Express, are absolutely crucial for the use of and research into accelerators. In most cases, it does not make sense to design an accelerator if it cannot interact with sufficient amounts of data. Moving up further in the layers of systems architecture, accelerators are not just used today as IP blocks in a system-on-chip, but also as discrete expansion boards added to conventional servers, e.g., for datacenter settings.

**Recommendation -** To enable easier design and use of novel accelerator designs open source system-on-chip templates should be developed providing all the required external (e.g., PCIe, network, memory) and internal interfaces (e.g., Arm AMBA AXI, CHI, DRAM and interrupt controllers etc.), and into which innovative new accelerator architectures can be easily integrated. These template SoCs could then be fitted to template PCBs providing a suitable mix of IO and memory (as inspired by FPGA development boards) to the custom SoC. Ideally, all of this would be offered in a "one-stop-shop" like approach, similar to the academic/SME ASIC tape-outs to EUROPRACTICE for fabrication but in this case functional PCIe expansion boards.

**This not only applies to Graphics Processing Units (GPUs), as the most common discrete accelerator today, but also to many machine learning accelerators such as Google's TPU series of devices**. This usage mode will become even more common, now that there is progress on the required peripheral interfaces for attaching such boards to a server, specifically: Peripheral Component Interconnect Express (PCIe) has finally picked up again with PCIe Gen4 and Gen5. Not only do these newer versions have higher transfer speeds, they also support the shared-virtual memory and cache-coherent operations between host and the accelerator board, using protocol variants such as Cache Coherent Interconnect for Accelerators (CCIX) or Compute Express Link™ (CXL). **Designing and implementing a base board for a PCIe-based accelerator, though, is an extremely complex endeavor.** Not just from a systems architecture perspective, but there are also many practical issues, such as dealing with high-frequency signals (and their associated noise and transmission artifacts), providing cooling in the tight space of a server enclosure, and ensuring reliable multi-rail on-board power-supplies.

These issues are much simplified when using one of the many FPGA based prototyping/development boards which have (mostly) solved these problems for the user. High-speed on-chip interfaces are provided by the FPGA vendor as IP blocks, and all of the board-level hardware comes pre-implemented. While these boards are generally not a perfect match to the needs of a specific accelerator (e.g., in terms of the best mix of network ports and memory banks), a reasonable compromise can generally be made choosing from the wide selection of boards provided by the FPGA manufacturers and third-party vendors. This is not available, however, to academic researchers or SMEs that would like to demonstrate their own ASICs as PCIe-attached accelerators. **To lower the barrier from idea to usable system in an open source ecosystem, it would be highly desirable if template Printed Circuit Board (PCB) designs like FPGA development boards were easily available, into which accelerator ASICs could easily be inserted, with all of the electrical and integration issues already being taken care of.** Providing these templates with well-documented and verified designs will incentivize designers to release their work in the public domain.

**Hardware is one aspect of an accelerator, but it also needs to be supported with good software**. This can range from generic frameworks, e.g., wrapping task-based accelerator operations using the TaPaSCo[26] system, to domain-specific software stacks like Tensor Virtual Machine (TVM [27] for targeting arbitrary machine-learning (ML) accelerators. Combinations of software frameworks are also possible, e.g., using TaPaSCo to launch and orchestrate inference jobs across multiple TVM-programmed ML accelerators [28].

Recommendatio**n** - For higher-level frameworks, future open source efforts should be applied to leveraging existing domain-specific solutions. Here, a focus should be on making the existing systems more accessible for developers of new hardware accelerators. Such an effort should not just include the creation of "cookbook"-like documentation, but also scalable code examples that can be easily customized by accelerator developers, without having to invest many person-years of effort to build up the in-house expertise to work with these frameworks.

**To enable broader and easier adoption of accelerator-based computing, a two-pronged approach would be most beneficial.** Lower-level frameworks, like TaPaSCo, should provide broad support for accelerators operating in different models of computation, e.g., tasks, streams/dataflow, hybrid, Partitioned Global Address Space (PGAS), etc., drawing from the extensive prior work in both theoretical and practical computing fields. Many ideas originating in the scientific and high-performance computing fields originally intended for supercomputer-scale architectures have become increasingly applicable to the parallel system-on-chip domain. Lower-level frameworks can be used to provide abstractions to hide the actual hardware-level interactions with accelerators, such as programming control registers, setting up memory maps or copies, synchronizing accelerator and software execution, etc. Application code can then access the accelerator using a high-level, but still domain-independent model of computation, e.g., launching tasks, or settings up streams of data to be processed by the hardware.

Even higher levels of abstraction, with their associated productivity gains, can be achieved by making the newly designed accelerators available from domain-specific frameworks. Examples include the TVM for machine learning, or Halide[29] for high-performance image and array processing applications. These systems use stacks of specialized Intermediate Representations (IR) to translate from domain-specific abstractions down to the actual accelerator hardware operations (e.g., TVM employs Relay[30], while Halide can use FROST[31]). Ideally, to make a new accelerator usable in one of the supported domains would just require development of a framework back-end for mapping from the abstract IR operations to the accelerator operations and the provision of an appropriate cost-model, to allow the automatic optimization passes included in many of these domain-specific frameworks to perform their work.

**It should be noted that the development of OpenCL 2.x is a cautionary tale of what to** avoid **when designing/implementing such a lower-level framework**. Due to massive overengineering and design-by-committee, it carried so many mandatory features as baggage that most actual OpenCL implementations remained at the far more limited OpenCL 1.x level of capabilities. This unfortunate design direction, which held back the adoption of OpenCL as a portable programming abstraction for accelerators for many years, was only corrected with OpenCL 3.0. This version contains a tightly focused core of mandatory functionality (based on OpenCL 1.2) supported by optional features that allow tailoring to the specific application area and target accelerators.

From a research perspective, it would also be promising to study how automatic tools could help to bridge the gap between the domain-specific frameworks, e.g., at the IR level, and the concepts used at the accelerator hardware architecture levels. Here, technologies such as the Multi-Level IR (MLIR) proposed for integration into the open source Low Level Virtual Machine (LLVM[32]) compiler framework may be a suitable starting point for automation.

### 5.4.3 Peripherals and SoC Infrastructure

#### 5.4.3.1 SoC Infrastructure

In addition to processor cores, it is also very important to have a complete infrastructure to make SoCs and be sure that all IPs are interoperable and well documented (industry grade IPs). This requires the necessary views of IPs (IDcard with maturity level, golden model, Register-Transfer Level (RTL), verification suite, integration manual, Design For Test (DFT) guidelines, drivers) which are necessary to convince people to use the IPs. As highlighted system-on-chip (SoC) templates are needed that provide all the required external (e.g., PCIe, network, memory) and internal interfaces and infrastructures (e.g., Arm AMBA AXI, Coherent Hub Interface (CHI), DRAM and interrupt controllers, etc.), and into which innovative new IPs could be easily integrated. High-speed lower-level physical interfaces (PHYs) to memories and network ports, are designed at the analog level, and are thus tailored to a specific chip fabrication process. The technical details required to design hardware at this level are generally only available under very strict NDAs from the silicon foundries or their Physical Design Kit (PDK) partners. Providing access to this information would involve inducing a major shift in the industry. As a compromise solution, though, innovation in open source hardware could profit immensely if these lower-level interface blocks could be made available in a low-cost manner, at least for selected chip fabrication processes supported by facilitators such as EUROPRACTICE for low-barrier prototyping (e.g., the miniASIC and MPW programs).

**Recommendatio**n - Blocks do not solely consist of (relatively portable) digital logic, but they also have analog components in their high-speed physical interfaces (PHY layer) that must be tailored to the specific ASIC fabrication process used. Such blocks should be provided for the most relevant of the currently EUROPRACTICE-supported processes for academic/SME prototype ASIC runs. The easy exchange of IP blocks between innovators is essential leveraged by both the EDA companies and IC foundries. An exemplar is the EUROPRACTICE enabled R&D structure of CERN where different academic institutions collaborate under the same framework to exchange IP.

**For open source hardware to succeed, standard interfaces such as DRAM controllers, Ethernet Media Access Controllers (MACs) and PCIe controllers need to be either available as open source itself, or at a very low cost at least for academic research and SME use.** If they are not, then the innovation potential for Europe in both of these areas will often go to waste, because new ideas simply cannot be realized and evaluated beyond simulation in real demonstrators/prototypes. For a complete SoC infrastructure, it is necessary to have an agreed common interconnect at the:

- processor/cache/accelerator level (similar to the Arm Corelink Interconnect, or the already existing interconnect specifications for RISC-V such as TileLink.[33]): in the open source area, support for cache-coherency exists in the form of the TileLink protocol, for which an open source implementation is available from UC Berkeley. However, industry standard protocols such as AMBA ACE/CHI do not have open source implementations (even though their licenses permit it). This makes integration of existing IP blocks that use these standard interfaces with open source systems-on-chips difficult.
- memory hierarchy level, for example between cores for many-core architectures (NUMA effects) and between cores and accelerators,
- peripheral level (e.g., Arm's AMBA set of protocols).

The communication requirements of the accelerators determine the specific flavor of interface used, which can range from APB for low-bandwidth interaction, or AHB/AXI for higher-performance accelerators.

### 5.4.3.2 Networks on a Chip

Networks on a Chip (NoCs) and their associated routers are also important elements for interconnecting IPs in a scalable way. Depending on requirements, they can be synchronous, asynchronous (for better energy management) or even support 3D routing. Continuous innovations are still possible (and required) in these fields.

### 5.4.3.3Verification and Metrics

IPs need to be delivered with a verification suite and maintained constantly to keep up with errata from the field. **For an end-user of IP the availability of standardized metrics is crucial as the application scenario may demand certain boundaries on power, performance, or area of the IP.** This will require searches across different repositories with standardized metrics. One industry standard benchmark is from the Embedded Microprocessor Benchmark Consortium (EEMBC)[34], however, the topic of metrics does not stop at the typical performance indicators. It is also crucial to assess the quality of the verification of the IP with some metrics. In a safety or security context, it is important for the end-user to assess in a standardized way the verification status in order to conclude what is still needed to meet required certifications. **Using standardized metrics allows end users to pick the most suited IP for their application and get an idea on needed additional efforts in terms of certifications.**

Another aspect is in providing trustworthy electronics. This is a continuous effort in R&D, deployment and operations, and along the supply chains. This starts with trustworthy design IPs developed according to auditable and certifiable development processes, which give high verification and certification assurance (safety and/or security) for these IPs. These design IPs including all artefacts (e.g., source code, documentation, verification suites) are made available ensuring integrity, authenticity and traceability using certificate-based technologies. Traceability along the supply chain of R&D processes is a foundation for later traceability of supply chains for components in manufacturing and deployment/operation.

### 5.4.3.4 Chiplet and Interposer Approach

Another domain which is emerging and where Europe can differentiate itself is in using the 2.5D approach, or "chiplets + interposers". This is already enabled by EUROPRACTICE for European academics and SMEs. **The idea is to assemble functional circuit blocs (called chiplets, see https://en.wikichip.org/wiki/chiplet) with different functions (processor, accelerator, memories, interfaces, etc.) on an "interposer" to form a more complex System-on-Chip**. The interposer technology physically hosts the chiplets and ensures their interconnection in a modular and scalable way, like discrete components on a Printed Circuit Board. This approach can range from low-cost systems (with organic interposers), to high-end silicon-based passive and active interposers, up to photonic interposers. In active interposers, the interposer also includes some active components that can help with interconnection (routers of a NoC), interfacing or powering (e.g., Voltage converters).

The industry has started shifting to chiplet-based design whereby a single chip is broken down into multiple smaller chiplets and then "re-assembled" thanks to advanced packaging solutions. **TSMC indicates that the use of chiplets will be one of the most important developments in the next 10 to 20 years. Chiplets are now used by Intel, AMD and Nvidia and the economics of this has already been proved by the success of the AMD chiplet-based Zen architecture.** As shown by the International Roadmap for Devices and Semiconductors (IRDS) roadmap, chiplet-based design is considered as a complementary route for More Moore scaling.

Chiplet-based design is an opportunity for the semiconductor industry, but it creates new technical challenges along the design value chain: architecture partitioning, chiplet-to-chiplet interconnect, testability, CAD tools and flows and advanced packaging technologies. None of the technical challenges are insurmountable, and most of them have already been overcome through the development and characterization of advanced demonstrators. They pave the way towards the "domain specific chiplet on active interposer" route for 2030 as predicted by the International Roadmap for Devices and Semiconductors.

With chiplet-based design, the business model moves from a soft IP business to a physical IP business, one in which physical IP with new interfaces is delivered to a new actor who integrates it with other outsourced chiplets, tests the integration and sells the resulting system. **According to Gartner, the chiplet market size (including the edge) will grow to $45B in 2025** and supporting chiplet-based design tools are available. A challenge is that the chiplet eco-system has not yet arrived due to a lack of interoperability between chiplets making chiplet reuse difficult. For instance, it is not possible to mix an AMD chiplet with a XILINX one to build a reconfigurable multi-core SoC. **Die-to-Die (D2D) communication is the "missing link" to leverage the chiplet-based design ecosystem, and its development in open source would enable a wide usage and could become a "de-facto" standard.**

The Die-to-Die interface targets a high-bandwidth, low-latency, low-energy ultra-short-reach link between two dies. Different types of interfaces exist and the final choice for a system lies in the desire to optimize six often competing, but interrelated factors:

1. Cost of packaging solutions

2. Die area per unit bandwidth (square mm per Gigabits per second)

3. Power per bit

4. Scalability of bandwidth

5. Complexity of integration and use at the system level

6. Realizability in any semiconductor process node

The ideal solution is an interconnect technology that is infinitely scalable (at fine-grained resolution), low power, area-efficient, totally transparent to the programming model, and buildable in a low-cost silicon and packaging technology. There are two classes of technologies that service this space:

- Parallel interfaces: High-Bandwidth Interface (HBI), Advanced Interface Bus (AIB) and "Bunch of Wires" (BoW) interfaces. Parallel interfaces offer low power, low latency and high bandwidth, but at the cost of requiring many wires between Die. The wiring requirement can only be met using Silicon interposer or bridging technology.
- Serial Interfaces: Ultra Short and eXtra Short Reach SerDes. Serial interfaces significantly reduce the total number of IOs required to communicate between semiconductor chips. They allow the organic substrate to provide the interconnection between dies and enable the use of mature System-in-Package technology.

**One difficulty of the Die-to-Die approach is that no communication standard currently exists to ensure interoperability**. In early 2020, the American Open Compute Project (OCP) initiative addressed the Die-to-Die standardization by launching the Open Domain Specific Architecture (ODSA) project that aims to bring more than 150 companies to collaborate on the definition of different communication standards suitable for inter-die communication.

**Recommendation** - The chiplet-based approach is a unique opportunity to leverage European technologies and foundries creating European HW accelerators and an interposer that could leverage European More-than-More technology developments. To achieve this, inter-operability brought by open source HW is key for the success, together with supporting tools for integration, test and validation.

The SoC infrastructure for "chiplet-based" components will require PHY and MAC layers of chiplet-to-chiplet interfaces based on standard and open source approaches. These interfaces could be adapted depending on their use: data for computing or control for security, power management, and configuration. This interposer + chiplet approach will leverage European technologies and even foundries, as the interposer does not require to be in the most advanced technology and could embed parts such as power converters or analog interfaces. The chiplets can use the most appropriate technology for each function (memory, advance processing, support chiplets and interfaces). **Interoperability, that could be brought by open source HW, is key for the success, together with supporting tools for integration, test and validation.**

Regarding the connection of SoCs to external devices, some serial interfaces are quite mature in the microcontroller world and there is little differentiation between vendors in the market. It would make sense to align on standard implementations and a defined set of features that can be used by different parties. Open source standard implementations could contribute to the distribution of standards. However, there are also domain specific adaptions that require special features which would make it hard to manage different implementations.

## 5.5 Supporting Software

The software infrastructure necessary for a successful hardware ecosystem contains Virtual Prototypes (Instruction Accurate and Clock Accurate simulators), compilers and linkers, debuggers, programmers, integrated development environments, operating systems, software development kits and board support packages, artificial intelligence frameworks and more. Indeed, **the idea of open source originates from the software world and there are already established and futureproof software projects targeting embedded systems and hardware development such as LLVM, GDB, OpenOCD, Eclipse and Zephyr**. The interoperability and exchangeability between the different parts of the SW infrastructure are important fundamentals of the ecosystem.

### 5.5.1 Virtual Prototypes

Virtual Prototypes (VP) play a major role in different phases of the IP development and require different types of abstraction. They can range from cycle accurate models which are useful for timing and performance estimations, to instruction accurate models, applicable for software development, design-space exploration, and multi-node simulation. **Independent of the VP abstraction level, these platforms should strive towards modelling the IP to be functionally as close to real hardware as possible**, allowing users to test the same code they would put on the final product.

As modeling IP is usually a task less complex than taping out new hardware revisions, VPs can be effectively used for pre-silicon development. Modeling can be either done in an abstract way, or using RTL, or by mixing these two approaches in a co-simulated environment. VPs can bring benefits not only to hardware manufacturers that want to provide software support for their customers but also to customers in that they can reuse the same solutions to develop end products. Having models for corresponding open source IP could be beneficial for establishing such IP. With this in mind it would be reasonable to provide a permissively licensed solution, allowing vendors to close their non-public models.

### 5.5.2 Compilers and Dynamic Analysis Tools

Compilers significantly influence the performance of applications. Important open source compiler projects are LLVM (Low Level Virtual Machine) and GCC (GNU Compiler Collection). The **LLVM framework is evolving to become the 'de facto' standard for compilers**. It provides a modular architecture and is therefore a future-proof solution compared to the more monolithic GCC.

**MLIR (Multi-Level Intermediate Representation) is a novel approach from the LLVM framework to building a reusable and extensible compiler infrastructure**. MLIR aims to address software fragmentation, improve compilation for heterogeneous hardware, significantly reduce the cost of building domain specific compilers, and aid in connecting existing compilers together. Such flexibility on the compiler side is key to providing proper software support for the novel heterogeneous architectures made possible by the flexibility and openness provided by RISC-V. Note that both LLVM and GCC include extensions such as AddressSanitizer or ThreadSanitizer that help developers to improve code quality.

In addition, there are various separate tools such as Valgrind[35] and DynamoRIO[36] that strongly depend on the processor's instruction set architecture. Valgrind is an instrumentation framework for building dynamic analysis tools to detect things like memory management and threading bugs. Similarly, DynamoRIO is a runtime code manipulation system that supports code transformations on any part of a program while it executes. Typical use cases include program analysis and understanding, profiling, instrumentation, optimization, translation, etc. **For wide-spread acceptance of RISC-V in embedded systems, it is essential that such tools include support for RISC-V.**

Similar to hardware components, for safety-critical applications compilers must be qualified regarding functional safety standards. Here, the same challenges and requirements exist as for hardware components. For this reason, today mainly commercial compilers are used for safety-critical applications. These compilers are mostly closed source.

### 5.5.3 Debuggers

In order to efficiently analyze and debug code, debuggers are needed that are interoperable with chosen processor architectures as well as with custom extensions. Furthermore, debuggers should use standard open source interface protocols such as GDB (GNU Project Debugger) so that different targets such as silicon, FPGAs or Virtual Prototypes can be seamlessly connected.

### 5.5.4 Operating Systems

Chip design consists of many tradeoffs, and these trade-offs are best validated early by exercising the design by system software. For instance, when providing separated execution environments, it is a good idea to validate early that all relevant shared resources are separated efficiently. While this in principle should be easy it can be surprisingly difficult as highlighted by the Spectre/Meltdown vulnerabilities.

### 5.5.5 Real Time Operating System (RTOS)

**Most of the common RTOS have already been ported to RISC-V** (**https://github.com/riscvarchive/riscv-software-list#p17_real-time-operating-systems**), including the most popular open source options such as FreeRTOS and Zephyr RTOS. Even Arm's mbed has been ported to one RISC-V platform (**https://github.com/GreenWaves-Technologies/mbed-gapuino-sensorboard**), though mainline/wide support will most likely not happen. One of the key aspects of the OS is application portability. This can be achieved by implementing standard interfaces like POSIX which does not lock the software into a certain OS/Vendor ecosystem. There are many RTOS, but two key examples of relevance are:

**Zephyr RTOS - Zephyr has been aligning with RISC-V as a default open source RTOS option**. Currently RISC-V International itself is a member of the Zephyr project, along with NXP and open hardware providers Antmicro and SiFive. Zephyr is a modular, scalable RTOS, embracing not only open tooling and libraries, but also an open and transparent style of governance. One of the project's ambitions is to have parts of the system certified as secure (details of the certification process and scheme are not yet established). It is also easy to use, providing its own SDK based on GCC and POSIX support. The RISC-V port of Zephyr covers a range of CPUs and boards, both from the ASIC and FPGA worlds, along with 32 and 64-bit implementations. The port is supported by many entities including Antmicro in Europe.

**Tock** - **Tock provides support for RISC-V.** Implemented in Rust, it is especially interesting as it is designed with security in mind, providing language-based isolation of processes and modularity. One of the notable build targets of Tock is OpenTitan. Tock relies on an LLVM-based Rust toolchain.

### 5.5.6 Hypervisor

A hypervisor provides virtual platform(s) to one or more guest environments. These can be bare-bone applications up to full guest operating systems. **Hypervisors can be used to ensure strong separation between different guest environments for mixed criticality**, such platforms also have been called Multiple Independent Level of Safety and Security (MILS) or a separation kernel[37]. When a guest is a full operating system, then that guest already uses different privilege modes (such as user mode and supervisor mode). The hypervisor either modifies the guest operating system (paravirtualization) or provides full virtualization in "hypervisor" mode. **RISC-V is working on extensions for hypervisor mode, although these are not yet ratified.** Some hypervisors running on RISC-V are listed at **https://github.com/riscvarchive/riscv-software-list#p17_hypervisors-and-related-tools**.

At the moment, a number of hypervisors for critical embedded systems exist, provided by non-European companies such as Data61/General Dynamics, Green Hills, QNX and Wind River, and in Europe by fentiss, Hensoldt, Kernkonzept, Prove & Run, Siemens and SYSGO. Many of these are being ported/or could be ported to RISC-V. A weakness is that these hypervisors usually have to assume hardware correctness. An open RISC-V platform would offer the opportunity to build assurance arguments that cover the entire hardware/software stack. **Any new European RISC-V platform should be accompanied by a strong ecosystem of such hypervisors.**

**Recommendation** - If publicly funded research in the open hardware domain makes available some core results such as the used software/hardware primitives (such as HDL designs and assembly sequences using them) under permissive or weakly-reciprocal licenses, then these results can be used by both kinds of systems.

In the field of system software such as RTOS/hypervisors, currently there are several products which are closed source and have undergone certifications for safety (e.g., IEC 61508, ISO 26262, DO-178) and security (e.g., Common Criteria), and others which have not undergone certification and are open source. The existence of value chains as closed products on top of an open source ecosystem can be beneficial for the acceptance of the open source ecosystem and is common to many ecosystems. An example is the Linux ecosystem which is used for all kinds of closed source software as well.

### 5.5.7 NextGen OS for Large Scale Heterogeneous Machines

To address the slowdown of Moore's law, current large-scale machines (e.g., cloud or HPC) aggregate together thousands of clusters of dozen of cores each (scale-out). **The openness of the RISC-V architecture provides multiple grades of heterogeneity, from specialized accelerators to dedicated ISA extensions, and several opportunities for scalability (e.g., large-scale cache coherency, chiplets, interconnects, etc.) to continue this trend (scale-in)**. However, manually managing the hardware-induced heterogeneity of the application software is complex and not maintainable.

**Recommendation** - There is a need for research on RISC-V flexibility to revisit how to design together hardware and operating systems in order to better hide the heterogeneity of large machines to users, taking into account potential disruptive evolutions (non-volatile memory changing the memory hierarchy, direct object addressing instead of file systems, Data Processing Units to offload data management from processors).

### 5.5.8 Electronic Design Automation (EDA) Tools

Implementing a modern design flow requires a significant amount of EDA tools as shown in **Figure 5.5** – see[38] which states **"With billions of transistors in a single chip, state-of-the-art EDA tools are indispensable to design competitive modern semiconductors"**.

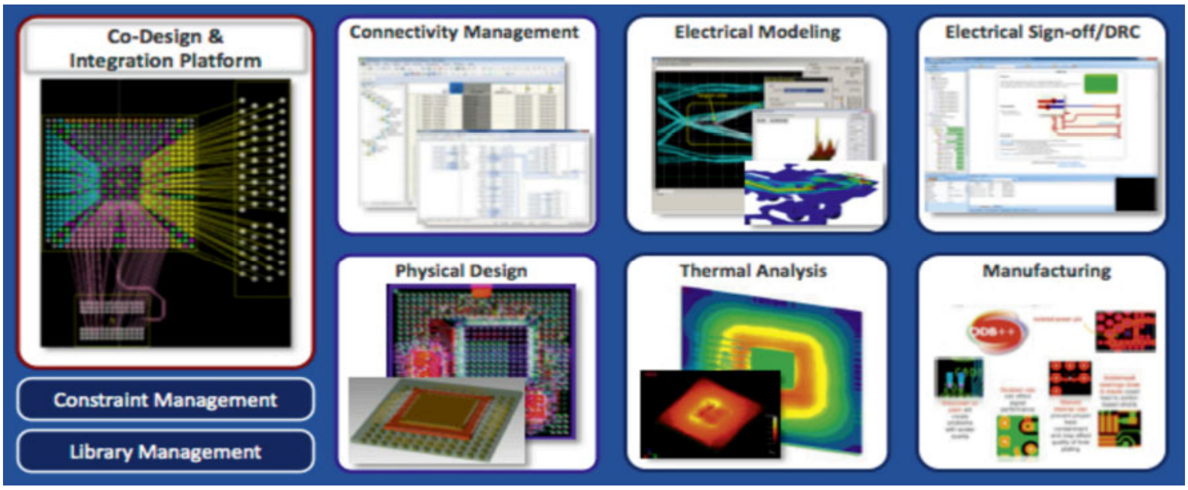


*Figure 5.5 - Xpedition Package Integrator Suite (Source: Siemens)*

Traditionally, EDA has been dominated by mostly US-based closed source commercial vendors. With projects like Verilator open source activities for specific parts of the design flow have also started to gain traction. However, open source support is still far from allowing a competitive fully open source design flow, especially when targeting digital design in advanced technologies, necessitating the co-existence of the existing commercial tools and upcoming open source ones for many years to come.

