E C S

Strategic Research and Innovation Agenda 2027

EXECUTIVE SUMMARY

ELECTRONIC
COMPONENTS AND SYSTEMS



Strategic Research and Innovation Agenda

ELECTRONIC COMPONENTS AND SYSTEMS

PREPARED BY:







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Strategic Research and Innovation Agenda

INTRODUCTION AND OVERVIEW

Introduction and Overview

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0.1 PART 1 – WHY? GOALS AND PURPOSES OF ECS SRIA 2027

Trade and geopolitical tensions, climate change, ageing societies and rapid advances in artificial intelligence are changing both the demand for Electronic Components and Systems (ECS) and the conditions under which they are developed. In particular, ECS bear the promise to be key enabling tools allowing to overcome many of the challenges Europe is facing. Europe's competitiveness and resilience depend on its ability to turn research excellence into dependable ECS at industrial scale. With many technology options and limited financial and human resources, Europe needs to focus collaborative research where it