**Open source tools are essential for introducing new companies and more developers into the field; especially developers with a software background who can bring in innovation in hardware-software co-design**. Developers typically do not need to license their daily tools anymore and can freely work together across teams and organizations using massive collaboration hubs such as GitHub or GitLab. These benefits and capabilities need to be enabled via open source tooling for the sector to keep up with the demand for talent and innovation. A vital EDA community already exists in Europe with companies focusing on point solutions within the broader semiconductor flow. **Significant investment into open source tooling as well as cross-region collaboration is needed to energize the sector.** Contrary to common belief, the current EDA giants stand to benefit significantly from open source tooling investment, as there will be continued need for large, experienced players while open source solutions will enable new use cases and provide improvements in existing flows. New business opportunities will be created for the existing EDA players by incorporating new open source development. The recent acquisition of Mentor (one of the three leading EDA companies) by Siemens, means that it joins the European EDA community and can collaborate with the local ecosystem to support European sovereignty. The top EDA companies spend USD $1 Bn+ annually on R&D costs to continue innovating, so to provide meaningful progress in the open source space, continued investment from the public sector and cross-border collaboration are needed to bridge the gap. **Open source EDA should be a long-term goal in order to further the European sovereignty objectives, but existing European proprietary EDA will need to be utilized when necessary in the short to mid-term due to the significant investment that would be required to create a competitive, full flow open source EDA solution.**

**Recommendation** - Current proprietary EDA tools can help open source design IP development get off the ground if they are available at sufficiently low cost and provided the tool licensing does not restrict the permissive open source usage of the developed design IPs, but a sustained and long term investment into open source tooling is needed to build a sustainable ecosystem.

Large semiconductor and system companies use their pool of proprietary EDA licenses to design, verify and get their open source-based designs ready for manufacturing with the expected productivity and yield. However, they may also be interested to introduce software-driven innovations into parts of the flows and can benefit greatly from the economies of scale of open source, enabling large teams to use the same tools free of charge. Smaller companies and research organizations need access to a comparable level of professional EDA tools which the large EDA vendors will most likely provide through a variety of business models (Cloud offering, specific terms for start-up, research licenses, Software as a Service (SaaS), etc.). The EC is continuing to invest to build a European open source EDA tooling ecosystem, encouraging open interchange formats and making sure current tools do not introduce restrictions on utilization on open source hardware designs independently from the open source hardware license used.

Considering the safety requirements of some of the IPs under discussion here, open source offers a unique possibility to create transparent, auditable processes for ensuring safety. Much like in the case of open source software, common procedures and pooling efforts through oversight bodies (such as the Zephyr RTOS or RISC-V Safety Committees) can be used to provide safety certificates or packages to reduce the burden of safety compliance off the shoulders of developers.

The key to enabling open source tooling in the EDA space (which will most likely also benefit existing, proprietary vendors) is in enabling specific components of the proprietary flows to be replaced by open source alternatives which can introduce point innovations and savings for the users. **This should be encouraged by focusing part of the EU investment on interoperability standards which could allow the mixing of open and closed ASIC tools**, much like the FPGA Interchange Format driven by CHIPS Alliance is doing for FPGAs. RISC-V is another example in the hardware space of how closed and open source building blocks can coexist in the same space and reinforce each other as long as there are common standards to adhere to. EDA tools are exploited in various parts of the development chain including lifecycle management, architecture exploration, design and implementation as well as verification and validation.

### 5.5.9 Lifecycle Management

A state-of-the-art development process comprising continuous integration and continuous delivery/deployment is at the core of typical projects. A key aspect is requirements traceability, both on the core and up to the system level to ensure that the verification of the requirements can be demonstrated. This is crucial for certification of safety (e.g., ISO 26262) where an IP can be used as a safety element by rigorously providing the requirements and then by ensuring that they are satisfied during integration. Another useful data point for users to decide if they should trust a particular configuration of an IP is the "proven in use" argument. This necessitates collecting data on which configurations of the IP has been taped out in given projects and the collection of related errata from the field. Here open source hardware provides the opportunity to propose better traceability metrics and methods than proprietary counterparts. Complete designs can be shared and even manufacturing information on proper processes and good practices, as well as lifecycle management for open source hardware. This does not preclude the “out of spec” use of open source hardware in other domains such as low critical applications and education.

**EDA tooling needs to support tracing the standardized verification metrics from IP level to system level. To successfully span the hierarchies from core to system level, a contract-based design is crucial, allowing to share interface contracts along the supply chain**. This needs language and tooling to make it accessible to architects and designers. The open source toolchains, IPs and verification suites allow scaling the continuous integration/continuous deployment systems in server infrastructure reducing the build and test time. Proprietary solutions often require dedicated licensing infrastructure effectively preventing it from being used in scalable, distributed testing infrastructure. Different licensing and/or pricing of proprietary EDA tools for open source development may help to leverage the existing technology at the early stage in the open source development, before the open source alternatives are readily available.

### 5.5.10 Architecture Exploration

It is crucial to make the right architecture choices for the concrete application requirements before starting down a particular implementation choice. This requires tool support to profile at a high abstraction level of the application before software is developed. Usually, hardware is first modeled as a set of parameterized self-contained abstractions of CPU cores. Additional parameterized hardware components can then be added and software can be modeled in a very abstract level, e.g. a task graph and memory that get mapped to the hardware resources such as processing units. **Simulating executions on the resulting model allows analysis of the required parameters for the hardware components. This can include some first impressions on power, performance, area for given parameter sets, as well as first assessments of safety and security.** The derived parameter sets of the abstract hardware models can then be used to query the existing IP databases with the standardized metrics to identify matching candidates to reach the target systems goals.

The profiling can provide Power Performance Area requirements for instructions and suggest ways of potentially partitioning between accelerators and the relevant ISA instructions can be explored to meet these requirements. Ideally, a differentiated power analysis can already be started at this level, giving a rough split between different components like compute, storage, and communication. This can then be refined the more detail.

A widely used methodology is Model-Based System Engineering (MBSE) which focuses on using modeling from requirements through analysis, design, and verification. For the application of processor cores, this would mean the use of Domain Specific Languages (DSLs) down to the ISA level to capture the hardware/software breakdown. The breakdown would then be profiled before starting implementation of any design or custom instructions on top of a core. The modeling should lend itself for use in High-Level Synthesis (HLS) flows.

**Recently, thanks to the popularization of open source hardware (which pushes more software engineers into the hardware industry) as well as a fast-moving landscape of modern AI software which in turn requires new hardware approaches, more software-driven architecture exploration methods are being pursued.** For example, the Custom Function Unit (CFU) group within RISC-V International is exploring various acceleration methods and tradeoffs between hardware and software. Google and Antmicro are developing a project called CFU Playground[39] which allows users to explore various co-simulation strategies tightly integrated with the TensorFlow Lite ML framework to prototype new Machine Learning accelerators using Renode and Verilator.

### 5.5.11 Design & Implementation

Architecture exploration leads to a generic parameterized model. This requires a modeling language that offers sufficient expressiveness and ease of use for wide acceptance. A challenge is that typically engineers engaged in the architecture exploration process do not come from a hardware background and are unfamiliar with SystemC or SystemVerilog, the established hardware languages. Modern programming languages like Python or Scala are thus gaining traction as they are more widely understood. An architecture exploration process requires the availability of models and an easy way to build a virtual platform and exchange models by implementations as soon as they become available. This procedure enables early HW/SW Co-Design in a seamless and consistent manner.

A traditional Register-Transfer Level development process manually derives RTL from a specification document. To address the large scope of parameterized IPs targeted in this initiative, more automation is required. **The parameterized Instruction Set Architecture (ISA) models for processors lend themselves for a high-level synthesis (HLS) flow where detailed pipeline expertise is not required by the users unless they require the highest performance. This is crucial for enabling a wider audience to design and verify processors.** The design process thus lends itself to a high degree of automation, namely offering some form of HLS starting from the parameterized models. For processors, for example, synthesizing the instruction behavior from an ISA model and thus generating the RTL is feasible for a certain class of processors. The design process should also generate system documentation in terms of:

- System memory map
- Register files of each component
- Top level block diagram
- Interconnection description

The documentation needs to be created in both user and machine-readable forms allowing manual and automated verification.

**Recommendation** - There is a need for a high degree of automation for adding various monitors in the design flow without having to manually pick a suitable monitor IP or even to design, configure and wire it up from scratch, which can be very error prone.

RTL development flows should rely on continuous integration processes, such as automated checking via linting and Design Rule Checks (DRC). There is a possibility for RISC-V specific linting or DRC. Similar checks can be applied down the flow after synthesis to catch simple mistakes which often result in huge consequences.

It is important to add some monitoring components in the design phase, among other things to address threats that cannot be fully verified during development or that arise because of hardware/software interaction. In addition to an early security threat warning, monitoring is also needed for the safety. Design integrity and performance should also be monitored. While RISC-V offers a generic performance counter mechanism, not much has been standardized, creating an overhead to get specific counters like cache statistics integrated into the toolchain. Common C++ libraries for accessing the counters should be available. Debug logic with a more active role is needed to replace today’s mostly passive monitors. Heterogeneous cores, each with their individual debug features, creates additional software challenges. The generated monitoring and debug data can be evaluated with in-system software or off-loaded from the chip. **In order to evaluate the comprehensive monitor and debug data from such a SoC new analytics and visualization tools will need to be developed. There is also a need for system level and context specific debug tailored to applications like automotive, 5G, HPC.**

### 5.5.12 Verification & Validation

Verification management needs to be tightly integrated with lifecycle management for traceability from requirements to verification. **Verification should benefit as much as possible from the models produced by architecture exploration creating golden models for verification with coverage goals.** At the system level there are hard challenges like cache coherency and there is a need for portability of tests across different levels. State-of-the art verification approaches use simulation based and formal approaches. The introduction of automated formal verification has made the approach available to typical design and verification engineers allowing them to set up the targeted checks of the application much faster than they would in a simulation-based flow. **The approaches are complementary, lowering the overall verification effort with formal verification applications, while at the same time increasing verification quality in the crucial areas with formal proofs compared to an incomplete simulation.** To further enable a broad user base for custom processors, the verification side of the flow also needs a high degree of automation, for example deriving large parts of the verification from the parameterized models also used on the HLS side to create the implementations. For safety related projects, state-of-the-art tools and methodologies must be used driving the use of formal verification.

Cores and IPs should come with a reference flow similar to what is provided by Arm, allowing to re-run the provided verification in various tools, be it proprietary or open source. The CHIPS Alliance is developing an open source RISC-V core code generator/verification framework called RISC-V DV[40] which the OpenHW Group [41] is also using as the base of a simulation-based environment for verification of their cores. The CHIPS Alliance is working towards a fully open source Universal Verification Methodology verification flow based on Verilator [42]. However, the OpenHW environment still needs a proprietary simulator to run the full verification. Only a small subset of the verification suite can be run on the open source EDA tool. **For open source design IPs with industrial strength verification, there is no short or mid-term availability of an open source EDA tool suite that provides simulation-based and formal verification. Achieving an industrial strength verification with open source EDA verification tools is a long term goal.**

Another example of open source verification work can be found in the OpenTitan project[43] which provides a valuable example of an open source, continuous delivery system whose coverage and status can be traced for every commit. Software-based frameworks like cocotb are also gaining traction, especially with engineers and teams with a software background, and while they are incompatible with traditional Universal Verification Methodology (UVM) style verification, many new open source IP implementations adopt them. Hardware description languages based on modern programming languages like migen/nMigen (Python based), CHISEL, SpinalHDL (Scala based) provide their own simulation and verification flows. Since the above languages are derived from modern programming languages, they can easily reuse testing methodologies known from the software world.

**Recommendation** - For open source EDA tools, establishing collaboration models realizing a sophisticated design and verification process is an important topic. Maintaining an EDA tool for safety-critical applications after an initial release also requires a significant amount of both manpower and computing resources to ensure persistent tool quality and up to date safety collaterals.

As an example Antmicro's Renode while used mainly for software development and testing, provides a means to create complex simulation environments based on the Hardware Description Language (HDL) code of both cores and peripheral IPs. This creates an easy way to test IP in complex software scenarios, instead of synthetic, hand-crafted tests. In addition, it gives the possibility to work on software development in the pre-silicon phase of an ASIC project reducing the overall time-to-market.

**Recommendation** - For the standard protocols used to connect the design IPs, the use of Verification IP (VIP) is strongly encouraged. VIP allows all protocol rules on the controller or peripheral sides to be checked, thus ensuring IP blocks from different vendors can properly communicate. Formal VIP is another typical application where formal verification is easy to setup and gives great verification results. A focus should be on the protocols used in the design IPs – be it the AMBA protocols or open source ones like OBI, OCP, or TileLink.

### 5.5.13 Tool Qualification for Safety-Critical Applications

In the automotive industry, a classification according to ISO 26262 is necessary for all design and verification tools that should be used in a safety-critical environment. If the classification shows that the tool could introduce errors into the design and these errors would not be detected by another step in the design flow, a tool qualification is needed.

This leads to a significant challenge for the quality of the tools. By having a sophisticated development process handling requirements traceability, change management and comprehensive documentation, the work on the user side to qualify a tool can be significantly reduced. Furthermore, proof of comprehensive test suites and therefore the complete verification of the tool is necessary for a tool verification.

## 5.6 Cross Cutting Requirements

Instruction sets have traditionally been managed by a single "owner" (Intel, Arm) and their evolutions over time have been slow, lagging application requirements. This is because the ISA-owners are not strongly motivated to modify or overhaul their ISA and they hesitate to invest the required R&D and engineering effort, typically engaging only under extremely heavy customer requests. This situation has completely changed with the advent of the RISC-V open ISA, mostly for two reasons:

(I) from a technical viewpoint the RISC-V ISA is designed to be modular and extensible, with adequate provisions for ensuring backward compatibility issues

(II) R&D and commercial efforts to extend the RISC-V ISA for specific application domains can be initiated as community efforts, with cost and risk sharing and can be also used to provide differentiated value-added solutions.

**As a consequence of this paradigm shift toward open ISAs enabled by RISC-V, major innovation opportunities are enabled on open cores with enhanced instruction sets**. The faster innovation cycle which is now possible by coupling ISA and core enhancements in an open source setting, has been demonstrated in several domains. Notable examples include: open extensions for supporting quantized computations in machine learning, with particular emphasis on deep neural network inference, general digital signal processing extensions (e.g. Single Instruction Multiple Data (SIMD), fixed-precision arithmetic), and security extensions (e.g. Galois field operations, bitwise operators). It is also important to note that extensions that have been successfully prototyped as non-standard ISA enhancements and have gathered wide adoptions, can then be moved toward new standardized parts of the ISA.

**Scalability is also another important opportunity created by the RISC-V instruction set architecture. RISC-V does not prescribe a limit to instruction encoding size.** In addition to the already standardized 16-bit, 32-bit and 64-bit instructions, it is also possible to specify intermediate (e.g., 48-bit) and even larger instructions sizes: 128-bit instructions are already being worked on in the RISC-V standardization committees.

### 5.6.1 Safety Certification – Open Standards; Safety-Ready Toolchains

**RISC-V is promising for applications in the high-assurance market due to potential cost reductions from easier access to innovation, flexible and rapid design processes, stability and modularity, and availability as white box**[44]. When considering safety there is a need to consider both the hardware component level and also the system level taking into account the interplay between hardware and software. At the hardware level the safety-critical hardware components should ideally be developed to sectoral safety standards. For example, in the automotive sector the key standard is the ISO 26262 standard which contains development process requirements in order to avoid systematic and random faults. These address management processes during the development lifecycle, role definitions, hazard analysis, risk assessment and development processes. These include conditions for requirements tracing, confidence levels of tools used for development and verification and verification requirements. Certifying a system that contains hardware components that are not developed according to the ISO 26262 is still possible but elaborate.

**Recommendation** - In order to make the use of open source hardware components possible in automotive applications, artifacts and methods have to be defined that help with certifying these components. A start could be the implementation of quality-management systems in open source projects.

In addition to the open source availability of source code, the open source availability of verification artefacts (verification plans, test benches, reference simulators, assertions, test sequences...) can be enablers of white-box analyses and certification processes. Notably the OpenHW Group already publishes these verification artefacts[45], however, available documentation of the verification process itself still might not be sufficient especially for the highest assurance levels (ISO 26262 ASIL D, DO254 DAL A...) where additional, and often very costly, verification practices might be needed.

EDA tools can be used for implementing and assessing the safety of hardware components. Automation plays a key role in order to avoid the need for RTL coding and development of verification strategies in the otherwise largely automated process. Similarly, tool support for adding and validating security mechanisms is needed. It is important to be able to assess the impact of safety or security mechanisms as much as possible based on models used as input to the design phase, i.e., before the design is completely done. In addition to assessing single safety/security mechanisms, the assessment at the system level is also crucial, including the fulfilling of critical timing deadlines in real-time safe systems. A key challenge is the huge parameter space of typical IPs as validation is needed for each and every concrete parametrization that is used. **For safety in particular, support for specific certification flows like Failure Modes, Effect and Diagnostic Analysis (FMEDA), is of huge value for integrators.**

**At the system level a key issue is to guarantee Worse Case Execution Time (WCET) deadlines for the execution of critical tasks.** For any time-critical system, requirements specify maximum response times. An issue is that most hardware manuals now do no not publish steps/cycles/execution times making a-priori determination of execution time difficult. In the past this information was available, e.g., Intel 486/Pentium manuals[46]. However, newer processor (Intel, PowerPC, Arm) manuals do not provide such numbers for multiprocessors like the P4080.[47] A workaround is to replace clock cycle analyses by own empirical time measurements which suffices for average case behavior but is inefficient and/or unsafe for assessing worst-case execution time.

### 5.6.2 Security

**Common Criteria security certifications for simple hardware IP such as smart cards[48] exist, however, for more complex processors, security is still in its infancy and it is not possible to buy a Common Criteria certified general purpose multicore processor**. To get around this currently companies have to make liability limiting statements such as "The underlying hardware [...] is working correctly and has no undocumented or unintended security critical side effect on the functions of ..." However, relying on the hardware's documented interface alone can be insufficient, as there may be parts of the hardware-software system architecture that cannot be inspected by the software developer. For instance, **the Spectre/Meltdown vulnerabilities which appeared in 2018 were unexpected for almost all OS vendors.**

In an exhaustive search of hardware-software systems (3800 publicly available security targets and evaluation reports available from **commoncriteriaportal.org**) it is noted that the focus is on describing hardware at a high level without going into the micro-architectural side effects. Often unjustified assumptions on hardware are made and no references were found to key issues such as "branch predict*", "translation lookaside buffer", or "branch history buffer" with very few mentions of "cache flush". Evaluation reports do, however, exist on the analysis of the security properties for public-key cryptography including both VHDL and software analysis. A recent effort on the security side is Accellera's SA-EDI (Security Annotation for Electronic Design Integration) that establishes a link to CWE (Common Weakness Enumeration). **A continuing challenge is long-term security as there is a need to continually innovate to guard against future new attacks.**

### 5.6.3 The Way Forward - Hardware-Software Contracts for Safety and Security

Safety and security properties need to be known and can be summarized in the concept of hardware-software codesign with contracts as shown in Figure 5.6. **In this open hardware allows development of hardware-aware system software and system software-aware hardware.**

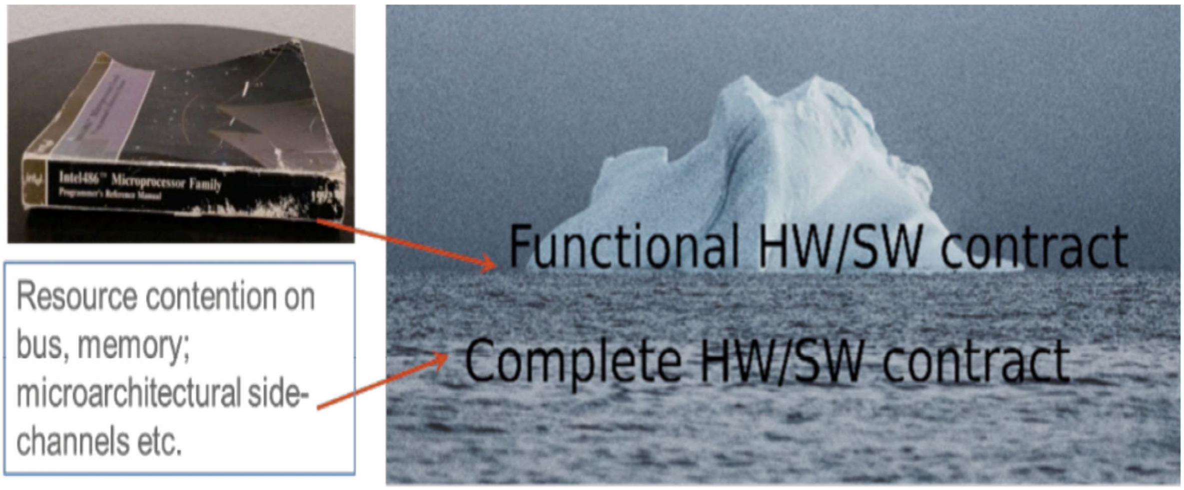


*Figure 5.6 - Hardware/Software Contracts*

In this approach rely-guarantee relations are made between hardware and software called "hardware-software contracts" [49]. Here there is a key need to bring together hardware providers and software providers to develop and produce a general-purpose open hardware platform or at least core components with access to the full hardware-software contract, allowing safety and security certification. This should be based on an instruction set architecture used in an existing or upcoming ecosystem, such as RISC-V. At the same time a verification methodology that provides reasonable assurance for the platform/its core components is needed. These verification artefacts need to be published to allow them to be used in use cases.

**Recommendation** - For supporting safety and security there is a need to demonstrate and share verification environments and artifacts of open source hardware at medium assurance levels and also at higher Safety Integrity Levels (SIL), e.g. safety SIL 4/ASIL D, security Common Criteria EAL 6 and higher, firstly addressing simple systems and then moving to complex systems.

## 5.7 Identified Gaps And Future Needs

The European economy consists of multiple industrial application domains which will be impacted by RISC-V and Open Source in different ways. These application domains include automotive, industrial manufacturing, consumer electronics, telecommunications, health, home applications, aerospace and defense. Within these domains there are some common requirements, and also specific challenges, such as security, safety, privacy and support for artificial intelligence. **Although these application domains can make use of generic common processor families, in many cases domain-specific processor families or specific features are needed to meet performance, reliability, cost, and energy consumption requirements.** In this section a number of common, as well as application/domain-specific gaps and needs are identified through the process chain as shown in Figure 5.7.

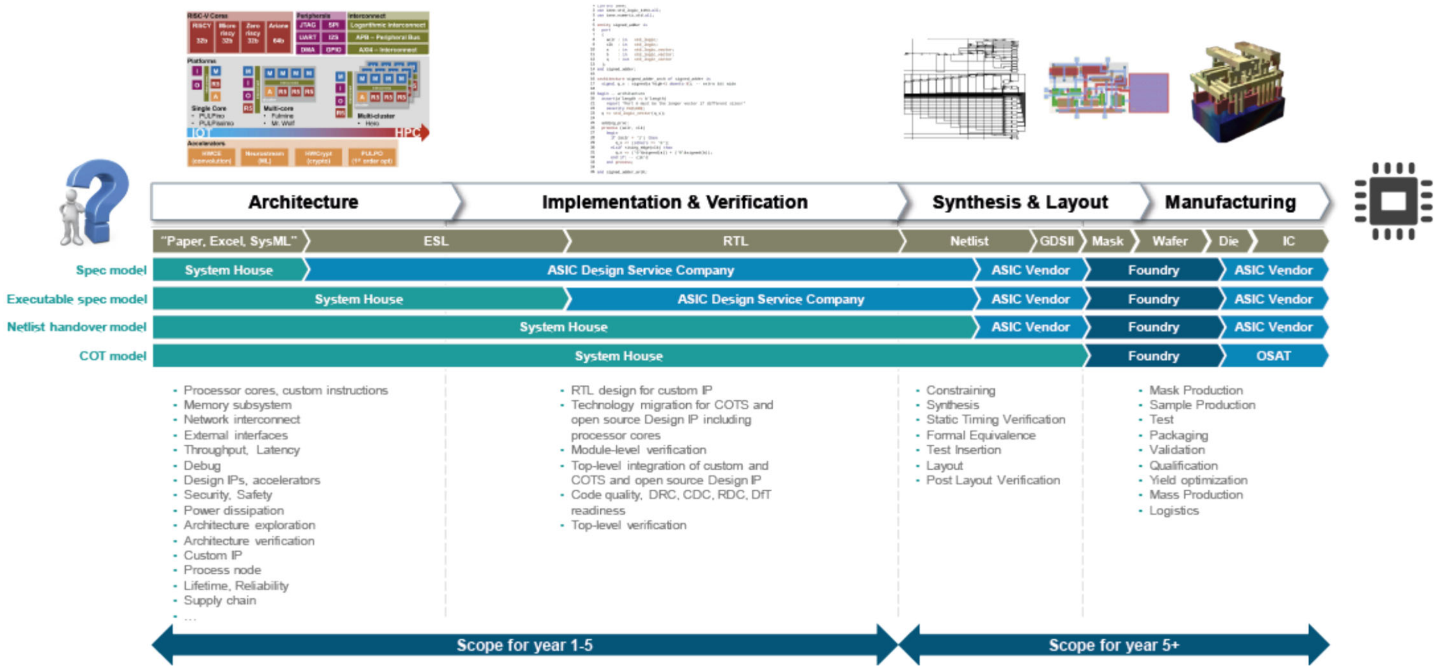


*Figure 5.7 - From Architecture to Manufacturing*

### 5.7.1 Processor Design

On the processor side, **European technology already is well established for low-end processors**, which could be considered micro-controller-class cores. Far fewer efforts deal with mid-end cores, which are sometimes called application cores. **The lack of European sovereignty is most pronounced, though, at the high-end, which includes server-grade and HPC cores**. In this area, there is a complete absence of European open source offerings.

### 5.7.2 Core Microarchitecture

**To close these gaps, there is a need to strengthen efforts for both the mid-end and the high-end. In the first case it will be possible to build/improve upon existing open source offerings. For high-end processors, work will have to start mostly from scratch, as only very limited prior work is available even internationally.** For instance, the BOOM processor initially developed at UC Berkeley, is still undergoing heavy revisions (e.g., from v2 to v3) and does not appear to be a stable base for future development yet. For the open source Alibaba Xuantie 910 core key documentation is only available in Chinese. A European effort should consider the results of these prior works but will most likely be starting (almost) from scratch for a European implementation. This is especially true when the high-end core should be evolvable towards advanced features such as multi-threading, smart prefetching, multi/many cores. Furthermore, the verification of the complex out-of-order superscalar microarchitectures required for high-end processors is considerably more difficult than the simpler in-order ones in the low-end and mid-end cores. Since Europe has a strong research background in formal verification techniques, the design of a high-end core could be a key opportunity for applying that expertise to practice. For instance, a result of formal verification techniques could be proofs of the absence of side channels.

### 5.7.3 Hardware Peripherals and Interfaces

In most cases, the processor cores described in the previous section will not operate completely stand-alone but will be integrated in a more complex system having additional components both on-chip and off-chip. Interaction between some of the components requires complex and challenging interfaces that are so-far mainly available as proprietary solutions from commercial vendors (such as physical interfaces to high-speed links or memories). More complex use-cases include the communication between core(s), between cores and accelerator(s), and also to memories (unified memory approach), especially when coherency between distributed local caches has to be covered as well. This problem becomes even more complicated when also considering safety-critical or mixed-criticality aspects in the solution. **Depending on the communication scenario, e.g., number of cores and accelerators, throughput and latency requirements, it may become necessary to upgrade from mostly passive interconnects (matrices of multiplexer-based switches) to active structures such as networks-on-chip (NoCs), which can scale better with more communication partners.** Open source baselines already exist for some of these requirements, e.g., cache coherency between a relatively small number of nodes. However, these do not scale to the more complex accelerator-intensive systems becoming more common today, and do not address the safety-critical or mixed-criticality aspects at all. There is a need for a flexible open source infrastructure for these on-chip communications, which should be easily customizable for the specific functional and non-functional requirements of a concrete SoC. In addition to the physical IPs there is also a need for tools to help in the design and the dimensioning of the infrastructure, the simulation, validation and verification views.

The complexity of off-chip interfaces spans an extremely wide spectrum, mostly depending upon the desired bandwidth. For low-speed interfaces, such as UART, SPI, I2C, I2S, etc., a wide variety of open source blocks exist. However, for higher speed (and more complex) interfaces such as USB3, 1G Ethernet, (LP)DDR2+ dynamic memories, and PCI Express, the design challenge increasingly moves from the digital into the analog domain. These interfaces require not only increasingly complex digital logic controllers (memory, PCI Express), but also high-speed off-chip communications using the appropriate I/O logic and so-called fast PHY/SerDes interfaces to achieve the required signaling rates. In general, the design of the PHY/SerDes blocks requires knowledge of low-level electrical characteristics of the underlying chip fabrication technology that is often only available under strict Non-Disclosure Agreements (NDA).

Many relevant system-on-chips that go beyond simple microcontrollers require these high-speed interfaces, e.g., to work with AI/ML datasets exceeding the (at most) single-digit megabytes of static memory storage that can economically be supported on-chip, or to communicate with other peripherals attached via PCI Express (e.g., to mass storage), or with other systems over the network. The lack of open source blocks for the tasks makes it extremely challenging for innovators to prototype solutions, e.g., to attract further investment, as **a commercial license for a DRAM interface (controller and PHYs, commonly provided by an extremely small number of non-European companies) may well cost over half a million USD.**

**Recommendation** – Effort should focus on areas where there is a current lack of technologies and tools to design and implement modern system-on-chips in order to strengthen European Digital Sovereignty.

To strengthen European Digital Sovereignty, it is essential that this scarcity of key technologies essential for the design and implementation of modern system-on-chips is alleviated. However, due to the confidentiality issue discussed above, realizing these high-speed mixed-signal peripheral interfaces blocks under an open source model is more complex than for the purely digital blocks (e.g., processor cores, many accelerators). **A potential approach could be to design the interface as much as possible in a portable, fabrication-process independent manner.** Only for those parts where it is unavoidable would a concrete ASIC process design be used, ideally one with fabrication facilities within Europe. The process-independent parts could then be customizable and freely open sourced under any suitable license. The process-specific parts, though, will require another approach, e.g., a multi-way NDA between the potential user, the foundry, and the designer of the interface IP. For any project involving such a mix of open and proprietary technologies, concrete work packages and tasks should be allocated to investigate and/or propose licensing strategies/legal frameworks for dealing with this scenario.

**In addition to the benefits of making the functionality of high-speed interfaces available to innovators in an open source manner, there is also a secondary benefit that due to their open nature, it is possible to** analyze and verify **open source peripherals and interfaces in far greater**

**depth than would be possible with closed-source offerings.** This is required as the communication protocol is often quite complex making it difficult to ensure that the IP is fully compliant with specifications or standards. This can also enable advances in the areas of security and safety-critical systems, e.g., where interference effects such as bus contention, or side-channels between applications, need to be closely monitored. This especially applies to architectures mixing different criticality levels on the same hardware. For instance, using the design techniques described above (highly focused on customizability), it should be possible to parametrize an interconnect IP block so that selected communications between specific execution environments are guaranteed to be performed in an interference-free manner.

### 5.7.4 Non-Functional Requirements

In addition to the design/improvement of the actual cores there is also the need to fulfill two key non-functional requirements: **As many of the European users of these cores come from industry (e.g., automotive, Industry 4.0, etc.) where** safety/security/reliability **and the associated certifications are often more important than the performance or power efficiency that would be focus of purely data-center oriented cores. Second, due to the domain-specific needs of these industries, there is a requirement to easily** customize the operation **of the core for applications, e.g., by adding specialized instructions or compute accelerators for operations in AI/ML, cryptography, signal and image processing, custom arithmetic, communications and storage, etc.** It is this need for flexibility with regard to safety/security/reliability and extensibility with custom operations that will be a key differentiator between European core design efforts and the more focused ones (e.g., for data centers, mobile communications, etc.) from existing players. Ideally, by employing state-of-the-art design methodologies leveraging, e.g., new hardware construction languages such as Chisel, Spinal, Bluespec, it should be possible to design the new cores as highly parametrizable base designs to/from which new features can easily be added/omitted as required for an industrial use-case. Note that these hardware construction languages are all open source and based on underlying languages such as Scala and Haskell, which historically have a strong European involvement. However, to fully unlock their productivity gains for industrial-strength use, verification support for these new languages needs to be significantly improved.

### 5.7.5 Software tools

On the software side, the existing baselines are much more mature than on the hardware side. The huge open source software ecosystem, grown around efforts such as GCC, LLVM, and Linux, has advanced the state-of-the-art considerably over the last 30 years. However, to fully exploit the open RISC-V ISA and the capabilities of the customizable processor cores described above, there are two areas where there is a need for key improvements. The first one is to support the customizability of the new cores also in the associated software. For instance, automatically integrating custom instructions and accelerators into the compilers and operating systems/middleware/hardware abstraction layers. **Without this kind of support, the capabilities of the newly designed hardware will remain inaccessible to most software developers**. The second area plays again to the traditional European strength in safety/security-critical systems. Again, to exploit safety/security-hardened cores the related software must also be extended, e.g., to be suitable for certification under standards such as DO254/DO178 or ISO 26262. This effort can also profit from new technologies, e.g., the combination of processor trace capabilities with dynamic verification techniques that, together, can monitor/enforce safety and security constraints in a running system.

### 5.7.6 Electronic Design Automation Tools

Electronic Design Automation tools are required to create new hardware. **Central to any hardware design targeting an integrated circuit are the ASIC front-end and back-end implementation tools.** At the front-end, these tools take a description of the function or structure of the electronic circuit, for digital logic circuits such as the RISC-V cores (most commonly in hardware design languages such as Verilog and VHDL), or the more modern hardware construction languages and translate it into more basic building blocks (e.g., logic gates and state elements) by logic synthesis. In the next step, these basic building blocks are mapped to the available hardware blocks in a given chip fabrication process (e.g., standard cells from a library). The geometrical arrangement of these cells is then determined by placing them on a 2-D plane (or in the future: a 3-D volume) and computing the best way to establish the required connections using a routing algorithm. Today, most of this software pipeline relies on proprietary tools developed and sold by a very small number of vendors, mostly from the US. **To strengthen European digital sovereignty in this area, it is crucial that open source solutions are created as an alternative.** Fortunately, initial open source efforts such as the OpenROAD project have already sprung up, sometimes utilizing European-developed tools for core functionality, such as the logic synthesis and mapping steps. These existing efforts could be used to bootstrap advances that would increase robustness of the tools, improve the quality of results by the integration of newer algorithms (e.g., AI/ML-based), and allow fundamental innovation on better tool support for the topics of specific interest to the European microelectronics industry, such as safety/security/reliability. **Additionally, the** practical usability **of such an open source ASIC implementation tool flow should be strengthened, e.g., by ensuring its full interoperability with the process technologies supported at chip manufacturing facilities located in Europe.**

### 5.7.7 Supplemental System-Level Tools

With modern systems-on-chip becoming ever more complex, there is a growing need for additional steps in the EDA tools workflow supplementing the ASIC implementation flow. These include, e.g., the ability to more abstractly describe the functions of a digital circuit at the purely behavioral level, and then employ a process called high-level synthesis to compile this behavioral description down to the traditional descriptions discussed above. Open source tools for high-level synthesis already exist, however, the approach has proven useful so far mainly for very specific use-cases, such as quickly creating specialized accelerators, but not so much for creating high-quality general-purpose processor cores. Thus, a greater focus should be applied to tools enabling more immediate practical benefits to a larger group of users. Two examples include architecture exploration/optimization as well as automated system-on-chip composition.

**Architecture Exploration – Architecture exploration takes place prior to chip design to determine the best hardware architecture for achieving the design goals**. It employs a number of techniques, such as virtual platforms and software frameworks to model application workloads, to quickly iterate on different hardware architecture choices before committing to a single one which is taken forward to the laborious and costly ASIC implementation and fabrication process. It is also required in the case of a parametrizable design to determine which parameters are best suited for the final design. Despite the importance of this step, as the architectural choices made for an actual chip implementation can have far-reaching consequences for the success of the entire endeavor, only very limited tool support, mainly from a small number of vendors of proprietary software, is currently available. Thus, it would be highly beneficial if a flexible tool framework for architecture exploration could be created in an open source fashion. The open source nature of the framework would then allow innovators to focus on key areas, e.g., the use of AI/ML techniques to optimize entire systems and help the designer to define the best system architecture, as well as alleviate the need to expend R&D effort on laborious engineering tasks, such as visualization, simulator interfaces, etc.

**Automated System-on-Chip Composition** – There is also a need for support for automated system-on-chip composition. Modern SoCs are, to a large degree, created by composing building blocks (also called IP blocks), where a block may be, e.g., a complete processor core, cache level, or memory controller. Although standards exist for the machine-readable description of individual blocks (e.g., IP-XACT), composing them into an entire system-on-chip encompassing the required hardware/software interfaces, is still mainly performed manually, at best aided by GUIs or low-level generic scripting languages such as Tcl. There is a need for more abstract descriptions of complete SoCs, above the view offered by formats such as IP-XACT. **A new class of EDA tool is needed that can interpret these more abstract descriptions to allow complete system-on-chips to be composed, including optimized design choices, e.g., for interconnect and bus protocol optimization.** Such an SoC composition tool could also be integrated with the architecture exploration flow discussed in the prior paragraph as one step of an automated design-space exploration mechanism. As before, having the SoC composition tool available as open source would enable both more innovation in the operation of the tool itself, but also allow its easier integration with other automation tools, such as architecture exploration tools. In this way, innovators in the hardware space could concentrate on their specific unique contributions (e.g., new AI/ML or cryptography accelerators), and expend less valuable engineering resources (especially for startups) on non-innovative, but complex engineering tasks such as manual SoC composition.

### 5.7.8 Verification

An overarching topic across all of the different hardware design and implementation steps already discussed is verification. This occurs at all levels, e.g., from architecture specifications, such as the formulation of custom instructions of a processor, down to the actual physical-level silicon design. **One of the crucial aspects for the success of design IPs is the completeness of specifications, validation of the architecture and verification quality of the resulting IP.** Efficient design exploration tools and simulators allow to identify and specify the best architecture parameters for an IP (some tools even allow to generate VHDL or Verilog code for particular specific domains). The earliest that bugs or deviations from the specifications are identified, the less expensive they are to correct. State of the art industrial strength functional verification is required for ASIC tape-outs, even more so in safety critical applications mandated by standards like ISO 26262. Such industrial strength functional verification cannot be achieved by constrained random simulation alone but requires formal verification and emulation in the tool portfolio. A tool agnostic verification flow spanning these three elements is the basis for achieving industrial strength verification. This flow should be compliant with safety standards to allow using the results for safety certification. Such a complete verification includes a safety certification-ready verification plan, shareable/reusable requirements and artifacts, requirements tracing through to the verification plan and the tests verifying them.

Verification of the embedded software stacks using virtual platforms and hybrid platforms (mixing high-level models, e.g., SystemC and RTL) in the system context, if it comes after RTL design & verification is too late. **Tools enabling this task to be performed much earlier in the design cycle are thus essential to cut design & verification time and cost**.

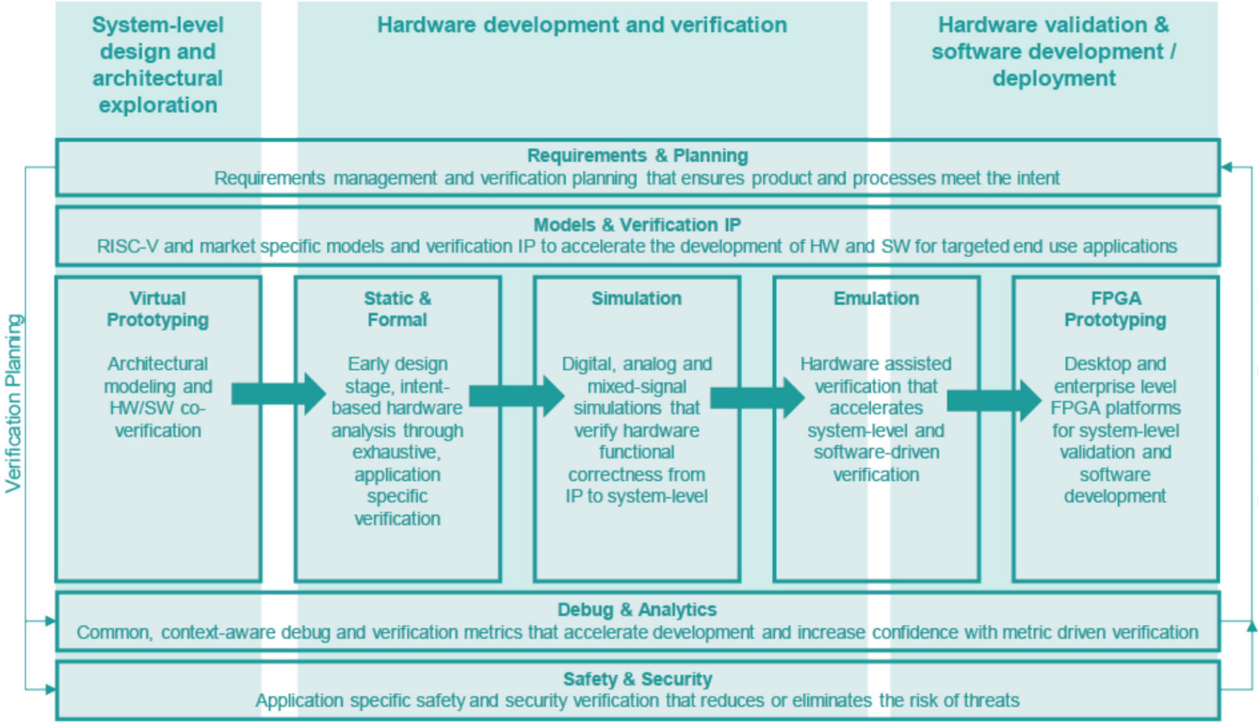


*Figure 5.8 - V Model at System and Hardware Level*

State of the art IP design also uses tools for linting or design rule check (DRC), clock domain crossing (CDC), reset domain crossing (RDC), X propagation and formal auto-checks. Additional tools may also be mandated for achieving compliance with downstream flows. **In order to achieve highest RTL verification quality in a manageable amount of time, automation is key.** The verification flow needs to be as automated as possible, from continuous integration (CI) to, for example, formal verification apps targeted at certain aspects of the design IP. **In the context of design IPs around RISC-V cores and other subsystem components, an automated formal verification is needed for those parts that are complex and hard to verify.** At the core, there is a need to verify a parameterized RISC-V core with custom instructions against its expected ISA. This requires checks that all instructions and registers behave according to the ISA and no other instructions or registers exist that could offer backdoors for malicious attackers. Beyond the mere core, other areas of interest for an automated formal app are caches, interconnect, prefetch, or consistency for memory systems with several hardware threads or cores.

In addition to functional verification, security topics are starting to play a more and more crucial role. Unexpected discovery of attacks like Spectre or Meltdown on state-of-the-art CPUs highlighted a verification gap that calls for a formal approach that can actually find all kinds of such attacks instead of patching designs after the fact whenever a new attack is found[50]. Design IPs have additional security requirements that must be part of the verification flow, including traceability. Verification goals may also apply for security, resulting in a set of security checks applicable to an IP. This is again a domain where automated formal apps can offer great benefits. In terms of standards, the field of security is less mature than safety. **Nevertheless, the verification flow should also allow integration with standards like Accellera's Security Annotation for Electronic Design Integration (SA-EDI) and offer the corresponding automation.**

On top of the RTL, there is also system software that has to interact correctly with the design in order for the system to work properly with respect to safety and security. **Here, there is a need to focus on boot code and firmware.** Both are critical components with large security impact, and both are very close to the hardware. Again, formal based apps could be used to investigate these software parts in conjunction with the hardware. Formal apps can identify unexpected sources that can influence the boot process or spot parts of firmware code violating the programming rules.

## 5.8 Identified Gaps Summary

### Conception Stage

- There is a need for tools allowing fast simulation and exploration of the design space configuration, and automated system-on-chip composition. Commercial tools exist already as well as open source ones, but they can be improved using new approaches such as ML/AI.
- The community would benefit from a repository of open source models and new technologies that can be used in both open source and commercial tools. New technologies, for example using Artificial Intelligence, can be specifically developed to increase the productivity of architects and designers.
- Simulation models for architecture exploration and optimization should be made available.
- Tools to support early verification of embedded software are needed.
- An open source repository of peripheral models, interconnect, etc., with different abstraction levels is needed.

### Automated Composition/Optimization Tools

- Tools are needed to support complex heterogeneous SoCs composed of a mix of RISC-V cores, accelerators and arbitrary design IP to increase productivity in SoC design.
- Integration with existing frameworks and development of extended capabilities including the generation of HW hardware/software interfaces and low-level FW is required.

### Functional Verification

- There is a need for an automated industry strength verification, including formal apps, of caches, interconnect, and memory consistency in multi core systems.
- An automated tool-agnostic verification flow integrating simulation-based, formal and emulation-based verification compliant with safety standards is essential to lower the adoption barrier of open source design IP and productivity of SoC design.
- Point technologies need to be integrated into automated flows to hide complexity of verification away from users.
- An open source verification database including artifacts along lifecycle of design and verification of IPs for AI/ML-enabled EDA tool R&D is required.
- To ensure system software in sync with the RTL, additional automated formal verification apps for boot code and firmware together with the RTL are crucial.
- Design IP code quality is crucial on top of functional correctness. Integration of Lint/DRC, CDC, RDC, formal auto-checks, compliance with downstream flows, CI/CD flows into open source design flow management frameworks and point technologies for individual analysis steps is needed.

### Functional Safety and Security

- Reference flows should be defined that describe and demonstrate the state-of-the-art methodologies in order to deliver products that maximize confidence and optimize development efficiency.
- Automated tools are needed to provide quantifiable verification and validation of safety and security allowing developers to focus on their core differentiation technologies.
- Tools, methodologies and associated work products should be developed to that they enable sharing of information throughout the supply chain to ensure the end system is free from safety and security vulnerabilities.

### Customization Tools

- Automated application-driven identification and implementation of custom instructions and accelerators is needed in order to customize generic RISC-V design IPs to specific application segments.

### Interoperability and Reuse

- There is a need for increased modularity and re-use of subsystems between building blocks. For the design of IP blocks, a gap is that the RISC-V foundation mainly focuses on the ISA interface specification and it has been argued there is relatively little / limited re-use between different components for RISC-V systems.[51]

**Hardware/Software Co-certification**

- Tool support is needed for co-certification of combined hardware/software systems.

## 5.9 Roadmap

In this section the important elements of the proposed Roadmap for European Sovereignty in Open Source HW & SW and RISC-V Technologies are given. This is based on the key messages derived from the previous discussions of hardware technology, supporting software and cross cutting requirement needs. These are summarized below:

- Domain-Specific Architectures/Accelerators are one of the major opportunities for advances in computer architecture and have great innovation potential for academia and industry.
- Accelerators need to be integrated with a general-purpose computing environment, in hardware at the chip- and system-levels, as well as into software stacks and programming tools to fully exploit their potential.
- Hardware integration requires significant engineering effort (interface IP blocks, high-performance printed circuit board design) that impedes innovation on accelerators by smaller players, such as the academia and SMEs, who often initiate open source efforts.
- The innovation potential could be unlocked by funding R&D into open standardized interfaces, and their corresponding hardware realizations, as well as scalable & reusable technology templates at both the system-on-chip and computing system-levels. These could then be used by innovators to turn their accelerator architecture ideas into practically usable artefacts (open source releases, products and services offered around the open source releases).
- The challenges of providing software support for innovative accelerators should be addressed. This requires R&D funding for new or improved general purpose accelerator integration software stacks, targeting one or [more] models of computation. Better developer support is also needed for adding new accelerators to established domain specific software frameworks, e.g., machine learning or image processing.
- The existing design sharing and commercialization mechanisms that exist within EUROPRACTICE should be leveraged to promote exchange of developed IP blocks between collaborators and commercialization of IP developed in whole or part within academia. (Note this is already done by the particle physics community to collaborate and contribute designs to CERN).
- Funding should be provided to commission the development/licensing of the required artefacts (e.g., for IP blocks, interfaces and templates) from academia or industry in an open source manner. These should then be made available to users in a "one stop shopping" approach similar to the existing EUROPRACTICE Foundry Access service. Support should also be provided for training & supporting users of the artefacts for a multi-year time period.
- For general-purpose and domain-specific accelerator software stacks a more decentralized approach is needed. Funding should be offered to academia and industry to create/provide the required artefacts in an open source manner, which could then be disseminated using established channels (e.g., github, local repositories). These artefacts may encompass documentation, training materials, and sample back-end implementations for established domain-specific accelerator frameworks. Training and support are also required for a multi-year time period.
- Creating an open source hardware/software ecosystem for innovation in accelerators and domain-specific architectures will require funding schemes which ensure that, after an initial broader experimentation phase, future funds are directed at those technologies that prove most beneficial in practice, e.g., measured in actual user uptake.

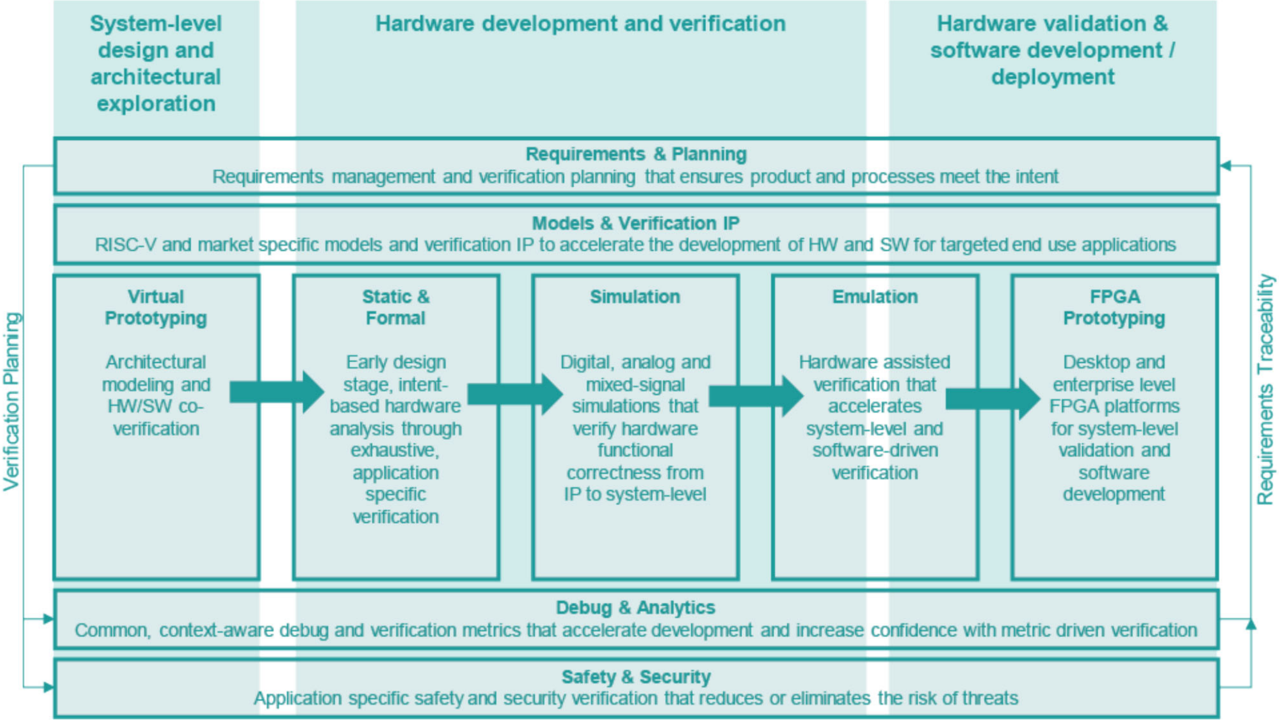
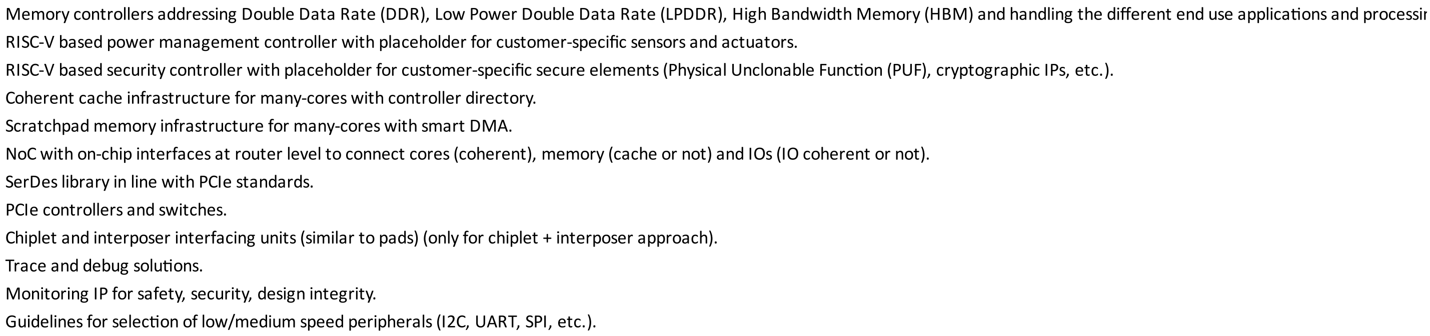


*Figure 5.9 - Example Process for RISC-V*

In order to meet the needs of the future it is important to sketch out a proposed process that is required to create a working processor. This is done in **Figure 5.9** highlighting the necessary steps and activities in terms of design, fabrication and testing considering the hardware and software aspects. At the application level non-functional properties such as WCET for safety and security need to be addressed. The process shown has been derived for RISC-V, but it could be updated at a later stage for other IP's.

Going beyond this there is a need to develop other IPs. A non-exhaustive list of other IPs identified by the Working Group that will be required in order to give a good coverage of open source cores for making SoCs is given in **Figure 5.9**. These could be used for monolithic SoC integration and for chiplet integration.


Memory controllers addressing Double Data Rate (DDR), Low Power Double Data Rate (LPDDR), High Bandwidth Memory (HBM) and handling the different end use applications and processi
RISC-V based power management controller with placeholder for customer-specific sensors and actuators.
RISC-V based security controller with placeholder for customer-specific secure elements (Physical Unclonable Function (PUF), cryptographic IPs, etc.).
Coherent cache infrastructure for many-cores with controller directory.
Scratchpad memory infrastructure for many-cores with smart DMA.
NoC with on-chip interfaces at router level to connect cores (coherent), memory (cache or not) and IOs (IO coherent or not).
SerDes library in line with PCIe standards.
PCIe controllers and switches.
Chiplet and interposer interfacing units (similar to pads) (only for chiplet + interposer approach).
Trace and debug solutions.
Monitoring IP for safety, security, design integrity.
Guidelines for selection of low/medium speed peripherals (I2C, UART, SPI, etc.).

List of IPs Required

All of these IPs have to be delivered with a verification suite and will need to be maintained constantly to keep up with errata from the field and to incorporate newer requirements.

The availability of standardized metrics is crucial. The application scenario may demand certain boundaries on power, performance, or area of the IP, so searches across different repositories with standardized metrics on these indicators are needed to successfully use these IPs. Building on standardized metrics for all these crucial features, end users will be able to pick the most suited IP for their application and get an idea on needed additional efforts in terms of certifications.

**Recommendation** - Innovation in open source hardware would profit immensely if lower-level interface blocks could be made available in a low-cost manner, at least for selected chip fabrication processes supported by facilitators such as EUROPRACTICE to allow low-barrier prototyping (e.g., the miniASIC and MPW programs). The availability of automated SoC composition is also desirable to quickly transform innovation into Proof of Concept and to bring productivity gains and shorter time-to-market for industrial projects.

IPs including all artefacts (e.g., source code, documentation, verification suites) should be made available ensuring integrity, authenticity and traceability using certificate-based technologies. Traceability along the supply chain of R&D processes is a foundation for later traceability of supply chains for components in manufacturing and deployment/operation.

Finally, an ecosystem of chiplet + interposers can be enabled via open source development. The key “missing link” here is Die-to-Die (D2D) communication. This is needed to create a chiplet-based design ecosystem. **Development of Open source D2D communication could become one of the most important developments in coming years enabling wide-scale use of chiplets with potential to become a “de-facto” standard.**

## 5.9 Prioritization of Open Source Ecosystem Needs

In this section the short-, mid- and long-term needs for different items on the roadmap are given. They are based on a detailed analysis of gaps and future needs identified. For some critical aspects, proof-of-concept down to physical implementation or layout is needed. For other aspects, a proof-of-concept at synthesis level (netlist) would be sufficient, e.g., for mapping onto a FPGA.

### 5.9.1 Repository of RISC-V based Processor Platforms

**Short-term needs (2-5 years):**

- High-end: Highly customizable Multi-core Out of Order 64-bit open source infrastructure with the associated memory hierarchies (caches&coherency, off-chip) and communication (fast cores to cores, cores to accelerators, cores/accelerators to system). This should be suitable for various instances of processor IP.
- Highly customizable high-end domain-specific cores for high-performance embedded system and/or general-purpose application (link with EuroHPC-call on HPC processors)
- Mid-end: Highly customizable mid-end Open Cores (32-bit) with support for advanced 32-bit ISA and system extensions such as security, scalable vector (Zve), tiny FP (Zfinx) or support for specific arithmetics, DSP, bit-manipulation, scalable and customizable interrupt management such as AIA/ACLINT, e.g., for low latency in critical workloads (TinyML, near-sensor processing, secure IoT stacks).

**Mid-term needs (5-10 years):**

- High-end: Moving coprocessor functions inside the core by adding new instructions (variable precision, customizable vector, tensor, etc.) with all the necessary software environment support (compiler, libraries, automated HW/SW co-design flows) and validation/verification environment.
- Mid-end: Parametrizable open source soft RISC-V cores, and a range of associated interoperable IPs (e.g., interconnect), in relationship with open source EDA flow (this can lead to a tool generating RTL code according to high-level specifications).

### 5.9.2 Domain-Specific Processor Features

A verified open source hardware for high-assurance and reliable systems via a whitebox approach.

**Short-term needs (2-5 years):**

- Provide public artifacts for safety and security by architecture at an initial assurance level.
- Provide public artifacts for safety and security by architecture at a high assurance level, e.g., including formal models.

**Mid-term needs (5-10 years):**

- Demonstrate how the approach can be carried over to more complex compositional architectures (e.g., multipipeline CPU, a full advanced embedded board or even general-purpose desktop computer mainboard).

### 5.9.3 Repository of Open Source HW Peripheral Blocks

Create in open source all the generic re-usable elements required to create a complete SoC. All the IPs should be interoperable and composable to build a complete SoC.

**Short-term needs (2-5 years):**

- High-speed open source memory infrastructure (DDR3+, SDRAM, HBM memories).
- Open source high-performance interfacing: PCIe Gen3+, Ethernet 1+G, and USB 2.0/USB 3++ interfaces and controllers, including process-specific analog PHY (SerDes) components.
- Open source test, trace, debug IP blocks (e.g., JTAG, etc.).
- All the ancillary functions (power management, SPI, I2C, etc.) as open source blocks.
- Support for heterogeneous many-core open source SoCs (e.g., scalable coherent caches, scratchpad memories, w/smart DMA, and a coherency-capable network-on-chip).
- Inter-chip communication links with 2+ Gb/s per pin.
- Template for ASIC SoC and PCB designs, the latter for PCIe-attached accelerators, similar to existing FPGA-based evaluation/prototyping boards, but for plugging in user-provided ASICs.
- Easy and affordable “one stop” access to and support for the IP and technologies developed above.
- Open source repository of peripheral models with different levels of accuracy with their verification artefacts.

**Mid-term needs (5-10 years):**

- Updates of base building blocks to track emerging standards, possibly also adding support for improvement of 2.5D/3D technologies such as High Bandwidth Memory.
- Support open source infrastructure for easy building of SoC from various sources of IPs, in an as automated way as possible.

**Long-term needs (beyond 10 years):**

- Updates of base building blocks to track emerging standards and technologies.

### 5.9.4 Interconnect for Real-Time and Mixed Criticality

Verified open source real-time interconnects between logical units such as cores, memory and other peripherals, regardless of whether they are on the same or different chiplet.

**Short-term needs (2-5 years):**

- Verified open source real-time interconnect proof-of-concept.
- Verified ready-to-use Design IP blocks for safety-critical interconnects.
- Demonstrate use of interconnects by integrating with existing RISC-V open hardware CPUs, memory controllers, and other relevant resources.
- Verification environment for targeting real-time interconnect, including formal proof of worst-case execution time.

**Mid-term needs (5-10 years):**

- Verified open source real-time interconnects, including mixed criticality, reliability and security, including industrial-grade verification artefacts.
- Verified ready-to-use Design IP blocks for real-time interconnect for mixed criticality. This interconnect shall give system integrators full control over allocation of available bandwidth to different subjects.
- Demonstrate use of interconnects by integrating with existing RISC-V open hardware CPUs, memory controllers, and other relevant resources.
- Verification environment for target for real-time interconnect, including formal proof of worst-case execution time, including mixed criticality cases.

### 5.9.5 Interconnect for System Integration

IP can be integrated in a monolithic SoC or can be part of chiplets that are physically interconnected through an interposer, which can also provide services (e.g., routing, power supply). A European ecosystem should emerge from this approach, as it is seen as a major evolution in the chip industry by TSMC for example, and now used by AMD, Intel, Nvidia, etc. Industrials are already working on setting up specifications for “Building an open ecosystem of chiplets for on-package innovations”, like ODSA with its “bunch of wires” and the Universal Chiplet Interconnect Express consortium (The promoter members of UCIe are AMD, Arm, Advanced Semiconductor Engineering, Inc. (ASE), Google Cloud, Intel, Meta, Microsoft, Qualcomm, Samsung, and Taiwan Semiconductor Manufacturing Company)[52].

**Short-term needs (2-5 years):**

- Verified open source interconnect between chiplets and Interposer.
- Verified open source interconnect for active interposers with parametrization bandwidth, latency, energy and performances.
- All the tools and views to easily use various chiplets and design affordable interposers.

- Tools to help the partitioning of complex designs (Design Space Exploration including chiplet/interposers and 3D technologies).

### 5.9.6 Domain-Specific Accelerators

Development of flexible hardware/software frameworks for accelerator-intensive System-on-Chips.

**Short-term needs (2-5 years):**

- Create open source template system-on-chip designs including processors, on-chip/off-chip memory and peripheral interfaces/controllers enabling the easy insertion of domain-specific accelerators.
- Create open source software-stacks (e.g., middleware, drivers, advanced OS integration, programming tools) for interacting with the accelerators from software.
- Create reusable and configurable state-of-the-art open source domain-specific accelerators for common operations, e.g., in the areas of security (crypto), ML/AI, communications, information/signal processing.

**Mid-term needs (5-10 years):**

- Update SoC templates, software stacks and reusable accelerators to track the state-of-the-art, possibly moving to full support for 2.5D/3D technologies such as multi-process heterogeneous stacks.

**Long-term needs (beyond 10 years):**

- Update SoC templates, software stacks and reusable accelerators to track the state-of-the-art.
- Interoperability with unconventional acceleration hardware solutions, e.g., neuromorphic computing and quantum computing.

### 5.9.7 Software

A successful processor requires industry-grade software and tools e.g., compilers/debuggers.

**Short-term needs (2-5 years):**

- Euro Centralized SW Open Source Consortium.
- Development of and or extension of existing compilers and core libraries with emphasis on:
  - Code density
  - Performance
  - Memory Hierarchy
- Safety-certified open source RTOS and/or hypervisor/separation kernel (e.g., Zephyr, Tock or other hypervisors/separation kernels).
- Open source AI codesign tools, HW/SW optimized, in order to tweak the application on the RISC-V platform.

**Mid-term needs (5-10 years):**

- Open source ISA Extension design tooling/management (Simulate/Iterate/Create).
- Open source Core Validation Test SW.
- Open source Safety/Security Cert Tooling.
- ISA migration tools.

**Long-term needs (beyond 10 years):**

- Unconventional acceleration software solutions, e.g., neuromorphic computing.

### 5.9.8 Methodology and EDA Tools

Development of open source SoC development tools and/or RISC-V specific enhancements of leading-edge closed source tools, including interoperability of open and closed source tools.

**Short-term needs (2-5 years):**

- Tools for design space and architecture exploration and fast simulation of RISC-V based SoC architectures to optimize processor core configuration, memory hierarchy and HW-SW-partitioning for multiple criteria like performance, latency, power and area (e.g., for integration with model-based systems engineering frameworks), tools for automated system-on-chip composition.
- Tools for automated exploration and implementation of RISC-V application specific customization like custom instructions and tightly coupled accelerators.
- Investment in developing open source interoperability standards to interface between different parts of the ASIC development toolchain (both open and closed), encouraging proprietary vendors to adopt the standard.
- Point investment in open source replacements for specific parts of the flow (synthesis, linting, formatting, simulation, DRC, etc.). Focus on integration and functionality, e.g., in the form of stable and easy-to-use reference flows, but less on state-of-the-art algorithms.
- Open source tools for new, more software-driven verification methodologies, possibly based on next-generation hardware description languages, tested on open source IP.
- Investment into open source Continuous Integration infrastructure for open source IPs/cores, extracting metrics, providing feedback to change requests.
- Open source infrastructure with a well-defined semantic layer enabling to use open source IPs and their associated design flows to train AI/ML models enabling faster, higher quality design and verification.
- Investment studies on using selected open source tools in the flow to realize and evaluate practically relevant sample designs, where innovation can be produced using older, lower-complexity processes.
- Automation support for the composition of complex SoCs (heterogeneous mix of cores and accelerators), including generation of hardware/software interfaces and integration/abstraction with ASIC development toolchain (both open/closed).
- Extending tools and tool flows for full compliance with domain specific standards and regulations like functional safety (e.g., ISO26262, IEC61508, EN50129).

**Mid-term needs (5-10 years):**

- Enhance open source verification tools towards the state of the art, adding more automation, point tools, interactive debug capabilities, and integration with requirements tracing.
- Extend open source tool flows to also cover non-functional aspects, allowing certifiably secure and/or safe designs.
- Update initial open source tools with more advanced algorithms for better Quality of Result and support for more advanced processes, focusing on those with fabrication capabilities located in Europe.
- Enhancing tools for the earlier phases of the EDA pipeline for high-end complex designs
- Enhancing sections of the complete flow for full automation without human expert intervention in the loop as a "push-button-flow".
- Extend open source tool flow to cover a larger part of the complete EDA pipeline. Focus on achieving a front-to-back open source tool flow capable of handling less complex designs on commodity processes.

**Long-term needs (beyond 10 years):**

- Complete front-to-back open source EDA tool flow capable of realizing even more complex industrial and academic designs with acceptable results, targeting current fabrication processes.

### 5.9.9 Domain-Specific Demonstrators

It is of key importance that the RISC-V processor families and related Open Source hardware, software and EDA tools are applied in challenging demonstrators.

**Short-term needs (2-5 years):**

- Domain specific adaptation of RISC-V based processor solutions for safe, secure and reliable computationally intensive applications, e.g., for automotive, industrial automation, medical applications, etc. Such solutions are expected to address appropriate functional and non-functional, high-performance requirements aiming at realizations on advanced technology, e.g., 16 nm Finfet or below.

**Mid-term needs (5-10 years):**

- Domain specific adaptation of RISC-V based processor solutions for safe, secure and reliable computationally intensive applications, e.g., for automotive, industrial automation, medical applications, etc. Such solutions are expected to address appropriate functional and non-functional, high-performance requirements aiming at realizations on advanced technology, e.g., 7 nm or below.

**Long-term needs (beyond 10 years):**

- Domain specific adaptation of RISC-V based processor solutions for safe, secure and reliable computationally intensive applications, e.g., for automotive, industrial automation, medical applications, etc. Such solutions are expected to address appropriate functional and non-functional, high-performance requirements aiming at realizations on advanced technology, e.g., 5 nm or below.

## 5.10 Recommendations

In the following sections the specific recommendations and needs are broken down.

### 5.10.1 Specific Recommendations

1. Development of Open Source Hardware
    - Fund the creation of open source or easily accessible low-cost/no-cost, fundamental building blocks (e.g., chip IPs (including processors – RISC V, accelerators, peripherals, data management IPs, debug, etc.), templates for SoCs/chiplets/interposers/PCBs, software frameworks for heterogeneous SoC operation) that reduce the high engineering effort required to practically realize a new hardware design and allow creators from academia and SMEs to focus on their actual innovation.
    - The building blocks should have all the views, software supports (drivers), test and documentation so that they can be easily combined (interoperable) and used (support).
    - Make these building-blocks available for free, or with only minimum financial and administrative overheads, from "one stop shops", e.g., by integrating them into service portfolios of organizations such as OpenHW Group or EUROPRACTICE.
    - Ensure that these building blocks are distributed under an open source license that is adapted to hardware artefacts allowing exploitation by all stakeholders (semiconductor industry, OEMs, SMEs, academy/research, etc.).
2. Community Support
    - Provide a one stop shop model with long-term activities and overall support (e.g., advice for licensing, productization, etc.) for SMEs and start-ups.
    - Encourage the use of standard specifications and standardization efforts when gaps are identified.
3. Development of a Chiplets + Interposer Ecosystem in Europe
    - Encourage an ecosystem of chiplet + interposers via open source development. Die-to-Die (D2D) communication is the "missing link" to leverage the chiplet-based design ecosystem, and its development in open source would enable a wide adoption and could result in a "de-facto" standard.
    - A SoC infrastructure template should be developed that includes communication between IPs, interfaces with memories and the external world, supported by tools that allow the easy integration of new chiplets. A validation suite should be developed allowing the rapid design of a complete SoC from various Open source (or not) IPs, together with a set of "best practices" allowing SMEs, start-ups and industries to "make the step" towards the chiplet+interposer approach.
4. Tools, Validation, Methods and Demonstration
    - The development of industrial strength open source design IPs would benefit greatly from proprietary EDA tools. The licensing of the EDA tools should be made available under appropriate conditions, not at the prohibitive prices paid by commercial end-users, and with permissive licensing of the designed IPs.
    - Funding should be provided to create an open source EDA ecosystem. The effort should be guided by the steps (e.g., logic synthesis, placement, routing) of a typical ASIC EDA flow, and proceed by incrementally replacing one or more closed-source steps with open source tools. To enable the required interoperability between open and closed source tools (similar to the FPGA/ASIC space) open interfaces (e.g., APIs, data formats) between the steps are required to allow open source in and open source out.
    - The development of re-usable verification infrastructure (e.g., IP blocks accompanied by test frameworks) should be supported.

    - Industrial demonstrators using Open Source IPs (RISC-V hardware, accelerators and SoC IPs) should be supported to validate the complete chain. If these industrial demonstrators include Printed Circuit Boards, the designs of the PCBs should also be licensed under an appropriate open hardware license. Similarly, software developed for these demonstrators and any documentation should be made available under appropriate software and documentation licenses.
5. Special focus on European Need in Terms of Safety/Security Solutions
    - Research projects creating methods to develop safety- and security-critical open source hardware should be supported. Key aspects are collaboration, documentation, verification and certification in open source communities.
    - A re-usable verification infrastructure (e.g., IP blocks accompanied by test frameworks) for safety/security should be established.
    - Industrial demonstrators using RISC-V hardware, especially in the safety/security area, should be supported to promote hardware/software co-certification for safety and security.

### 5.10.2 Global Longer-Term Recommendations

In addition to short term goals there are also longer-term goals that need to be supported to create a European critical mass and ecosystem in open source. At the same time there is a need to educate the public and industry on the economic and sovereignty benefits of open source approaches.

1. Non-profit Organisation for Coordinating European Open Source HW IP providers
    - A neutral non-profit organisation could be set up for coordinating European Open Source HW IP providers. The aim of this organisation would be to develop a compliance standard that certifies interoperability and industrial readiness of Open Source HW solutions. The organisation would also orchestrate market specific requirements (e.g., safety and security features for the automotive or industrial automation domains). Although the organisation could be funded by the EU, it may have to be open also for companies outside the EU to avoid the emergence of closed Open Source HW IP clusters around the world.
    - Set-up an IP exchange system between academia and industry (integrated in a one stop shop model). This will encourage new business models for EDA vendors, design & IP houses and IC foundries.
    - Ensure that services that allow the realization of test chips or small production runs will continue to support prototyping and small series manufacturing in Europe. This includes providing all the libraries (PDKs) and support for transforming open sources IPs into silicon chips.
2. Educational measures
    - It is very important to communicate the advantages and reasons for open source hardware to the public and industry in an effective way. This requires development of appropriate pedagogical material and communication campaigns. In particular, it is necessary to explain how open source hardware can have a very positive impact on the economy of the EU, and why it is strategically important in guaranteeing digital sovereignty.
    - To change mind sets the EC should provide incentives to public institutions in the EU, including e.g., universities and research laboratories, so that workers in those institutions contribute more to open hardware developments, with that work appropriately recognized in their career development. Open Hardware should become the default paradigm for all hardware development in publicly financed institutions.
3. Summary Table: Key Topics and Timescales

A roadmap needs concrete actions and timescales in order to become operational. The Working Group has thus developed a detailed list of key topics which need addressing in the short term (2-5 years), medium term (5-10 years) and long term (>10 years). These can be used as input into strategic actions to address the core aspects and needs highlighted in this report. Notably there will also be a need for political or bilateral actions between specific stakeholders to take the roadmap forward.

| **Topics** | **Overall Topics** | **Short Term (2-5 years)** | **Mid Term (5-10 years)** | **Long Term (> 10 years)** | |
|---|---|---|---|---|---|
| **Open HW Base Building Blocks** | Repository for open source HW base building blocks. | Create in open source all the elements required to create a complete SoC:<br>(1) Support the creation of:<br>• High-speed open source memory infrastructure (DDR3+, SDRAM, HBM memories);<br>• Open source High performance interfacing: PCIe Gen3+, Ethernet 1+G, and USB 2.0+ interfaces and controllers, including process-specific analog PHY (SerDes) components;<br>• Open source Test, trace, debug IP blocks (e.g., JTAG, etc.);<br>• All the ancillary functions (power management, SPI, I2C, etc.) as open source blocks.<br>• Remark: All the IPs should be interoperable and composable to build a complete SoC.<br>(2) Create support for heterogeneous many-core open source SoCs (e.g., scalable coherent caches, scratchpad memories, w/ smart DMA, and a coherency-capable network-on-chip).<br>(3) Create open source Inter-chip communication links with 2+ Gb/s per pin.<br>(4) Create open source template ASIC SoC and PCB designs, the latter for PCIe-attached accelerators, similar to existing FPGA-based evaluation/prototyping boards, but for plugging-in user-provided ASICs.<br>(5) Establish easy and affordable “one stop” access to and support for the technologies developed in (1-5). | Support updates of base building blocks to track emerging standards, possibly also adding support for 2.5D/3D technologies such as HBM.<br>Supporting open source infrastructure for easy building of SoC from various sources of IPs, as automated as possible. | Support updates of base building blocks to track emerging standards and technologies. | |
| **Processors** | Verified open source hardware for high-assurance systems by whitebox approach. | Provide public artifacts for safety and security by architecture at low assurance level.<br>Provide public artifacts for safety and security by architecture at high assurance level, e.g., including formal models. | Demonstrate how the approach can be carried over to more complex compositional architectures (e.g., multipipeline CPU, a full advanced embedded board or even general purpose desktop computer mainboard). | Based on feedback of previous work. | |

| Topics | Overall Topics | Short Term (2-5 years) | Mid Term (5-10 years) | Long m (> 10 years) | |
|---|---|---|---|---|---|
| | High-end application cores for High-performance embedded system and/or general-purpose application (link with EuroHPC-call on HPC processors). | Develop Multi-core Out of Order 64-bit open source infrastructure with all the near memory communication support (caches) and communication (fast cores to cores and core to accelerators). This should be suitable for various instances of processor IP. | Move coprocessor functions inside the core by adding new instructions (variable precision, vector, tensor, etc.) with full software environment support (compiler, libraries) and validation/verification environment. | | |
| | Open Cores (32-bit) with support for advanced 32-bit ISA and system extensions such as security, vector (Zve), tiny FP (Zfinx), DSP, bit-manipulation, fast interrupts (CLIC) for critical workloads (TinyML, near-sensor processing, secure IoT stacks). | | Create parametrizable open source soft RISC-V cores and a range of associated interoperable IPs (e.g. interconnect), supported by open source EDA flow. | | |
| **Domain-Specific Accelerators** | Flexible Hardware/Software Frameworks for Accelerator-intensive System-on-Chips. | (1) Create open source template system-on-chip designs including processors, on-chip/off-chip memory and peripheral interfaces/controllers enabling the easy insertion of domain-specific accelerators.<br>(2) Create open source software-stacks (e.g., middleware, drivers, advanced OS integration, programming tools) for interacting with the accelerators from software.<br>(3) Create reusable and configurable state-of-the-art open source domain-specific accelerators for common operations, e.g., in the areas of security (crypto), Machine Learning/AI, communications, information processing, etc. | Update SoC templates, software-stacks and reusable accelerators to track the state-of-the-art, possibly moving to full support for 2.5D/3D technologies such as multi-process heterogeneous stacks). | Update SoC templates, software-stacks and reusable accelerators to track the state-of-the-art. | |

| Topics | Overall Topics | Short Term (2-5 years) | Mid Term (5-10 years) | Long Term (> 10 years) | |
|---|---|---|---|---|---|
| **Interconnect for al-time and mixed criticality** | Verified open source interconnects. | Create a verified open source real-time interconnect PoC<br>Develop verified ready-to-use Design IP blocks for safety-critical interconnects.<br>Demonstrate use of interconnects by integrating with existing RISC-V open hardware CPUs, memory controllers, and other relevant resources.<br>Provide verification environment for real-time interconnect, including formal proof of worst-case execution time. | Create verified open source real-time interconnects, including mixed-criticality and security.<br>Develop verified ready-to-use Design IP blocks for real-time interconnect for mixed criticality. This interconnect shall give system integrators full control over allocation of available bandwidth to different subjects.<br>Demonstrate use of interconnects by integrating with existing RISC-V open hardware CPUs, memory controllers, and other relevant resources.<br>Provide verification environment for target for real-time interconnect, including formal proof of worst-case execution time, including mixed criticality cases. | Based on feedback of previous work. | |
| **Software** | Organize: Open Source SW.<br>Develop: Software Tools.<br>Execute: Real Time Operating Systems. | Establish Euro Centralized SW Open Source Consortium.<br>Support compiler projects<br>• Code density<br>• Performance<br>• Memory Hierarchy<br>Create Safety Certified Open Source RTOS (e.g., Zephyr). | Create Open source ISA Extension design tooling/management (Simulate/Iterate/<br>Create).<br>Create Open source Core validation Test SW.<br>Create Open source Safety/Security Certification Tooling<br>ISA migration tools. | Create Open source AI Codesign tools, HW/SW optimized. | |
| **Methodology & EDA Tools** | Open source ASIC development tools, including interoperability of open and closed source tools. | (1) Develop open source interoperability standards to interface between different parts of the ASIC development toolchain (both open and closed), encouraging proprietary vendors to adopt the standard.<br>(2) Identify and target investment in open source replacements for specific parts of the flow (synthesis, linting, formatting, simulation, place and route, Static Timing Analysis, Design Rule Checking etc.). Focus on integration and functionality, e.g., in the form of stable and easy-to-use reference flows, rather than state-of-the-art algorithms. | (1) Enhance open source verification tools towards state of the art, adding more automation, point tools, interactive debug capabilities, and integration with requirements tracing.<br>(2) Extend open source tool flows to also cover non-functional aspects, allowing certifiably secure and/or safe designs.<br>(3) Update initial open source tools with more advanced algorithms for better QoR and support for more advanced processes, focusing on those with fabrication capabilities located in Europe.<br>(4) Extend open source toolflow to cover a larger part of the complete EDA pipeline. Focus on achieving | Complete front-to-back open source EDA tool flow capable of realizing even more complex industrial and academic designs with acceptable results, targeting current fabrication processes. | |

| Topics | Overall Topics | Short Term (2-5 years) | Mid Term (5-10 years) | Long m (> 10 years) | |
|---|---|---|---|---|---|
| | | (3) Create Open source tools for new, more software-driven verification methodologies, possibly based on next-generation hardware description languages, tested on open source IPs.<br>(4) Investment in open source CI infrastructure for open source IPs/cores, extracting metrics, providing feedback to change requests.<br>(5) Perform investment studies on using selected open source tools in the flow to realize and evaluate practically relevant sample designs, where innovation can be produced using older, lower-complexity processes. | a front-to-back open source tool flow capable of handling less complex designs on commodity processes. | | |
| | Chiplets & interposers for modular architectures. | Develop an Open source Die-to-Die (D2D) communication interface to leverage the chiplet-based design ecosystem to enable wide usage with target to become a “de-facto” standard. | Develop and promote a SoC infrastructure for “chiplet-based” components, with all the views and tools allowing easy partitioning and use of various chaplets (from various origins). Provide support for active interposers. | Develop support for photonic interposers and evolution of automated toolset environment to increase productivity of developers. | |
| | Analog IPs. | For SoC, develop analog IPs which are an inherent part of the design solutions (PLL, FLL, DC/DC, ADC/DAC...). This will also help address the resistance of EDA companies to allow open sourcing of Analog IPs. | | | |
| | Economics and social aspects of open hardware. | Perform research on economics and social aspects of open hardware. | | | |

## 5.11 Need for Horizontal And Vertical Activities

It is clear that in order to address the needs of Open Source development within Europe both horizontal and vertical activities are needed. These can be summarized as:

### Horizontal Activities

- Fundamental Research
- Capacity Building
- Platform Components

### Vertical Activities

- Use Case Scenarios
- Application Platforms
- Platform Usage

**Recommendation** – Horizontal foundational activities and vertical application driven activities are needed to develop new tools and IP libraries which can be built upon, re-used and exploited in future horizontal and vertical calls, systematically growing a repository of benefit to European stakeholders. In parallel with this there is a need for a strategic "Governance Initiative'' to coordinate activities, maintain and promote the repository.

In **Figure 5.11** a proposed vision is given on how these horizontal and vertical activities could be combined to support a European RISC-V and Open Source ecosystem. This requires work on "Foundational Building Blocks" to provide both HW and SW building blocks, along with the development of tools to integrate these building blocks into complex SoC designs. Evolution is needed in both the vertical and horizontal activities. Vertically, the basic foundation infrastructure needs to be expanded with new IP's and different technological dimensions. Horizontally, there is a need for development of three types of processor families, ranging from low- via mid- to high-end generic processors. In addition, there is a need to develop application-specific elements that can be added to the generic processors in order to create dedicated solutions for specific domains, e.g., automotive, industry, telecommunications, health, aerospace, defense, etc. There is also a need for horizontal activities addressing security, verification and certification which can then be exploited in the vertical domains targeting specific implementations.

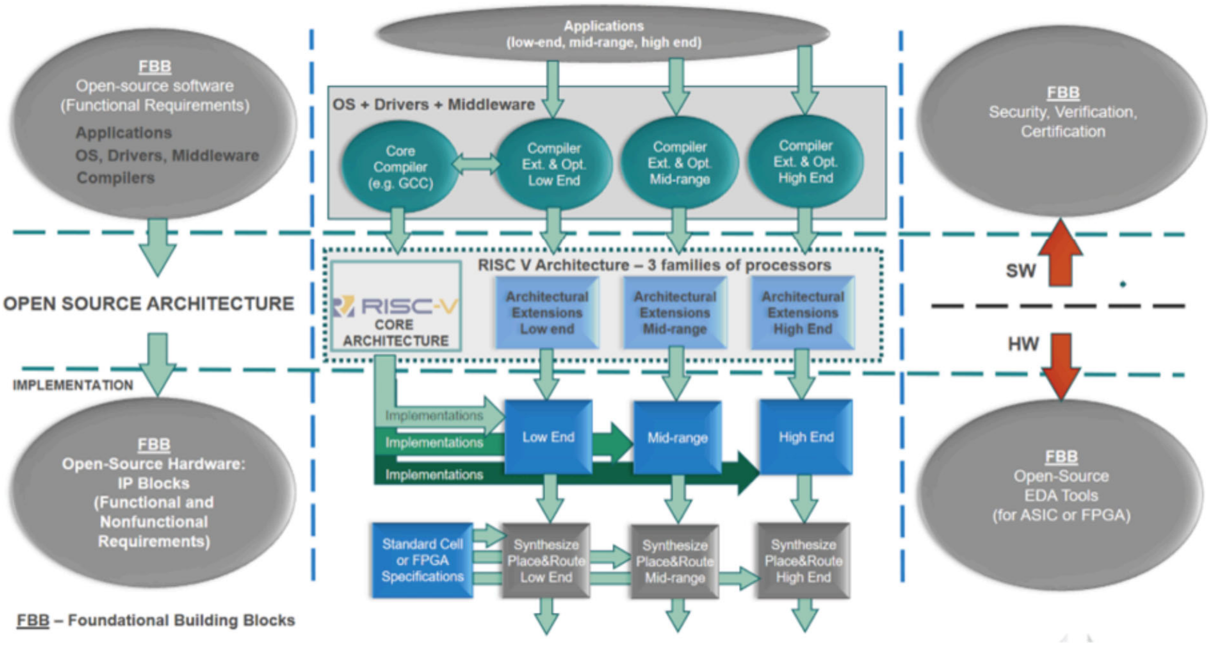


*Figure 5.11 - Horizontal Foundational Activities and Vertical Industry Facing Activities*

Developing the IP and tools to support the design of new processor architectures will not result in European benefits unless these designs can be physically realized. To support this there is a need for further horizontal and vertical activities as shown on **Figure 5.12** to address the needs of fabrication considering the non-functional properties. Here there is a need for linkage to pilot lines to fabricate, test and package chips, firstly at a prototyping level, and then considering fabrication for specific application sectors.

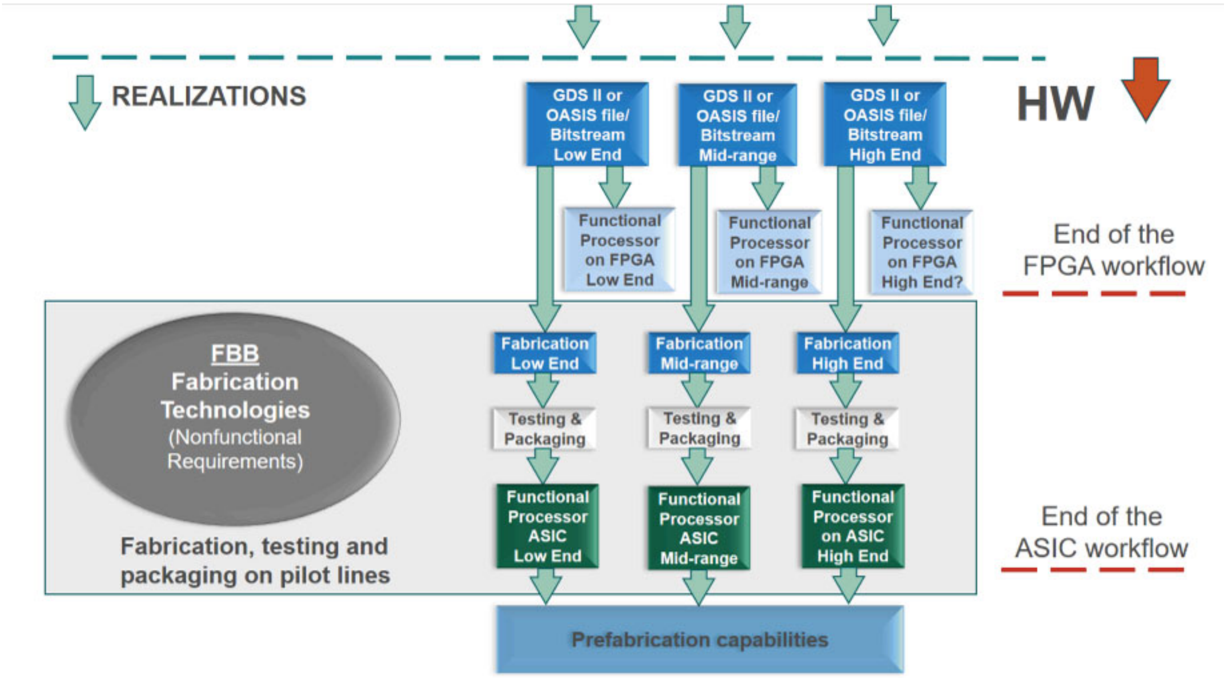


Figure 5.12 -Horizontal and Vertical Fabrication and Testing Activities

For the vertical application demonstrators key strategic areas are automotive, industry, high performance computing and communication. A first key vertical application demonstrator could be in the automotive sector in cooperation with OEMs, TIER 1's and TIER 2's. To support development of applications there is a need to intensify interaction with key strategic European stakeholders in application sectors and in other relevant PPPs (e.g., EuroHPC, SNS, etc.) to jointly define specifications, development plans and financing models.

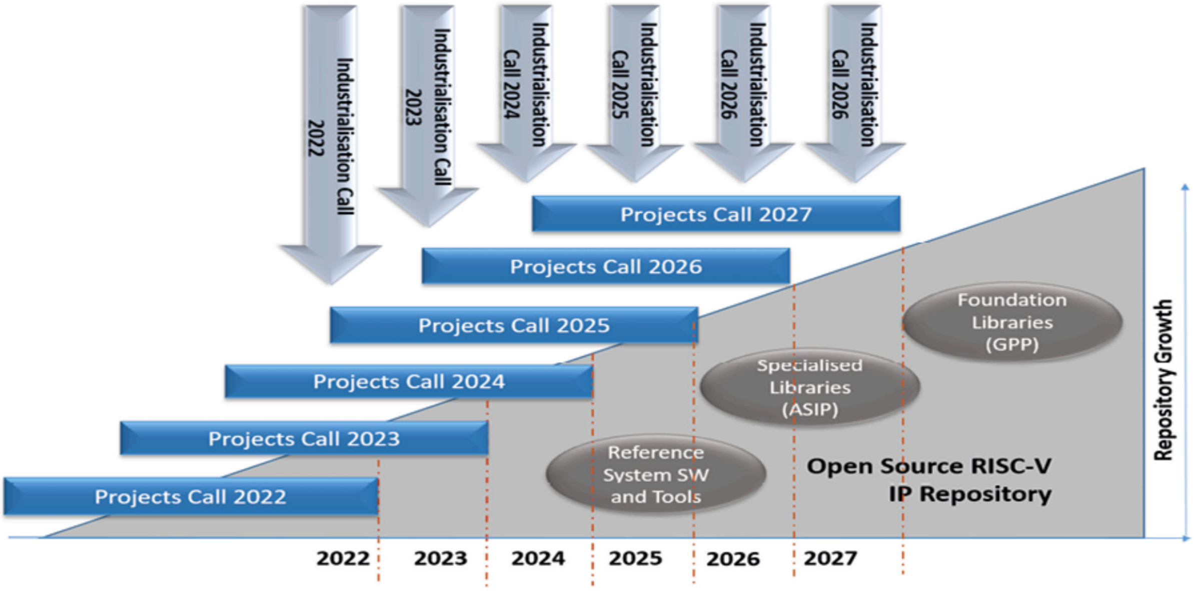


Figure 5.13 - Coordination of Horizonal and Vertical Calls to Create an Open Source RISC-V IP Repository

A possible approach to the coordination of the horizontal and vertical activities is shown in Figure 5.13 which shows the coordination of project calls addressing both the horizontal aspects as well as application driven vertical calls. In this approach new tools, foundation and specialized IP libraries will be created that are open to the ecosystem. These can be built upon, reused and exploited in future horizontal and vertical calls systematically growing a repository which will be of benefit to European stakeholders.

In parallel with this there is a need for a strategic "**Governance Initiative**" which should be launched as early as possible that orchestrates the EU activities in a top-down manner (to avoid fragmentation), maintains and curates the repository, and promotes the repository to both the open source community and industry. The governance initiative should also define the strategic roadmap of activities, how they interrelate and define expected achievements with milestones. An explicit aim is to ensure multi-year continuity, for instance by reviewing as well as potentially amending submitted research project proposals from a long-time perspective, and by supporting the refinement and definition of future calls.

The governance initiative should be sufficiently supported to be able to technically as well as administratively provide an optimal governance, that takes into account the special needs and characteristics of open source hardware, e.g., with regards to licenses, its economics across different design and production stages, etc. It also can optimize and monitor the submissions, and outcomes of calls, e.g., supervise a study on economic and social aspects of open source hardware innovation. It may additionally have responsibility to maintain the repository and create visibility. The governance initiative could be implemented by an existing organisation, by an agreement between existing organisations, or by a new organisation. The governance initiative should be backed by industry, academia, and users. Members of the working group that wrote this report (i.e., the Open Source Hardware & Software Working Group), are willing to support its initial setup, e.g., by widening the working group and eventually via exchanging with other organisations such as DARPA initiatives on open source hardware.

Already work has begun on developing the Open Source strategy with the launch of the Call 2021-1-IA - Focus Topic 1: Development of open-source RISC-V building blocks with funding of EUR 20 million from Horizon Europe. This addresses mainly horizontal foundational work on RISC-V IP cores, methodologies and tools as well as system software. A further call was launched in 2022 (2022-1-IA- Focus Topic 3) addressing the Design of Customizable and Domain Specific Open-source RISC-V Processors. This call is supported by both national and EUR 20 million of Horizon Europe funding and addresses vertical aspects in terms of specialized processors, e.g., for automotive. The expectation is that the horizontal activities will contribute to the open-source RISC-V IP repository, which is shared and reusable, and the vertical activities will provide domain-specific cores, ready for industrialization which can be either shared or proprietary.

## 5.12 Concluding Remarks

This report highlights the need for a strong European open source ecosystem to drive competitiveness and enable greater and more agile innovation. There are increasing concerns over security and safety in application markets such as automotive, industrial automation, communications, health and defense where there is a reliance on non-EU developed technologies. Notably open source can be used as a means of retaining sovereignty when the only alternative is to license IPs from non-EU $3_{rd}$ parties. This is only possible if there is a critical mass of European contributors to open source projects so that a European fork is possible (i.e., create a fully equivalent variant of a given technology) if necessary.

A key message is that there is a need to build or take part in sustainable open source communities such as OpenHW Group, CHIPS Alliance, etc. This is important to get and maintain industrial-grade solutions. Care must be taken to avoid fragmentation by creating too many communities. A challenge is that the current communities are young and deliver limited processor cores and toolchains. There is a need to extend the offer to the community with high-end processors, interconnects, peripherals, accelerators, Operating Systems and SW stacks, Integrated Development Environments (IDE)/Software Development Kit (SDK) with supporting documentation.

A major issue is the availability of Open Source EDA and CAD tools. In addition to open source hardware targeting ASIC implementations there is a need for development tools that do not incur significant licensing costs. Here high-quality open source EDA tools are needed for industrial-grade open source IP cores. A challenge is that Europe has a low footprint in the world of CAD tools, which are critical assets to design and deliver electronics solutions, but there are open source CAD tool initiatives which may bridge this gap.

Considering processors, the involvement in RISC-V International should be strongly encouraged to influence and comply with the “root” specifications. Currently, RISC-V standardizes the instruction set, but additional fields will be needed in the future for more interoperability considering SoC interconnect, chiplet interfaces, turnkey trust and cybersecurity, safety primitives, etc. At a European level it is important to support open source cooperative funded projects to maximize collaborations and create a significant European critical mass to compete with China and the USA. The goal should be to ensure that intellectual property produced is delivered as open source so that European actors can exploit these results.

For open source to be broadly adopted by the European ecosystem, a number of barriers need to be addressed. In particular, there is a perception that building defendable intellectual property is difficult, if not impossible, with open source. This is a key challenge for obtaining financing for open source based start-ups. This requires a redefinition of the business model for many European IP providers, design service providers and public research centers. EU advocacy and financial support is needed for start-ups, SMEs and public research centers to encourage the adoption of open source. At the same time public endorsement of open source and material contribution to open source projects from the leading European semiconductor vendors is critical to provide credibility and momentum to open source at European level. The European design service vendors can also play a key role in supporting the open sourcing of major vendors’ IPs, with financial support from the EU.

In order to meet the needs of applications there is a need to address a number of cross cutting issues such as scalability, certification for safety in different application domains, and security. This requires consideration at both the component level and system level.

**Key Topics**

A number of key topics which need addressing are highlighted in the report. These include “open hardware base building blocks”, “verified open source hardware & interconnect” “chiplets and modular interposers”, and EDA-tools. More specifically work on open hardware base building blocks should target highlighting benefits of open hardware through proprietary demonstrations (including software, other hardware, mechanical systems) to push the acceptance of open hardware. Considering processors, verified open source hardware should consider leveraging existing open hardware design IP suitable for high-assurance verification and the development of a re-usable verification infrastructure, which includes a complete verification plan considering module level verification, silicon technology specific verification and system integration verification including safety, security and other non-functional aspects (e.g., code quality, clock domain crossing, reset domain crossing, power domain crossing, resource efficiency, power efficiency). This should also consider IP blocks accompanied by verification frameworks for safety/security starting from ESL down to RTL. The aim here would be to release these frameworks and tests under permissive or weakly reciprocal licenses. The use of open source verification technology should be encouraged but leveraging non-open source verification technologies (e.g., simulation tools, formal verification tools, HW emulators) is also possible, as long as the output of the tools can be integrated and checked with open source verification environments. Going a step further to gain acceptance of open source it would be beneficial to demonstrate certification according to relevant safety and security standards with use cases/demonstrations. This should also include verified open source real-time interconnects, considering mixed-criticality and security.

Chiplets and interposers for modular architectures have been highlighted as an opportunity for the semiconductor industry and here there is a need to address the technical challenges such as architecture partitioning, chiplet-to-chiplet interconnect, testability, CAD tools and flows, advanced packaging technologies. Die-to-Die (D2D) communication, in particular, is the “missing link” to leverage the chiplet-based design ecosystem, and its development in open source would enable a wide use of the approach and could become a “de-facto” standard. This needs to target a high-bandwidth, low-latency, low-energy, ultra-short-reach link between dies.

Open source ASIC development tools are a necessary element of the hardware ecosystem, enabling unlimited access to experimentation and lowering barriers to implementing new ideas by all actors, including new players with a more software background. The availability of at least some open source components that could be used for ASIC design will allow for increased automation, new developer-focused workflows and open the door for cloud- and AI-assisted EDA design.

Finally, other important topics that need addressing are the economics and social aspects of open source hardware innovation as the approach is a significant disruptive change from current practice.

To achieve all of these aims a strategy based on addressing both horizontal foundational aspects of open source development and targeted activities addressing vertical sectors is proposed that will contribute to the creation of a European open source repository of IP blocks and tools.

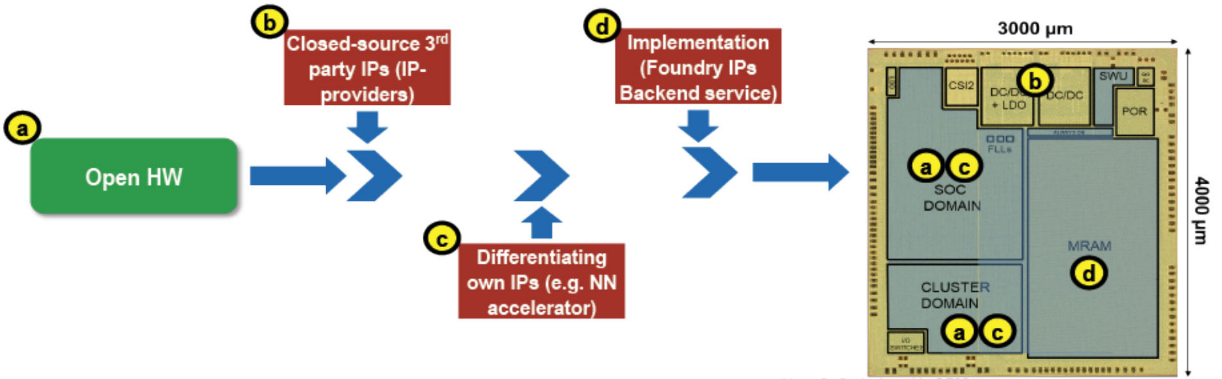
## 5.13 ANNEX A – Open Source – what, why, how

### 5.13.1 Benefits of Open Source within the Value Chain

The ecosystem is wide ranging and diverse including the semiconductor industry, verticals and system integrators, SMEs, service providers, CAD tools providers, open source communities, academics and research. It is an area with many opportunities to create innovative start-ups and service offers. The benefits and attraction of adoption of open source depends on the type of actor and their role within the value chain. These can include:

- Creating innovative products with lower costs and access barriers.
- Providing a faster path to innovation and smoother cooperation between actors (academic, research, industry, SME, alliances) as no Non-Disclosure Agreement (NDA) and commercial license need to be negotiated.
- Influencing technical choices and specifications.
- Allowing customization of open source IP to user needs, delivering differentiating products.
- Sharing development costs.
- Reducing risks related to third-party IP (unbalanced commercial relationship, end of maintenance/ discontinued products, export control and trade wars).
- For RISC-V compliant processors, the advantage of the open source SW ecosystem (compilers, debuggers, Operating Systems, frameworks, etc.).
- Building support and design service businesses based on open source IP.
- Conducting research with easier access to digital technologies.
- Using open source material to educate talented students who will fuel future European successes.
- Better auditing of security and safety, ensuring that solutions can be fully audited and checked/verified (e.g., possibility to look for back doors in open source IPs). This is not possible for IPs licensed from $3_{rd}$ parties.

**The Open Source Ecosystem**



Vega SoC, designed in GF22nm
https://greenwaves-technologies.com/processor_noise_cancellation/

*Figure 5.14 - Example Flow of IP Creation of Open Hardware*

**Open hardware IP is part of an ecosystem composed of other IPs (open source or not), tools to design, simulate, estimate, integrate, synthesize and validate the integration of all IPs** (as shown conceptually in Figure 5.14) as well as PDK tools to translate the RTL into a low-level representation specific to the foundry. The foundry utilizes the file generated (generally in GDSII/OASIS format) to produce the masks and the technology process. This is then used to produce a wafer from which the dies are extracted, tested, and packaged, before the final testing and the integration into the final electronic board. At each step significant financial investment is needed.

Although it is generally accepted that high-quality industry ready open source IP that has been through extensive testing, validation and documentation has a lot of value, **it is also believed that there is even greater value from using the RISC-V and Open Source HW/SW IP in the community rather than from the IP itself**. There are different levels of ''Open Source" IP, ranging from standard peripherals to complex application-specific multi-processor-based IP. Business can be made from all types of IP, dependent on the markets addressed, the customers involved and the application needs. Ongoing research, such as by Professor Nagle[53], illustrates the economic benefits of contributing to open source at the state level[54], which would become even more compelling if done at the EU level. The RISC-V ecosystem has the open RISC-V ISA as common starting point for flexibility and interoperability. **The openness of RISC-V also allows inspection which is important for hardware auditability.** Hardware needs to be trusted by consumers and experts alike. This was emphasized by the occurrence of security vulnerabilities such as Meltdown and Spectre which only became visible in 2019 after being deployed in billions of x86 and Arm devices for many years. Open hardware and RISC-V offer a very good chance to improve the situation and the wide acceptance of the RISC-V ISA also allows some degree of interoperability among devices.

### 5.13.2 Key players in Open Source

The attraction of open source is clear and there is a growing community of developers and contributors to open source repositories both within Europe and at the global scale. A danger is fragmentation of effort and there is a need to strengthen European activities to create a critical mass that can contribute both at the European level, but also on the world stage. This is to ensure that European needs are serviced and that there is more resilience to forks in development that may be deleterious to European interests. Key initiatives identified by the Working Group are described in **Figure 5.14**.

Business can be made on all types of IP, dependent on the markets addressed, the customers involved and the application needs.

RISC-V International is probably one of the most well-known players in open hardware, but it only works on the RISC-V Instruction Set Architecture (ISA) and related specifications. Many entities and individuals have designed RISC-V compatible cores, processors and SoC (https://riscv.org/exchange/cores-socs/). Among them, there are two well-known organizations that host open source co-operations: CHIPS Alliance and OpenHW Group. lowRISC is also notable being mostly recognized for the OpenTitan project.

OpenHW Group is a not-for-profit, global organization driven by its members and individual contributors where hardware and software designers collaborate in the development of open source cores, related IP, tools and software. OpenHW provides an infrastructure for hosting high-quality open source HW developments in line with industry best practices and builds upon the ETH-Zurich/University of Bologna PULP open source project. A good fraction of its 60+ members are from the EU (companies and research centers), some being involved in its governance. The Group hosts the development of several RISC-V cores, CV32E4 embedded family deriving from RI5CY and CVA6 application cores deriving from ARIANE and will extend with TAIGA (from Simon Fraser University) and CV32E20 (compact core deriving from Ibex/Zero-riscy). SoC-level projects are also in the pipeline, as well as several software projects relating to the cores. The list and status of projects can be found at

https://github.com/openhwgroup/core-v-docs/blob/master/program/dashboard/Dashboard.md

CHIPS Alliance is pursuing a vision of creating a completely open hardware ecosystem, with tools, IP, cores, interconnects and more. As a Linux Foundation project it is based in USA but includes parties from all over the world, including EU companies like Antmicro. CHIPS should be viewed as a key strategic partner in pushing the open source technologies to the market. CHIPS Alliance is developing a number of improvements in the open tools workflow, verification, standardization, chiplets and other fields, including:

- SystemVerilog parsers, formatters, linters and other tooling – Verible, Surelog, UHDM, sv-tools (led by Google & Antmicro)
- Open source Universal Verification Methodology (UVM) support in Verilator (led by Antmicro & Western Digital)
- The OpenROAD/OpenLANE and OpenFASoC Application Specific Integrated Circuit (ASIC) design flows (led by Precision Innovation UCSD/UMich, etc.)
- A number of open source Analog tools (with diverse university involvement)
- The RISC-V Domain Validation (DV) verification environment (led by Google)
- The Chisel Hardware Description Language (HDL) and related tools (led by SiFive / Berkeley)
- Advanced Interface Bus (AIB) open source chiplet standard and reference implementation (spearheaded by Intel)
- Field Programmable Gate Array (FPGA) Interchange format, an interoperability standard for open and closed source FPGA tooling which can be used as a reference for similar activities in the ASIC domain (Antmicro / Google)

SkyWater technologies are pursuing a new, open foundry model where their 130nm Process Design Kit (PDK) has been open sourced together with Google, E-Fabless, Antmicro and a number of university partners in a crowdsourcing design platform leveraging also open source IPs and EDA tools. Other PDKs are likely to follow suit. The 3-some partnership offers free access to MPW (Multi Project Wafers) sponsored by Google. SkyWater is considered to be quite US-Centric.

**EUROPRACTICE** is a highly effective integrated service for Europe, that has been supported by the European Commission for more than 25 years. EUROPRACTICE lowers the entry-barrier for academic institutions and less well-established companies (i.e., start-ups and other SMEs) by offering affordable access to a rich portfolio of industrial-grade design tools and prototyping technologies for customized ASICs, Micro-electromechanical Systems (MEMS) and photonics. The service includes initial advice, training and ongoing support, reduced entry costs and a clear route to chip manufacture and product supply.

**FOSSi:** The Free and Open Source Silicon (FOSSi) Foundation predates the OpenHW Group and the CHIPS Alliance, with a strong European presence on its Board of Directors. It is completely different in that no big corporate actors are involved in its governance. Its legitimacy in the open source silicon arena is derived from their long-standing commitment to facilitate the sharing of open source digital designs and their related ecosystems. In this regard, they are well known for organizing the ORConf and LatchUp conference series, as well as managing librecores.org, a place on the Web to share HDL code, seen as the evolution of the old opencores.org.

Key Open Source Initiatives

**Going forward the Working Group advocates for building upon and consolidation of Open Source Hardware (OSH) communities where there is a significant participation of European actors, e.g., the OpenHW Group, which is a worldwide initiative, and the CHIPS Alliance, which has a strong US footprint**. Notably OpenHW is registered in Canada (a more neutral country) and is in the process of creating OpenHW Europe, as a working group hosted by the Eclipse Foundation (registered in Belgium). The OpenHW Group pays strong attention to verification (processes, environment, coverage, etc.) and open source availability of most verification artefacts. There is also a focus on designs written in widespread Hardware Description Languages (HDLs) to ease adoption by many teams and a rule not to include technology subject to export control laws in any jurisdiction. The CHIPS Alliance provides governance, structure and legal assistance including patents and export controls offering the opportunity for collaboration on legal aspects of open hardware.

Key in Europe is EUROPRACTICE and this already offers significant support for open hardware ICs through a design sharing agreement, which is a legal agreement that requires EUROPRACTICE members to share the IP that they have developed with other members. The standard academic license agreements for IC design tools preclude the sharing of IP, so this design sharing agreement is absolutely essential for any serious open source hardware endeavour. **EUROPRACTICE could extend its current offering and organize an IP exchange system, where academic members could submit their IC IP and gain access to all of the member contributed IP by signing a single agreement to join this ‘club’ rather than concluding a design sharing agreement for each individual piece of IP. Routes to commercialization from this pool would also exist. Furthermore,**

**EUROPRACTICE could negotiate with its European foundries (such as GlobalFoundries, STMicroelectronics and X-FAB) to organize low-cost themed design challenges, similar to the Google-Skywater sponsorship**. Ideally, this should fuel hardware exchange between innovators (in the form of chiplets), which would require a standard interposer offer on which chiplets can be tested and brought together into a system.

### 5.13.3 Business Strategies

There are a number of different business models for commercializing Open Source[55]:

- Service and support firms
- Single-vendor open source firms
- Open source distributor firms

These can be driven by different business models or motivations:

- **Aggressive**: customizing Open Source HW to provide differentiation, e.g., with respect to current commercial cores (e.g., Arm) and targeting advanced processing nodes.
- **Cost-sensitive**: using Open Source HW ''as is'' to reduce cost with respect to licensing costs (e.g., from Arm), or with respect to in-house effort, targeting older processing nodes.
- **Efficiency increase**: design priority setting to re-use standard blocks and focus on the application-specific differentiating elements in the SoC-design, in order to get to the market faster.
- **Share development costs:** share costs for pools of open source IP blocks between actors and manage joint projects in communities, such as the OpenHW Group, the Eclipse Foundation, etc.

The creation of value and the path to real chip production differs according to the types of users of the Open Source IP, such as IDMs, IP vendors, fabless companies, foundries, service companies, etc. From the perspective of a private company, one example on how to address Open Source is the following:

- Commit with academic partners to open source some IPs (theirs or their partners') at the latest when they go into production. This provides them with a time advantage where they think it is critical, i.e., for differentiating features, in an industry where competitive advantage that is driven by timing. Those IPs then enrich the Open Source ecosystem.
- Most of the constituents of an SoC are not differentiating. They are basic constituents that can be easily reused from one design to another. Having a rich open source ecosystem allows companies to focus their efforts on the differentiating features.

### 5.13.3 Licensing models for Open Source

**A key aspect of open source business models is the licensing model** and Open Hardware projects typically also include extensive documentation and software for simulation, validation and testing.

**Permissive licensing** is a mechanism whereby the rights holder gives permissions and imposes very few and lightweight obligations in exchange. For example, one obligation might be to explicitly mention the original author in a piece of modified work. The piece of modified work, and any larger work in which it is included, do not need to be released under the same license.

**Weakly-reciprocal licensing**, whereby a licensee who modifies the work must release the modified version under the same license. This is where reciprocity comes in. The licensee gets a piece of work with a number of permissions, but must share back in exchange, therefore contributing to a virtuous circle of sharing. The "weak" in "weakly reciprocal" refers to the fact that the reciprocity obligations do not extend beyond the initial piece of work that was shared. The original piece of work can be embedded in a larger work and the sources for that larger work do not need to be released under an open source license.

**Strongly-reciprocal licensing** is a sharing regime whereby the obligations to share back extend to any larger piece of work embedding the originally licensed work.

**Documentation Licensing** - When considering documentation, the de-facto standard for sharing is the Creative Commons family of licenses. These include CC0 (permissive with no attribution requirement), CC-BY (permissive with an obligation to recognize the original authors) and CC-BY-SA (reciprocal). These three licenses are adequate to share documentation in the context of the open hardware developments.

Key Licensing Approaches

It is important to choose appropriate licenses for each of the released components. Copyright law is "all rights reserved" by default. This means that putting a file somewhere on the web is not enough because the recipients of that file do not have the basic permissions they need to allow copying, modification and publishing of modified versions of that file. Licenses provide the permissions that the rights holder grants to users so they can benefit from and contribute to the open source effort. There are several pros and cons to different licensing approaches. For software, the best choice of license depends on the project. Apache v2 is a modern permissive license which is used in many successful open source software projects. GNU Lesser General Public License (LGPL v3) and Mozilla Public License (MPL2) are also good choices in weakly-reciprocal contexts, and GNU General Public License (GPL v3) is the de-facto standard for strongly reciprocal work. When considering hardware and IC design there are some issues with using open source software licenses. This applies mainly to reciprocal regimes and permissive licensing is a much simpler in practice. As such Apache v2 can be used as a permissive license for hardware projects in the IC design realm with alternatives being Solderpad v2.1, which takes Apache v2 as a basis and modifies some terms to better adapt them to a hardware context. More specifically the CERN Open Hardware License comes in three variants: permissive, weakly-reciprocal and strongly-reciprocal, providing a one stop shop for hardware licensing. The reciprocal variants take into account the specificities of IC design and its legal and commercial environment.

### 5.13.4 Approaches to licensing in Europe

Past efforts show that, **in order to reap the benefits of open source, it is vitally important to communicate clearly from the beginning the line between open source and proprietary for a given project/initiative (and how they complement in certain cases), as well as to stick to standard commonly agreed practices and definitions within the open source realm**. In practice this is a very challenging endeavor, so it important to agree on some principles. Open source provides a more level playing field for all actors, and this is an integral part of its success. Many people have tried to get one thing without the other and failed as they both go together. There are ways to give industry a competitive edge inside an open source ecosystem, but it should be understood that preferential access to the source for a component automatically makes that component proprietary. Existing licensing terms include:

- **Truly open source** (i.e., a license approved by OSI). This should already ensure it is not discriminatory to the EU or any other state or group of states.
- **Meaningful for Open Hardware**. Some OSI-approved licenses which were drafted for software are difficult to interpret in the hardware case, which can be very confusing and bring legal uncertainty.
- **Permissive or weakly-reciprocal**

Another approach could be to use exclusive licenses for EU projects. However, as the whole world is embracing the use of RISC-V and both open as well as proprietary IP, there is no need for a special or separate license model for EU purposes only. Despite this there is still a need to select the right licenses using European laws. **Licenses need to be carefully selected to avoid potential contamination or being used for restricting usages for European companies**. Export control laws can restrict the use even of Open Source in some cases, for example, in case of not (yet) fully public disclosure. Some countries' export control regulations, such as the United States, may require taking additional steps to ensure that an open source project is satisfying obligations under local regulations[56].

In many cases the value of Open Source IP is questioned by industry for critical designs. **Open source is considered a risk because of lack of available support and because of the fact that it is open towards the whole world, which could make it difficult to differentiate with competitors.** As Europe is lagging behind today in some domains, it can remain a net beneficiary of open source projects for years, provided that it builds the community and the infrastructure capable of leveraging and influencing those projects. EU funding can contribute to this.

There is a fear of giving everything away to competitors. This is based on an incomplete understanding of best practices to combine open source with commercial activity.

The other big family of relevant actors is that of public institutions. In these institutions there is an ongoing debate as to how much of their work should be made open source. The fear that "giving everything away" to competitors will harm the economy is largely based on an incomplete understanding of best practices to combine open source and commercial activity. One reason why groups in public institutions do not share much publicly is the perception that the results of research should benefit exclusively the subset of people who have financed it. For national and international laboratories, one often hears the objection in terms of the problem of offering all our knowledge and technology for free to others in the world. One possible line of reasoning is that this knowledge can then be used by these external actors to harm our economy, by letting 'them' cheaply manufacture what companies in the financing states could have offered for sale, using profit margins to properly pay their employees and reinvest in innovation. This reasoning is incomplete and can lead to decisions which forego important opportunities to benefit our societies. The opening of the RISC-V Instruction Set Architecture (ISA) itself is a good example of a strategic move from a country (the US) in which the open sourcing was crucial in the generation of large benefits for that country. **RISC-V created a new market because it is open and the main beneficiaries of that new market were institutions and companies which were physically and strategically close to the originating university.**

## 5.14 ANNEX B – Market trends in the chip market

RISC-V and OpenSource HW/SW IP can be applied in strategic SoC designs targeting specific application domains, thanks to an extensible Instruction Set Architecture (ISA). **The value of the global chips market in 2021 was around USD $550 billion.**[57] The bulk of global demand comes today from end-use applications in computing, including PCs and data centre infrastructure (32%), communications, including mobile handsets and network infrastructure (31%), and consumer electronics (12%). **The growth rate is highest, however, in segments previously ruled by analogue and mechanical technology, such as automotive and industrial manufacturing (12% each)**, as shown in **Figure 5.16**[58].

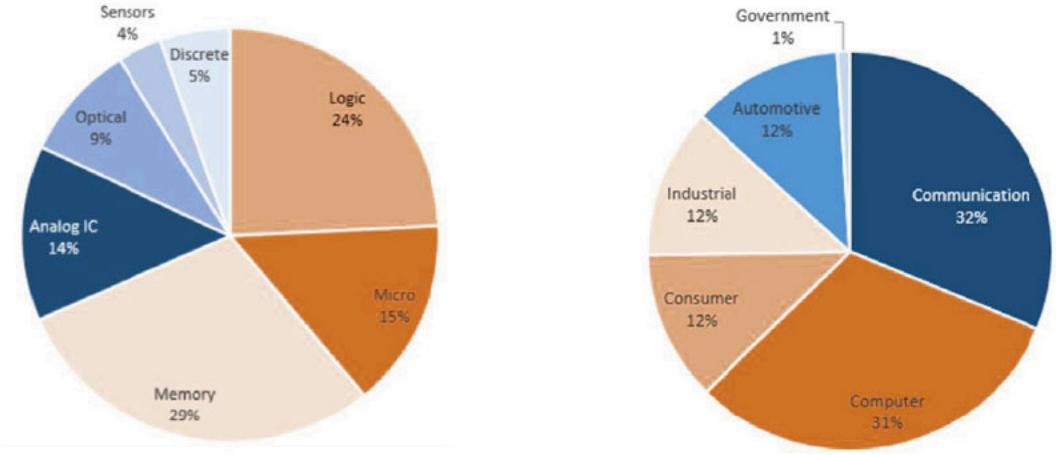
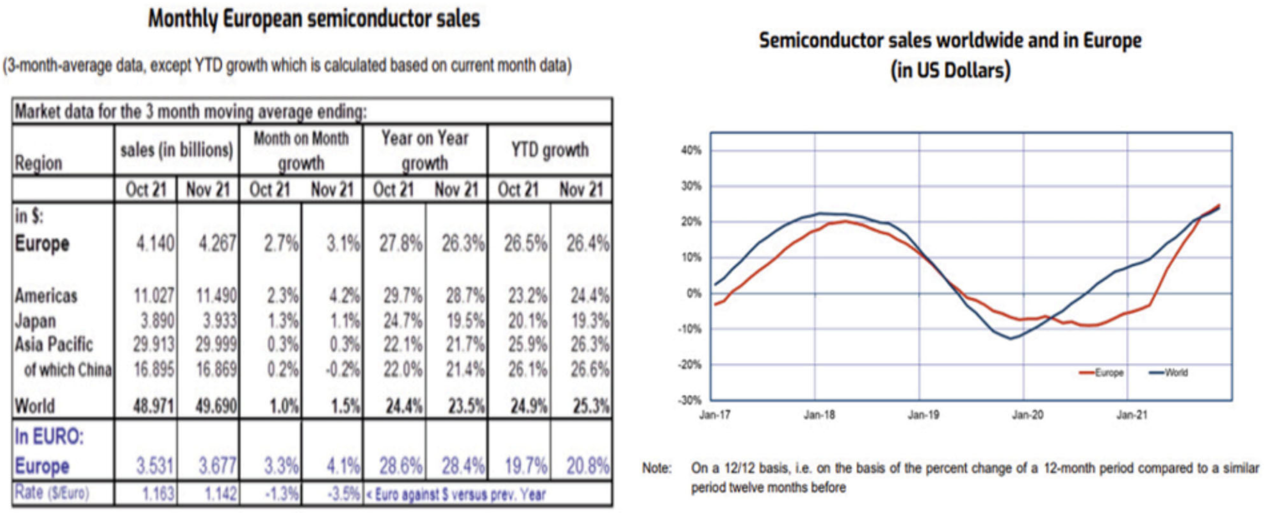


*Figure 5.17 - Semiconductor Market Segments, by Device Type and by End-user Sector Demand*

Due to strong industry sectors within Europe the split across different domains differs from the worldwide situation with the automotive semiconductors market being 37% of the total European market, the industrial market being 25%, and less of a presence in the computing (15%), communication (15%) and consumer markets (7%)[59]. Overall, the European Semiconductor Industry Association (ESIA) reported that yearly **semiconductor sales in the European market reached USD $ 47.757 Bn in 2021, a 27.3% increase from 2020 and a 27% increase considering the same month in 2020**. At the global scale semiconductor sales in 2021 amounted to USD $ 555.893 Bn, a 26.2% increase from 2020. All figures are based on World Semiconductor Trade Statistics (WSTS) and represent a three-month rolling average unless otherwise indicated. In the table and the graph shown in **Figure 5.18** this growth in European semiconductor sales is clearly shown[60].



**Monthly European semiconductor sales**

(3-month-average data, except YTD growth which is calculated based on current month data)

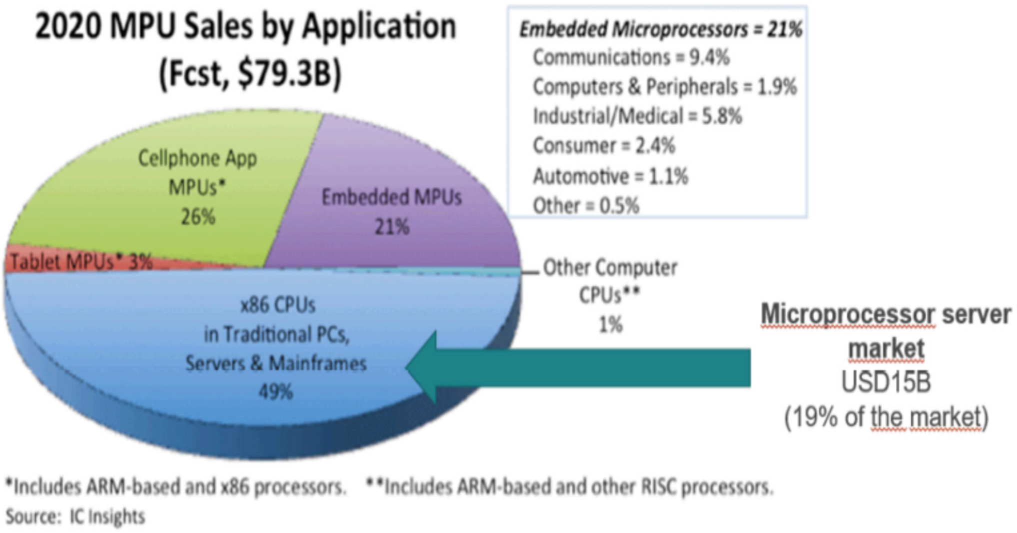
| Market data for the 3 month moving average ending: | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Region | sales (in billions) | | Month on Month growth | | Year on Year growth | | YTD growth | |
| | Oct 21 | Nov 21 | Oct 21 | Nov 21 | Oct 21 | Nov 21 | Oct 21 | Nov 21 |
| in $: | | | | | | | | |
| Europe | 4.140 | 4.267 | 2.7% | 3.1% | 27.8% | 26.3% | 26.5% | 26.4% |
| Americas | 11.027 | 11.490 | 2.3% | 4.2% | 29.7% | 28.7% | 23.2% | 24.4% |
| Japan | 3.890 | 3.933 | 1.3% | 1.1% | 24.7% | 19.5% | 20.1% | 19.3% |
| Asia Pacific | 29.913 | 29.999 | 0.3% | 0.3% | 22.1% | 21.7% | 25.9% | 26.3% |
| of which China | 16.895 | 16.869 | 0.2% | -0.2% | 22.0% | 21.4% | 26.1% | 26.6% |
| World | 48.971 | 49.690 | 1.0% | 1.5% | 24.4% | 23.5% | 24.9% | 25.3% |
| In EURO: | | | | | | | | |
| Europe | 3.531 | 3.677 | 3.3% | 4.1% | 28.6% | 28.4% | 19.7% | 20.8% |
| Rate ($/Euro) | 1.163 | 1.142 | -1.3% | -3.5% | < Euro against $ versus prev. Year | | | |

**Semiconductor sales worldwide and in Europe (in US Dollars)**

Note: On a 12/12 basis, i.e. on the basis of the percent change of a 12-month period compared to a similar period twelve months before

*Figure 5.18 - Monthly European Semiconductor Sales and Worldwide Growth in Semiconductor Sales<*

The global Microprocessor market was estimated to be almost USD $80Bn in 2020 with the main markets being in computing and communication as shown in **Figure 5.19**. **Europe has a strong position in the embedded market and this rapidly growing market is estimated to account for 21% of sales[61]** .



**2020 MPU Sales by Application (Fcst, $79.3B)**

*Includes ARM-based and x86 processors. **Includes ARM-based and other RISC processors.
Source: IC Insights

*Figure 5.16 - Microprocessor Sales by Application*

This is important for Europe as with a global output of more than €1,000 billion, Electronic Systems for embedded and professional applications have overtaken, in production value in 2018, the amount dedicated to the traditional stand-alone electronic goods encompassing smartphones, PCs, TVs, etc. (see **Figure 5.17**[62]).

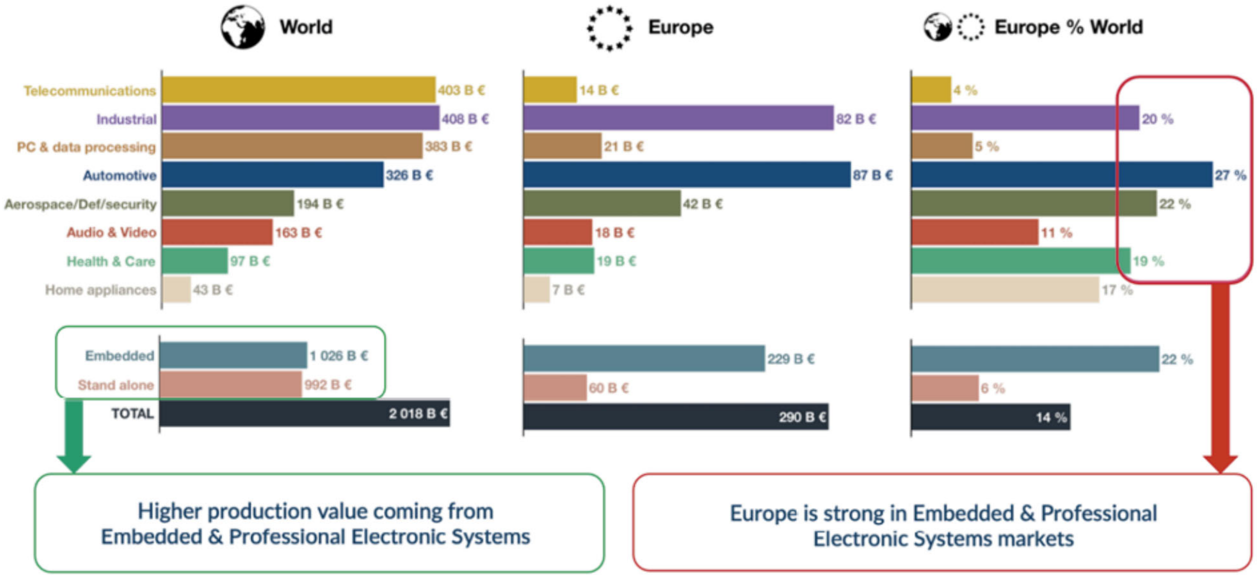


*Figure 5.20 - World & Europe Production of Electronics Systems by Application Domain*

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# 6 APPENDIX B

## 6.1 Acronyms used in the document

| | |
|---|---|
| **2D, 3D** | *Two dimension(al), three dimension (al)* |
| **5G** | *Fifth-generation communication network* |
| **6G** | *Sixth-generation communication network* |
| **A&P** | *Assembly and packaging* |
| **AAL** | *Ambient Assisted Living* |
| **ACA** | *Anisotropic conductive adhesive* |
| **ACES** | *Autonomous, connected, electric and shared* |
| **ACK** | *Alexa Communication Kit* |
| **ADAS** | *Advanced driver-assistance system* |
| **AF-EAF** | *Air Force Enterprise Architecture Framework* |
| **AFIoT** | *Architecture Framework for the Internet of Things* |
| **AFM** | *Atomic force microscopy* |
| **AI** | *Artificial Intelligence* |
| **AIOTI** | *Alliance for the Internet of Things Innovation* |
| **AIoT** | *Artificial Intelligence of things* |
| **AlN** | *Aluminum nitride* |
| **ALU** | *Arithmetic logic unit* |
| **ANN** | *Artificial Neural Network* |
| **AMD** | *Age-related macular degeneration* |
| **AMS** | *Analogue/mixed signal* |
| **API** | *Application programming interface* |
| **AR** | *Augmented reality* |
| **AS** | *Autonomous system* |
| **ASIC** | *Application-specific integrated circuit* |
| **AUTOSAR** | *AUTomotive Open System Architecture* |
| **B2B** | *Business-to-business* |
| **B2C** | *Business-to-consumer* |
| **BATX** | *Baidu, Alibaba, Tencent and Xiaomi* |
| **BCI** | *Brain–computer interface* |
| **BDVA** | *Big Data Value Association* |
| **BEOL** | *Back end of line* |
| **BEV** | *Battery electric vehicle* |
| **BGA** | *Ball grid array* |
| **BiCMOS** | *Bipolar CMOS* |
| **BIST** | *Built-in self-test* |
| **BOM** | *Bill of materials* |
| **BOX** | *Buried oxide* |
| **C&K** | *Competence and knowledge* |
| **CAD** | *Computer-aided design* |
| **CAFCR** | *Customer Objectives, Application, Functional, Conceptual and Realisation Model* |

| | |
|---|---|
| **CAGR** | *Compound annual growth rate* |
| **Cath lab** | *Catheterisation laboratory* |
| **CAV** | *Connected autonomous vehicle* |
| **CB** | *Conductive-bridge* |
| **CBRAM** | *Conductive-bridging RAM* |
| **CCAM** | *Connected, Cooperative and Automated Mobility* |
| **CDR** | *Carbon dioxide removal* |
| **CEAP** | *Circular Economy Action Plan* |
| **CFD** | *Computational fluid dynamics* |
| **CMOS** | *Complementary metal–oxide–semiconductor* |
| **cMUT** | *Capacitive micromachined ultrasound transducer* |
| **CNN** | *Convolutional neural network* |
| **CNT** | *Carbon nanotube* |
| **CPS** | *Cyber-physical system* |
| **CPU** | *Central processing unit* |
| **CrMMC** | *Carbon-reinforced metal matrix composites* |
| **CRM** | *Critical Raw Material* |
| **CT** | *Computed tomography* |
| **CVD** | *Chemical vapour deposition* |
| **D2D** | *Device-to-device* |
| **DCS** | *Distributed control systems* |
| **DfA** | *Design for assembly* |
| **DfM** | *Design for manufacturing* |
| **DfR** | *Design for reliability* |
| **DfX** | *Design for excellence* |
| **DL** | *Deep learning* |
| **DMA** | *Direct Memory Access* |
| **DNN** | *Deep neural network* |
| **DPP** | *Digital Product Password* |
| **DPU** | Data Processing Unit |
| **DRAM** | *Dynamic random access memory* |
| **DSA** | *Directed self-assembly* |
| **DSL** | *Domain-specific language* |
| **DSS** | *Decision-support system* |
| **DT** | *Drug-targeted* |
| **DUV** | *Deep ultraviolet* |
| **E/E** | *Electrical/electronic* |
| **EC-RAM** | *Error correction RAM* |
| **ECPS** | *Embedded and cyber-physical system* |
| **ECS** | *Electronic components and systems* |

| | |
|---|---|
| **ECSO** | *European Cyber Security Organisation* |
| **ECU** | *Electronic control unit* |
| **EDA** | *Electronic design automation* |
| **EFFRA** | *European Factories of the Future Research Association* |
| **eHPC** | *Embedded high-performance computing* |
| **EHR** | *Electronic health record* |
| **EIP-AGRI** | *European Innovation Partnership "Agricultural Productivity and Sustainability"* |
| **EMC** | *Electromagnetic compatibility* |
| **EMI** | *Electromagnetic interference* |
| **EMR** | *Electronic medical record* |
| **EMS** | *Energy management systems* |
| **eNVM** | *Embedded non-volatile memory* |
| **EOL** | *End-of-life* |
| **EP** | *Engineering process* |
| **EPI** | *European Processor Initiative* |
| **ERP** | *Enterprise resource planning* |
| **ERTRAC** | *European Road Transport Research Advisory Council* |
| **ESAAF** | *European Space Agency Architecture Framework* |
| **ESS** | *Electronic smart system* |
| **ETP** | *European Technology Platform* |
| **ETP4HPC** | *European Technology Platform for High Performance Computing* |
| **EU** | *European Union* |
| **EUV** | *Extreme ultraviolet* |
| **EV** | *Electric vehicle* |
| **FAIR** | *Facebook AI Research* |
| **FAIRness** | *Findability, accessibility, interoperability and reuse* |
| **FCC** | *Federal Communications Commission* |
| **FDSOI** | *Fully depleted SOI* |
| **Fe** | *Ferroelectric* |
| **FEM** | *Finite element method* |
| **FEOL** | *Front end of line* |
| **FET** | *Future and emerging technologies* |
| **FFT** | *Fast Fourier transform* |
| **FinFet** | *Fin field-effect transistor* |
| **FLOPS** | *(flops or flop/s) Floating point operations per second* |
| **FMEA** | *Failure mode and effect analysis* |
| **FMI** | *Functional mock-up interface* |
| **FMIS** | *Farm management information system* |
| **fMRI** | *Functional magnetic resonance imaging* |
| **FMU** | *Functional mock-up unit* |

|  |  |
|---|---|
| **FPGA** | *Field-programmable gate array* |
| **GAA** | *Gate All Around* |
| **GAFAM** | *Google, Apple, Facebook, Amazon and Microsoft* |
| **GAMAM** | *like GAFAM but with the new name of Facebook (Meta)* |
| **GaN** | *Gallium nitride* |
| **GDPR** | *General data protection regulation* |
| **GHG** | *Greenhouse gas* |
| **GPS** | *Global Positioning System* |
| **GPU** | *Graphics processing unit* |
| **HAD** | *Highly automated driving* |
| **HCI** | *Human–computer interaction* |
| **HEMT** | *High-electron-mobility transistor* |
| **HEV** | *Hybrid electric vehicle* |
| **HF** | *High-frequency* |
| **HIL** | *Hardware-in-the-loop* |
| **HIR** | *Heterogeneous Integration Roadmap* |
| **HMI** | *Human–machine interface* |
| **HMLV** | *High mix low volume* |
| **HPC** | *High-performance computing* |
| **HTA** | *Hexagon Tensor Accelerator* |
| **HVAC** | *Heating, ventilation and air conditioning* |
| **HVDC** | *High-voltage direct current* |
| **HW** | *Hardware* |
| **I/O** | *Input/output* |
| **IC** | *Integrated chip* |
| **IC** | *Integrated circuit* |
| **ICT** | *Information and communications technology* |
| **IDM** | *Integrated device manufacturer* |
| **IEA** | *International Energy Agency* |
| **IGBT** | *Insulated-gate bipolar transistor* |
| **IIA** | *Industrial Internet Architecture* |
| **IIoT** | *Industrial IoT* |
| **IIRA** | *Industrial Internet Reference Architecture* |
| **IMC** | *In Memory Computing* |
| **INCOSE** | *International Council on Systems Engineering* |
| **iNEMI** | *International Electronics Manufacturing Initiative* |
| **IoMT** | *Internet of Medical Things* |
| **IoT** | *Internet of Things* |
| **IP** | *Intellectual property* |
| **IP** | *Internet protocol* |

| | |
|---|---|
| **IPCEI** | *Important project of common European interest* |
| **IPM** | *Integrated pest management* |
| **IPSR** | *Integrated Photonic Systems Roadmap* |
| **IR** | *Infrared* |
| **IRDS** | *International Roadmap for Devices and Systems* |
| **ISOC** | *Internet Society* |
| **IT** | *information technology* |
| **IVD** | *in vitro diagnostic* |
| **IXP** | *Internet exchange point* |
| **JU** | *Joint undertaking* |
| **KDT** | *Key Digital Technologies* |
| **KFI** | *Key failure indicator* |
| **KPI** | *Key performance indicator* |
| **LAE** | *Large-area electronics* |
| **LCA** | *Lifecycle assessment* |
| **LCP** | *Liquid crystal polymers* |
| **LCOE** | *Levelised cost of electricity* |
| **LED** | *Light Emitting Diode* |
| **LLM** | *Large Language Model* |
| **LoC** | *Lab-on-a-chip* |
| **LV** | *Low voltage* |
| **M2M** | *Machine-to-machine* |
| **MaaS** | *Manufacturing as a service* |
| **MaaS** | *Mobility-as-a-service* |
| **MCM** | *Multi-chip module* |
| **MCU** | *Microcontroller unit* |
| **MDM** | *Multi-dimensional metrology* |
| **MEC** | *Multi-access edge computing* |
| **MEC** | *Mobile edge computing* |
| **Medtech** | *Medical technology* |
| **MEMS** | *Micro-electromechanical systems* |
| **MES** | *Manufacturing execution system* |
| **MES** | *Multi-energy system* |
| **MIL** | *Model-in-the-loop* |
| **ML** | *Machine learning* |
| **MM-ENS** | *Multimodal energy system* |
| **MNBS** | *Micro-nano-bio system* |
| **MNS** | *Micro-nanosystems* |
| **MODAF** | *Ministry of Defence Architecture Framework (UK)* |
| **MOEMS** | *Micro-opto-electro-mechanical system* |

| | |
|---|---|
| **MOF** | *Metal–organic framework* |
| **MOOC** | *Massive open online course* |
| **MOSFET** | *Metal–oxide–semiconductor field-effect transistor* |
| **MPU** | *Microprocessing unit* |
| **MRAM** | *Magnetic RAM* |
| **MUT** | *Micromachined ultrasonic transducer* |
| **MV** | *Medium voltage* |
| **NB** | *Narrowband* |
| **NEMS** | *Nano-electromechanical systems* |
| **NFV** | *Network functions virtualisation* |
| **NFVI** | *Network functions virtualisation infrastructure* |
| **NLU** | *Natural language understanding* |
| **NMC** | *Near Memory Computing* |
| **NoC** | *Network on Chip* |
| **NPU** | *Neuromorphic processing unit* |
| **NVM** | *Non-volatile memory* |
| **OCT** | *Optical coherence tomography* |
| **ODD** | *Operational design domain* |
| **OECD** | *Organisation for Economic Co-operation and Development* |
| **OEF** | *Organisation Environmental Footprint* |
| **OEM** | *Original equipment manufacturer* |
| **OLED** | *Organic LED* |
| **OOC** | *Organ-on-a-chip* |
| **OPV** | *Organic Photovoltaics* |
| **OSI** | *open systems interconnection* |
| **OSS** | *Operations support system* |
| **OT** | *Operational technology* |
| **OTA** | *Over-the-air* |
| **OXRAM** | *Oxide-based RAM* |
| **P2P** | *Peer-to-peer* |
| **P4** | *Predictive, preventive, personalised, participatory* |
| **PAD** | *Productivity-aware design* |
| **PCB** | *Printed circuit board* |
| **PCM** | *Phase-change memory* |
| **PCRAM** | *Phase-change RAM* |
| **PDMS** | *Polydimethylsiloxane* |
| **PEALD** | *Plasma-enhanced atomic layer deposition* |
| **PEF** | *Product Environmental Footprint* |
| **PFAS** | *Per- and Polyfluorinated Substances* |
| **PFI** | *Physical and functional integration* |

| | |
|---|---|
| **PGHD** | *Patient-generated health data* |
| **PHM** | *Prognostic health management* |
| **PI** | *Polyimide* |
| **PIII** | *Plasma-immersion ion implantation* |
| **PIC** | *Photonic Integrated Circuit* |
| **PLC** | *Programmable logic controllers* |
| **PLM** | *Product lifestyle management* |
| **PMIC** | *Power management integrated circuit* |
| **PMUT** | *Piezoelectric micromachined ultrasound transducer* |
| **PoC** | *Point-of-care* |
| **PoCT** | *Point-of-care testing* |
| **PoF** | *Physics of failure* |
| **PPAC** | *Power, performance, area and cost* |
| **PPE** | *Personal protective equipment* |
| **ppm** | *Parts per million* |
| **PPP** | *Public/private partnership* |
| **PSiP** | *Power source in a package* |
| **PTEMM** | *Process technologies, equipment, materials and manufacturing* |
| **PV** | *Photovoltaics* |
| **PVD** | *Physical vapour deposition* |
| **PwrSiP** | *Power system in a package* |
| **PwrSoC** | *Power source on a chip* |
| **PZT** | *Lead zirconate titanate* |
| **QIP** | *Quantum information processing* |
| **QoS** | *Quality of service* |
| **QRSC** | *Quality, reliability, safety and cybersecurity* |
| **Qubit** | *Quantum bit* |
| **qZSI** | *Quasi-impedence source inverter* |
| **R&D** | *Research and development* |
| **R&D&I** | *Research and development and innovation* |
| **RAM** | *Random-access memory* |
| **RAMI 4.0** | *Reference Architecture Model for Industry 4.0* |
| **ReRAM** | *Resistive RAM* |
| **RES** | *Renewable energy system* |
| **RF** | *Radio frequency* |
| **RFID** | *Radio-frequency identification* |
| **RL** | *Reinforcement learning* |
| **RNN** | *Recursive neural network* |
| **ROHS** | *Restriction of Hazardous Substances Directive* |
| **ROI** | *Return on investment* |

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|---|---|
| **RPA** | *Robotic process automation* |
| **RRAM** | *Resistive RAM* |
| **RT-PCR** | *Real-time reverse transcription polymerase chain reaction* |
| **RTE** | *Run-time environment* |
| **RTO** | *Research and technology organisation* |
| **RUL** | *Remaining useful life* |
| **SaaS** | *Software as a service* |
| **SAC** | *Conventional SnAgCu* |
| **SAC** | *Tin-silver-copper alloy (SnAgCu)* |
| **SAE** | *Society of Automotive Engineers* |
| **SCADA** | *Supervisory control and data acquisition* |
| **ScAlN** | *Scandium aluminium nitride* |
| **SCM** | *Storage class memory* |
| **SCM** | *Supply chain management* |
| **SDDS** | *Smart drug delivery system* |
| **SDG** | *Sustainable Development Goal* |
| **SDK** | *Software development kit* |
| **SDN** | *Software-defined networking* |
| **SDR** | *Software-defined radio* |
| **SEAP** | *Strategic Environmental Assessment Plan* |
| **SECAP** | *Sustainable Energy and Climate Action Plan* |
| **SEES** | *Self-powered electrochemical energy storage system* |
| **SGD** | *Speech-generating device* |
| **SiC** | *Silicon carbide* |
| **SIL** | *Software-in-the-loop* |
| **SiP** | *System in a package* |
| **SKC** | *Skills, knowledge and competence* |
| **SME** | *Small and medium-sized enterprise* |
| **SNN** | *Spiking Neural Network* |
| **SoA** | *Service-oriented architecture* |
| **SoC** | *System on a chip* |
| **SoCPS** | *System of cyber-physical systems* |
| **SOI** | *Silicon-on-insulator* |
| **SoS** | *System of Systems* |
| **SOT** | *Spin-orbit torque* |
| **SOTIF** | *Safety of Intended Functionality* |
| **SPIRE** | *Sustainable Process Industry through Resource and Energy Efficiency* |
| **SRAM** | *Static RAM* |
| **SRGM** | *Software reliability growth models* |
| **SRIA** | *Strategic Research and Innovation Agenda* |

| | |
|---|---|
| **SSI** | *Smart systems integration* |
| **STDP** | *Spike-timing-dependent plasticity* |
| **STEM** | *Science, technology, engineering and mathematics* |
| **STS** | *Socio-technical system* |
| **STT** | *Spin-transfer torque* |
| **SUMP** | *Sustainable Urban Mobility Plan* |
| **SUT** | *System-under-test* |
| **SW** | *Software* |
| **SWM** | *Smart Water Management* |
| **TCP** | *Transmission control protocol* |
| **TEV** | *Through-encapsulant via* |
| **TOPS** | *Tera operations per second* |
| **TOU** | *Time of use* |
| **TPU** | *Tensor processing unit* |
| **TPU** | *Thermoplastic Polyurethane* |
| **TRL** | *Technology readiness level* |
| **TSMC** | *Taiwan Semiconductor Manufacturing Company* |
| **TSN** | *Time-sensitive network* |
| **TSO** | *Transmission system operator* |
| **TSV** | *Through-silicon via* |
| **TV&V** | *Testing validation and verification* |
| **UAV** | *Unmanned aerial vehicle* |
| **UAV** | *Unmanned autonomous vessel* |
| **ULP** | *Ultra-low power* |
| **UN** | *United Nations* |
| **UPS** | *Uninterruptible power supply* |
| **UXV** | *Unmanned vehicle* |
| **V&V** | *Verification & validation* |
| **V2G** | *Vehicle to grid* |
| **V2X** | *Vehicle-to-everything* |
| **VCMA** | *Voltage-controlled magnetic anisotropy* |
| **VIL** | *Vehicle-in-the-loop* |
| **VLSI** | *Very large-scale integration* |
| **VOC** | *Volatile organic compound* |
| **VR** | *Virtual reality* |
| **WBG** | *Wide bandgap* |
| **WHO** | *World Health Organization* |
| **WLP** | *Wafer-level packaging* |
| **WLTP** | *Worldwide Harmonised Light Vehicle Test Procedure* |
| **XR** | *Extended reality* |

### 6.2 Glossary

The scope of the ECS SRIA is very broad and spans many disciplines, each of which has developed a specific understanding of some of the terms used in this report. As a result, the same term can have different meanings for specialists in different ECS domains. This glossary defines some of those terms in an exclusive way to ensure there are no inconsistencies across the various chapters. Although there may be readers that feel uncomfortable with a few of the definitions provided here if they differ from what they commonly mean in their own areas, we feel that developing a common language is important in building a strong and integrated ECS community.

## SRIA DEFINITIONS

**2D materials:** materials that can be obtained in a single or very few monolayers, and whose advantageous properties derived from this fact; as opposed to much thicker 'thin films', and even thicker 'bulk materials'

**3D integration:** a vertical stack of circuitry or integrated circuits (ICs) for meeting electronic device requirements such as higher performance, increased functionality, lower power consumption, and a smaller footprint. In general, 3D integration is a broad term that includes technologies such as: 3D wafer-level packaging; 2.5D and 3D interposer-based integration; 3D stacked ICs (3D-SICs), monolithic 3D ICs; 3D heterogeneous integration; and 3D systems integration.

**3D printing:** also known as additive manufacturing, this is the construction of a three-dimensional object from a computer-aided design (CAD) model or digital 3D model. The term “3D printing” can refer to a variety of processes in which materials are deposited, joined or solidified under computer control to create a three-dimensional object, with typically the materials (such as liquid molecules or powder grains being fused together) being added on a layer-by-layer basis.

**5G:** fifth-generation wireless (5G) is the latest iteration of cellular technology, engineered to greatly increase the speed and responsiveness of wireless networks. With 5G, data transmitted over wireless broadband connections can travel at multi-gigabit speeds, with potential peak speeds as high as 20 gigabits per second (Gbps) by some estimates. These speeds exceed wireline network speeds and offer latency of 1 millisecond (ms) or lower, which is useful for applications that require real-time feedback. 5G will enable a sharp increase in the amount of data transmitted over wireless systems due to more available bandwidth and advanced antenna technology. 5G networks and services will be deployed in stages over the next few years to accommodate the increasing reliance on mobile and internet-enabled devices. Overall, 5G is expected to generate a variety of new applications, uses and business cases as the technology is rolled out.

**6G:** (sixth-generation wireless) is the successor to 5G cellular technology. 6G networks will be able to use higher frequencies than 5G networks and provide substantially higher capacity and much lower latency. Millimeter waves (30 to 300 GHz) and terahertz radiation (300 to 3000 GHz) will most likely be used in 6G. Hundreds of gigabits per second transmission rates will be obtained. One of the important goals of the 6G internet is to support one microsecond latency communications. Artificial Intelligence will be important in designing and optimizing 6G architectures, protocols, and operations.

**Advanced Packaging :** suite of novel technologies, processes and competences that in a cost-and resource-efficient way allows the physical, electrical and functional integration of any set of technological diverse components required to build an advanced electronic system.

**Ambient Assisted Living (AAL):** information and communication-based products and services that integrate modern technologies (sensors, microcontrollers, connectivity, secure elements, Artificial Intelligence, etc) into the homes and lives of disabled persons, and vulnerable or older adults. These technologies aim to improve the lives of those facing some of the challenges of ageing, and those who care for older people if they need help. An impact of AAL is also in reducing the costs of health and social care.

**Artificial Intelligence (AI):** the theory and development of information processing systems able to perform tasks usually requiring human intelligence (such as visual perception, speech recognition, decision-making, and translation between languages) with a certain degree of autonomy. Currently, Large language models, or LLMs have received most attention in AI. They are a type of AI that can mimic human intelligence. They use statistical models to analyze vast amounts of data, learning the patterns and connections between words and phrases.

**Augmented reality (AR):** an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.

**Autonomous system (AS):** performs desired tasks in unstructured environments without continuous human guidance.

**Biologic drugs:** products that are produced from living organisms or contain components of living organisms. Biologic drugs include a wide variety of products derived from human, animal or microorganisms by using biotechnology. Types of biologic drugs include vaccines, blood, blood components, cells, allergens, genes, tissues and recombinant proteins.

**Blockchain:** decentralised, chronologically updated database with a consensus mechanism created from a network for the permanent digital securitisation of property rights.

**Brain–computer interface (BCI):** a direct communication interface between a (biological) brain and a technical (IT- and/or ECS-based) system. A BCI can transfer information in both directions – e.g. enabling the brain to control the technical system or enhancing human perception (such as hearing) with additional information from the technical system (e.g. hearing aid).

**Care pathway:** the sequence of health and care services a patient receives after entering the care systemduring an episode of care.

**Cath lab:** examination room in a hospital or clinic with diagnostic imaging equipment used to visualise thearteries of the heart and the chambers of the heart.

**Cloud:** the on-demand availability of computer system resources, especially data storage (cloud storage) and computing power, without direct active management by the user. The term is generally used to describe data centres available to many users over the internet (from Wikipedia).

**Component:** a combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case. A component is not self-contained in all its functions, as it requires the close support of other components for operation (e.g. in data processing, power handling, embedded software).

**Computer-aided design (CAD):** the use of computers (or workstations) to aid in the creation, modification, analysis or optimisation of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

**Conformal electronics:** newly developed microelectronics that overcome the standard planar paradigm and can be prepared on arbitrary curvilinear surface.

**Contract-based design:** a design methodology where the system, itself as well as its constituents (subsystems, components, modules, etc), are described by contracts that are formalised by specifications of their functional behaviour and properties. This is often given in a "assume-guarantee" format (e.g. for a certain software module a contract could be: "If the other components of the system guarantee the availability of input data at certain, well-defined times and if the hardware platform on which this module is running guarantees the availability of certain processing and memory resources (assumptions), then (guarantee) this module will produce its output within a certain, guaranteed time interval"). In this methodology, a designed system is "correct" if (informally): (i) all assumptions of all constituents are met by guarantees of other constituents; and (ii) the contracts of all constituents together imply the contract of the complete system.

**Coopetition:** a neologism for the act of cooperating and competing at the same time. Companies that compete in the market with their products might still cooperate on topics that are either pre-competitive or non-product differentiating. Typical examples here are interoperability, standards and development processes.

**Cyber-physical system (CPS):** an ECS in which a physical artefact is controlled or monitored by algorithms. A CPS is the result of tight intertwined hardware and software components capable of creating a link between the physical world and the digital world, to operate on different spatial and temporal scales, exhibit multiple and distinct behavioural modalities, and interact with each other in ways that depend on the context. Examples of CPS include smart grid, autonomous automobile systems, medical monitoring, industrial control systems, robotics systems and automatic pilot avionics.

**Cybersecurity:** the protection of information against unauthorised disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).

**Deep edge:** the farthest extreme node where subsystems (sensors, actuators, data loggers) interface with the real world. This node is connected to the cloud, but the connection can be intermittent or absent for long periods of time. The emergence of "tiny machine learning" is based on this premise to enable AI in performance-constrained environments (ultra-low power, limited memory size and calculation power), but always very close to the subsystem.

**Deep learning (DL):** a special form of machine learning based on artificial neural networks, DL is where the system is able to automatically discover the representations needed for feature detection or classification from raw data. The adjective "deep" in deep learning comes from the use of multiple layers in the network (from Wikipedia).

**Deeply embedded software:** software that runs on dedicated hardware and not on standard microprocessors. In its simplest form, it is called "firmware".

**Dependability:** according to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here can be a device, component, module or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01-27) and maintenance support performance (192-01-29), and in some cases other characteristics, such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).

**Development or design tools, development or design frameworks, design flow:** design tools are software tools supporting engineers with different tasks during system designs. Ideally, these tools are integrated into frameworks that: (i) provide a uniform user interface to all tools; (ii) "sort" the tools according to the different steps in the design process; and (iii) ensure interoperability between the integrated tools. Regardless of whether the tools used are integrated into a framework or not, the order in which the tools are used is called the "design flow".

**Device:** in the context of the SRIA, and if it is not further qualified, a device will designate a "packaged chip", whether it is a packaged integrated circuit (e.g. system on a chip, memory, processor, microcontroller) or a micro-electromechanical system (MEMS)/micro-opto-electro-mechanical system (MOEMS). A device performs a general electrical, electronic or electrical/electronic-physical transduction role.

**Digital infrastructure:** foundational services necessary to the IT capabilities of a nation, region, city or organisation.

**Digital Product Passport:** digital identity of a physical product gathering information about the entire product lifecycle.

**Digital twin:** a digital replica of a living or non-living physical entity. Digital twin refers to a digital replica of potential and actual physical assets, processes, people, places, systems and devices that can be used for various purposes. The digital representation provides both the elements and the dynamics of how the physical entity operates and "lives" throughout its lifecycle. To be useful in systems engineering, digital twins need to be executable (i.e. engineers must be able to use them in simulations as representatives of the actual physical entity) and/or amendable to formal analysis methods. The more aspects of the physical entity are represented in a digital twin, the more useful it becomes.

**Divide and conquer strategy:** a strategy in systems engineering where a large problem (i.e. designing and building a complex system or even System of Systems) is iteratively broken down ("divided") into smaller problems (i.e. designing subsystems, modules and components), which are then divided further or solved ("conquered"). The results of each step are then integrated into a solution for the next-level larger problem. Divide and conquer typically leads to hierarchical designs; it is also a strategy well suited for distributed developments within supply chains and platform economies.

**Edge computing:** a computing paradigm where computation and data storage are close to the location where they are needed, to improve response times, save bandwidth and increase independence. It can also include the gateway between deep edge devices and other edge devices (organised in a federation of devices, see fog computing), or with the cloud (modified from Wikipedia).

**Embedded (or edge) high-performance computing:** provides supercomputing processing performance in rugged, compact and easily deployable computing architectures optimised to work in harsh environments in the field. Bringing high-performance computing capabilities from data centres to field-deployable applications means reducing space, weight and power absorption, increasing resistance, robustness and reliability while maintaining the same advanced computational performance and energy efficiency. Embedded (or edge) high-performance computing is an enabling technology for many vertical domains, such as autonomous driving, UAV, and security and surveillance systems.

**Embedded software:** the software that runs on embedded and cyber-physical systems, providing the low-level functionalities required to use the available hardware resources, dedicated operating systems, run-time environments, virtualisation and containerisation platforms, application software, micro-services, etc. Embedded software is specifically conceived to optimally exploit the limited hardware resources of embedded and cyber-physical systems. For deeply embedded software, see the separate definition.

**Embedded system:** an ECS generated from the combination of a microprocessor(s), GPUs or system on a chip, memory, input/output peripheral devices and embedded software that have a dedicated function within a larger mechanical or electrical system.

**Extended reality (XR):** refers to all real and virtual combined environments and human–machine interactions generated by computer technology and wearables, where the "X" represents a variable for any current or future spatial computing technologies.

**Fog computing:** an architecture that uses edge devices to carry out a substantial amount of computation, storage and communication locally, and routed over the internet backbone (from Wikipedia).

**Functional safety:** the ability of a system or piece of equipment to control recognised hazards to achieve an acceptable level of risk – such as maintaining the required minimum of operation even in case of likely operator errors, hardware failures and environmental changes – to prevent physical injuries or damages to the health of people, either directly or indirectly.

**Prosthetics:** the branch of medicine or surgery that deals with the production and application of artificial body parts.

**Healthcare:** the preservation of mental and physical health by preventing or treating illness through services offered by the health profession.

**Heterogeneous integration:** refers to the integration of separately manufactured components into a higher-level assembly (system in a package) that, in the aggregate, provides enhanced functionality and improved operating characteristics. In this definition, components should be taken to mean any unit, whether individual die, MEMS device, passive component or assembled package or subsystem, that are integrated into a single package. The operating characteristics should also be taken in its broadest meaning to include characteristics such as system-level performance and cost of ownership (from ITRS Assembly & Packaging chapter).

**Industry 4.0:** the application of technology to digitally transform how industrial companies operate. These technologies include the industrial Internet of Things (IoT), automation and robotics, simulation, additive manufacturing, and analytics. Industry 4.0 is driven by a need to boost efficiency, become more agile to respond to market unpredictability, improve quality, and to enable new business models.

**In silico clinical trials:** in silico means performed on a computer or via computer simulation. The term characterises biological experiments carried out entirely on a computer. Although in silico studies represent a relatively new avenue of inquiry, they have begun to be used widely in studies that predict how drugs will interact with the body and with pathogens.

**In vitro diagnostics:** the technique of performing a given procedure in a controlled environment outside of a living organism. Many experiments in cellular biology are conducted outside of organisms or cells. One of the abiding weaknesses of in vitro experiments is that they fail to replicate the precise cellular conditions of an organism, particularly a microbe.

**In vivo clinical trials:** experimentation using a whole living organism as opposed to a partial or dead organism. Animal studies and clinical trials are two forms of in vivo research. In vivo testing is often employed over in vitro because it is better suited for observing the overall effects of an experiment on a living subject. Integrated practice unit: Involves a shift from the current siloed organisation by specialty department and discrete service to being organised around the patient's medical condition. Care is delivered by a dedicated multidisciplinary team of clinicians who take responsibility for the full cycle of care for the condition, encompassing outpatient, inpatient, and rehabilitative care, and supporting services (e.g. nutrition, social work, behavioural health). The team measures processes and outcomes as a team not individually, and accepts joint accountability for outcomes and costs.

**Integrated circuit:** an electronic circuit formed on a small piece of semiconducting material, performing the same function as a larger circuit made from electronic building blocks.

**Integrated Photonics:** technology that in a microchip embodiment produces systems that detect, generate, transport and process light.

**Integration platform:** an ECS allowing the integration of different systems, applications and services into a single system. They can be found on all layers of the design hierarchy, ranging from "communication backplanes" in hardware design to "reference architectures" and "middlewares" in system engineering, to distributed service platforms in System of Systems. Integration platforms are an important basis for: (i) standardisation; and (ii) platform-based economies.

**Internet of Things (IoT):** the set of technologies that bring intelligence to objects, enabling them to communicate with other objects or with other devices. IoT describes the network of physical objects – "things" – that perform functions. For example, with these technologies, billions of sensors embedded in everyday devices can be designed to record, process, store and transfer data, and to interact with other devices or systems that use the network's capabilities.

**Interoperability:** the capability of computing systems to exchange information that can be understood and used by the receiving system.

**Key digital technologies:** electronic and photonic components, and the software that defines how they work. These technologies underpin all digital systems, including Artificial Intelligence and the Internet of Things.

**Lab-on-a-chip (LOC):** a miniaturised device that integrates one or several biological or chemical analysis functions on a single chip (e.g. detecting specific proteins).

**Large-area electronics (LAE):** electronics fabricated utilising printing and roll-to-roll fabrication methods that, as opposed to integrated circuit technologies, can be used on significantly larger substrates. Inorganic and organic inks and pastes are used for printing conductors and active components such as transistors. Substrates in LAE are typically flexible, such as plastic films or paper, giving rise to the term "flexible electronics".

**Large Language Model (LLM):** A large language model is a type of language model notable for its ability to achieve general-purpose language understanding and generation. LLMs acquire these abilities by using massive amounts of data to learn billions of parameters during training. LLMs are artificial neural networks (mainly transformers) and are (pre-)trained using self-supervised learning and semi-supervised learning.

**Machine learning:** ability for a machine to learn by example without being explicitly programmed to perform the target function. This is one method for implementing Artificial Intelligence.

**MEMS, MOEMS, NEMS, MNS, MNBS:** micro-electromechanical systems (MEMS) originally referred to miniaturised devices that provided a precise mechanical output (typically a small vertical, horizontal, or rotary displacement) upon an electric excitation (e.g. a microrelay), or vice versa, or an electronic signal from a mechanical excitation (e.g. a microaccelerometer or gyroscope). When the objective of such displacement was to interact with light (e.g. a micromirror), the term "micro-opto-electromechanical systems (MOEMS) was used. Gradually, the transduction domain was extended beyond the mechanical one and chemical and biological mediation were also considered. The overall size of MEMS devices could be in the mm or cm range, the term "micro" referring to the dimension of the device's internal features to be mastered for the device to be functional. The term "nanoelectromechanical systems" (NEMS) is used when such critical dimension falls back into the nano domain. The terms "microsystem", "micro-nanosystem" (MNS), or "micro-nano-bio system" (MNBS) were alternatively introduced for those small devices amenable to such generalised transduction principles. This kind of device could be fabricated in principle with different materials, but silicon technologies provided a micromachinable material and a miniaturised technology responsive to the integration of the electronic signal to be conveyed or transduced. MEMS, MOEMS, NEMS, MNS and MNBS are very successful means of interaction between the physical and digital worlds, providing information systems with the means to interact with their environment, sensing it, actuating on it or being powered by it.

**Model-based design:** where design artefacts (the system, subsystems, component, modules, as well as their connections and the environments in which they will be used), are represented by models that are abstract descriptions of certain aspects of such artefacts (typically, their functional behaviour, timing properties, etc). Ideally, these models are: (i) executable, thus usable in simulation and early verification and validation (V&V); and (ii) detailed enough to be usable in formal analysis and test methods.

**Module:** ensemble of properly integrated components so that their reunion embodies a definite functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and software, making it interchangeable between systems, and allowing higher abstraction level in systems design.

**Molecular biology:** study of phenomena in terms of biology molecular (or chemical) interactions. Molecular biology emphasises chemical interactions involved in the replication of DNA, its "transcription": into RNA, and its "translation" into or expression in protein – that is, in the chemical reactions connecting genotype and phenotype.

**Open source hardware:** the blueprint of hardware artefacts that is (partially) freely available and which anyone can use, modify or enhance (depending on different licences associated with the blueprint).

**Open source software:** software with source code that is (partially) freely available and which anyone can use, modify or enhance (depending on different open source licensing models existing).

**Operational design domain (ODD):** comprises the "operating conditions under which a given […] system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain [environmental] characteristics" (Surface Vehicle Recommended Practice — Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE: J3016, 2018).

**Optical coherence tomography (OCT):** a non-invasive imaging test that uses light waves to take cross-section pictures of the retina to help with diagnosis. They also provide treatment guidance for glaucoma and diseases of the retina such as age-related macular degeneration (AMD) and diabetic eye disease.

**P4 medicine:** a shift in medicine from a reactive to a proactive discipline that is focused on predictive, personalised, preventive and participatory (P4). P4 medicine will be driven by system approaches to disease, emerging technologies and analytical tools.

**Patient-generated health data (PGHD):** health-related data created, recorded or gathered by or from patients (or family members or other caregivers) to help address a health concern.

**Personalised medicine:** tailoring of medical treatment for patient cohorts to be treated in a unique manner depending on their health status and previous course of a disease and analysis of personal characteristics.

**Photonics:** Photonics is the science and technology of light. It encompasses generating, guiding, manipulating, amplifying and detecting light. Photonic components process photons (light) analogous to electronic components processing of electrons. A photonic integrated circuit (PIC) or integrated optical circuit is a microchip containing two or more photonic components which form a functioning circuit.

**Plug and play components:** component with a specification that facilitates the discovery of a hardware component in a system without the need for physical device configuration or user intervention in resolving resource conflicts.

**Point of care:** the location at which patient services are delivered (excluding hospital, doctor's office, patient's home).

**Point-of-care testing (POCT or bedside testing):** performance of clinical laboratory testing at the site of patient care rather than in a laboratory, often by non-laboratorians.

**Point of need:** new model of having critical data and information when and where it is needed rather than at the point of care. These are diagnostics that can be done anytime, anywhere, for anyone – for instance, as a vital part of managing a chronic disease over time, resulting in improved treatment and patient outcomes.

**Predictive maintenance:** techniques designed to help determine the condition of in-service equipment to estimate when maintenance should be performed.

**Product lifecycle management (PLM):** process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products.

**Prognostics (a.k.a. health management):** a method that permits the assessment of the reliability of the product (or system) under its application conditions. It predicts the occurrence of an event based on current and future operational and environmental conditions to estimate the time at which a system no longer fulfils its function within desired specifications ("remaining useful life").

**Prosthetics:** the branch of medicine or surgery that deals with the production and application of artificial body parts.

**Quality:** in this SRIA, quality is defined as "the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (burn-in) but no other type of testing". In this way, reliability, dependability and cybersecurity, which some readers may have expected to be included under quality, will be treated separately.

**Quantum computing:** an area of computing focused on developing computer technology based on the principles of quantum theory, which explains the behaviour of energy and material on the atomic and sub-atomic levels. A quantum computer utilises quantum entanglement between qubits to solve a set of computationally complex problems efficiently. The computational power of quantum computers is estimated to grow faster than classical computers in the future.

**Quantum sensing:** sensor technologies that make use of quantum technology.

**Quantum technology:** the creation, manipulation and detection of single particle quantum states accurately, enabling the use of quantum superposition and entanglement, where quantum states of several particles cannot be described independently, even when spatially separated. Currently, quantum effects typically require very low temperatures and the use of cryogenic technologies.

**Recommender-based (methods and) tools:** methods and tools in which the current status of a system under design is analysed and evaluated by design-supporting software, which then gives recommendations to the engineer as to possible further steps and/or options for completing the design, ideally together with an evaluation of the pros and cons for each option.

**Reliability:** the ability or probability, respectively, of a system or component to function as specified under stated conditions for a specified time (ISO 25010).

**Safety (a.k.a. functional safety):** freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or the environment (IEC 61508).

**Security of ECS (a.k.a. IT security/cybersecurity):** in this SRIA, security of ECS is defined as the prevention of illegal or unwanted penetration, intentional or unintentional interference with the proper and intended operation, or inappropriate access to confidential information. Security is considered to be composed of confidentiality, integrity and availability (ISO 21549-2).

**Self-X:** in self-X, X stands for adaptation, reconfiguration, etc. Usually in self-reorganising systems the major issue is how to self-reorganise while preserving the key parameters of a system, while being coherent with the initial requirements (e.g. performance, power consumption, real time constraints). Self-adaptation and self-reconfiguration has an enormous potential in many applications.

**Smart city:** an urban area that uses different types of electronic methods and sensors to collect data. Insights gained from that data are used to manage assets, resources and services efficiently; in return, that data is used improve the operations across the city (from Wikipedia).

**Smart drug delivery system (SDDS):** an advanced method of drug-targeted (DT) delivery. The smart drug delivered by this system must fulfill the following criteria: (i) increase the doses of delivered drug to the targeted body part of interest (tissue/cells/organs); (ii) not be degraded by any of the body fluids; (iii) diminish side effects by improving the efficacy of drug treatment; (iv) absorption of the delivered drug must cross a biological membrane; and (v) drug is released in appropriate dosages to the body part of interest. SDDS is highly complex and involves an integration of various disciplines, such as biology, chemistry and engineering.

**Smart systems integration (SSI):** (integrated) smart systems incorporate sensing, actuation and control up to cognitive functions to describe and analyse a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. The enabling principles of these functions include nanoelectronics, micro-electromechanics, magnetism, photonics, chemistry and radiation. SSI is an assembly of technologies that: build products from components; combine functions in products and systems; connect and network systems to other systems; and, importantly, enable systems to receive and store a "knowledge base" – the software that makes them "smart".

**Stretchable electronics:** newly developed microelectronics that overcome the standard planar paradigm and can be prepared on stretchable substrates.

**Structural electronics:** integrating electronics into the body of structural parts of products of different materials.

**System:** for the purpose of this SRIA, a system is a set of electronic-based constituents (subsystems, modules and components, realised in hardware, software, or both) that are integrated in a way to together allow the system to perform a desired (set of) function(s).

Note that:

- Due to ECS typically being constructed hierarchically, a (e.g. camera or other sensor) "module" being part of the electronic "system" in an autonomous car might itself be referred to as a "system" when designing it (e.g. while integrating lower-level components to together achieve the "camera function") (see also: system in a package, system on a chip, and others).
- The difference between a "system" (comprising subsystems, modules and components) and a "System of Systems" (also comprising subsystems) is that the constituents of a system are chosen and integrated during design-time (i.e. completely under control of the engineers), while in a System of Systems the constituent (sub)systems are independent and dynamically form (and disband) a System of Systems at run-time.

**System in a package (SiP):** a number of integrated circuits and other electronics building blocks (e.g. MEMS, antennas) enclosed in one single package.

**System on a chip (SoC):** an integrated circuit that incorporates multiple building blocks of an electronic system, including processors, memory units, accelerators, and input/output ports, and which covers the complete functionality of an electronic system.

**System of Systems (SoS):** a collection of independent and distributed embedded and cyber-physical systems dynamically composed to generate a new and more complex system, provided with new functionalities and driven by new goals not present in the constituent embedded and cyber-physical systems individually. An SoS must satisfy five characteristics: operational independence of constituent systems; managerial independence of constituent systems; geographical distribution; emergent behaviour; and evolutionary development processes. A system that does not satisfy these characteristics (specifically the first two) is not considered an SoS.

**Teleoperation:** teleoperation (or remote operation) indicates operation of a system or machine at a distance. It is similar in meaning to the phrase "remote control" but is usually encountered in research, academia and technical environments. It is most commonly associated with robotics and mobile robots, but can be applied to a whole range of circumstances in which a device or machine is operated by a person from a distance.

**Telepresence:** the use of virtual reality technology, especially for remote control of machinery or for participation in distant events.

**Tracking mode simulation:** adapting simulation by respective measurements of the real counterpart.

**(Technical) Trustworthiness:** having some reasonably well thought-out assurance that the technical realisation of a system is worthy of being trusted to satisfy certain well-specified requirements (e.g. safety, security, reliability, robustness and resilience, ease of use and ease of system administration, and predictable behaviour in the face of adversities, such as high-probability real-time performance).

**Value-based healthcare:** a healthcare delivery model in which providers, including hospitals and physicians, are paid based on patient health outcomes. Under value-based care agreements, providers are rewarded for helping patients improve their health, reduce the effects and incidence of chronic disease, and live healthier lives in an evidence-based way.

**Verification and validation (V&V):** independent procedures that are used together for checking that a product, service or system meets requirements and specifications, and that it fulfills its intended purpose. Verification checks whether the development implemented the specified requirements of a product correctly ("are we building the product right"), while validation is a system test checking whether a product can fulfil its intended purpose in a real environment ("are we building the right product?").

**Virtual commissioning:** the practice of using "virtual" simulation technology to "commission" – design, install or test – control software with a virtual machine model before it is connected to a real system.

**Virtual reality (VR):** computer technology that makes a person feel like they are somewhere else. It uses software to produce images, sounds and other sensations to create a different place so that the user feels they are really part of this other place. Applications of virtual reality can include entertainment (e.g. video games) and educational purposes (e.g. medical or military training).

**Wearables:** wearable technology is a category of electronic devices that can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin.

**X-in-the-loop:** where "X" can be hardware-, software-, models-, systems-, etc. The term is used when testing ECS (or parts of an ECS). The system (e.g. component, module) to be tested is called "system-under-test" (SUT). This SUT is embedded into a testbed (or test environment) that provides the necessary input data (according to a specific test scenario), and which then monitors its outputs, comparing these actual outputs to the expected/specified ones. Within these testbeds, data flow therefore forms a “loop” (from the testbed through the SUT back to the testbed). Depending upon the realisation of the SUT (e.g. as a hardware component/module, software module, simulation model, complete system), different testbeds are needed and the resulting test process is called “hardware-in-the-loop”, “software-in-the-loop”, etc, or when referred to in a general way “X-in-the-loop”.

### 6.3 Main objectives: An analysis of all major challenges

In this ECS-SRIA the Major Challenges identified by the different chapter teams were analysed and finally merged into Main Common Objectives for the ECS community as shown in the following tables.

In the table, Major Challenges numbering is composed by three digits X.Y.Z, where:

- x is the ECS-SRIA Part (1, 2 or 3);
- y is the ECS-SRIA Chapter (1-4 for Part 1, 1-4 for Part 2 and 1-6 for Part 3);
- z is the Major Challenge number in the specific Chapter.

| EC STRAT. TARGETS | INDUSTRIAL COMPETITIVENESS | EU SOVEREIGNITY | SUSTAINABILITY AND GREEN DEAL | DIGITAL AGE (AI, NGC) |
|---|---|---|---|---|
| ECS R&I OBJEC-TIVES | Boost industrial competitiveness through interdisciplinary technology innovations | Ensure EU sovereignity through secure, safe and reliable ECS supporting key European application domains | Establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal | Unleash the full potential of intelligent and autonomous ECS-based systems for the European Digital Era |
|  | Interdisciplinary technology innovation | Secure, safe and reliable ECS | Sustainable & resilient ECS | Intelligent and autonomous ECS |
| **Major Challenges in ECS Research and Innovation** | **1.1.1** Advanced computing, memory and in-memory computing concepts | **1.3.5** Software reliability and trust | **1.1.4** World-leading and sustainable semiconductor manufacturing equipment and technologies | **1.1.1** Advanced computing, memory and in-memory computing concepts |
|  | **1.1.2** Novel devices and circuits that enable advanced functionality | **1.4.2** SoS interoperability | **1.2.4** Sustainability and Recyclability | **1.1.2** Novel devices and circuits that enable advanced functionality |
|  | **1.1.3** Advanced heterogeneous integration and packaging solutions | **1.4.3** Evolvability of SoS composed of embedded and cyber-physical systems | **1.3.5** Support for Sustainability by embedded software | **1.3.4** Embedding Data Analytics and Artificial Intelligence |
|  | **1.1.4** World-leading and sustainable semiconductor manufacturing equipment and technologies | **1.4.5** Control in SoS composed of embedded and cyber-physical systems | **1.4.2** SoS interoperability | **1.4.5** Control in SoS composed of embedded and cyber-physical systems |
|  | **1.2.2** Integration technologies, processes and manufacturing | **2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain | **1.4.5** Control in SoS composed of embedded and cyber-physical systems | **2.1.1** Increasing the energy efficiency of computing systems |
|  | **1.2.3** Technologies, Manufacturing and Integration Processes | **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity | **2.1.1** Increasing the energy efficiency of computing systems | **2.1.3** Supporting the increasing lifespan of devices and systems |
|  | **1.4.1** SoS architecture and open integration platforms | **2.4.1** Ensuring HW quality and reliability | **2.1.3** Supporting the increasing lifespan of devices and systems | **2.1.4** Ensuring European sustainability in embedded architectures design |
|  | **1.4.2** SoS interoperability | **2.4.2** Ensuring dependability in connected software | **2.1.4** Ensuring European sustainability in embedded architectures design | **2.2.3** Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics |
|  | **1.4.5** Open "system of embedded and cyber-physical systems" platforms | **3.1.1** Enable CO$_2$ neutral (electrified or sustainable alternative fuels based) mobility and required energy transformation | **2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain | **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity |
|  | **2.1.1** Increasing the energy efficiency of computing systems | **3.1.2** Enable affordable, automated and connected mobility for passengers and freight on or off road, rail, air and water | **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity | **3.1.3** Modular, scalable, re-usable, flexible, cloud-based, safe&secure end-to-end software platform able to manage software-defined mobility of the future |
|  | **2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain | **3.1.5** Achieve real-time data handling for multimodal mobility and related services. | **2.4.4** Ensuring of safety and resilience | **3.1.5** Achieve real-time data handling for multimodal mobility and related services. |
|  | **2.2.2** Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership | **3.2.2** Energy Management from On-Site to Distribution Systems | **3.1.1** Enable CO$_2$ neutral (electrified or sustainable alternative fuels based) mobility and required energy transformation | **3.2.1** Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems |

| | | | | |
|---|---|---|---|---|
| | **2.2.5** Network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures | **3.2.4** Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply | **3.1.2** Enable affordable, automated and connected mobility for passengers and freight on or off road, rail, air and water | **3.3.1** Responsive and smart production |
| | **2.3.2** Managing new functionality in safe, secure and trustworthy systems | **3.4.1** Enable digital health platforms based upon P4 healthcare | **3.1.3** Modular, scalable, re-usable, flexible, cloud-based, safe&secure end-to-end software platform able to manage software-defined mobility of the future | **3.3.3** Artificial Intelligence in Digital Industry |
| | **2.3.4** Managing Diversity | **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies | **3.2.1** Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems | **3.3.6** Autonomous systems, robotics |
| | **3.1.5** Achieve real-time data handling for multimodal mobility and related services. | **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system | **3.2.3** Future transmission grids | **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies |
| | **3.2.2** Energy Management from On-Site to Distribution Systems | **3.4.5** Ensure more healthy life years for an ageing population | **3.2.4** Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply | **3.4.4** Enhance access to personalized and participative treatments for chronic and lifestyle related diseases |
| | **3.2.3** Future transmission grids | **3.5.1** Food Security | **3.3.1** Responsive and smart production | **3.4.5** Ensure more healthy life years for an ageing population |
| | **3.2.5** Cross-Sectional Tasks for Energy System Monitoring & Control | **3.5.2** Food Safety | **3.3.2** Sustainable production | **3.5.1** Food Security |
| | **3.4.1** Enable digital health platforms based upon P4 healthcare | **3.6.3** Facilitate inclusion and collective safety | **3.4.1** Enable digital health platforms based upon P4 healthcare | **3.5.3** Environmental protection and sustainable production |
| | **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies | | **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies | **3.5.4** Water resource management |
| | **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system | | **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system | |
| | **3.5.3** Environmental protection and sustainable production | | **3.4.4** Enhance access to personalized and participative treatments for chronic and lifestyle related diseases | |
| | **3.5.4** Water resource management | | **3.4.5** Ensure more healthy life years for an ageing population | |
| | **3.5.5** Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation | | **3.5.3** Environmental protection and sustainable production | |
| | **3.6.1** Facilitate individual self-fulfilment | | **3.5.4** Water resource management | |
| | **3.6.2** Facilitate empowerment and resilience | | **3.5.5** Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation | |
| | **3.6.3** Facilitate inclusion and collective safety | | **3.6.2** Facilitate empowerment and resilience | |
| | **3.6.4** Facilitate supportive infrastructure and a sustainable environments | | **3.6.4** Facilitate supportive infrastructure and a sustainable environments | |

| | Ensure engineering support across the entire lifecycle of complex ECS-based systems<br>Lifecycle engineering support | | | |
|---|---|---|---|---|
| **Major Challenges in ECS Research and Innovation** | **1.2.1** Enabling new functionalities in components with More-than-Moore technologies. | **1.3.2** Continuous integration and deployment | **1.3.1** Efficient Engineering of Embedded Software | **2.1.2** Managing the increasing complexity of systems |
| | **1.3.1** Efficient Engineering of Embedded Software | **1.3.3** Life cycle management | **1.3.2** Continuous integration and deployment | **2.3.1** Extending Development Processes and Frameworks (to handle connected, intelligent, autonomous, evolvable systems) |
| | **1.3.2** Continuous integration and deployment | **1.4.1** SoS architecture and open integration platforms | **1.4.1** SoS architecture and open integration platforms | **2.3.3** Managing Complexity |
| | **1.3.3** Life cycle management | **1.4.4** SoS integration along the life cycle | **1.4.6** SoS Monitoring and management | **3.1.4** Provide tools and methods for validation & certification of safety, security and comfort of embedded intelligence in mobility |
| | **1.4.1** SoS architecture and open integration platforms | **1.4.1** SoS architecture and open integration platforms | **2.1.2** Managing the increasing complexity of systems | **3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation |
| | **1.4.3** Evolvability of SoS composed of embedded and cyber-physical systems | **1.4.6** SoS Monitoring and management | **2.3.3** Managing Complexity | **3.3.5** Digital twins, mixed or augmented reality, telepresence |
| | **1.4.4** SoS integration along the life cycle | **2.1.2** Managing the increasing complexity of systems | **2.3.4** Managing Diversity | |
| | **2.1.2** Managing the increasing complexity of systems | **2.3.2** Managing new functionality in safe, secure and trustworthy systems | **2.4.5** Human Systems Integration | |
| | **2.4.5** Human Systems Integration | **2.3.3** Managing Complexity | **3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation | |
| | **3.3.5** Digital twins, mixed or augmented reality, telepresence | **2.3.4** Managing Diversity | | |
| | | **2.4.3** Ensuring cyber-security and privacy | | |
| | | **3.1.4** Provide tools and methods for validation & certification of safety, security and comfort of embedded intelligence in mobility | | |
| | | **3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation | | |

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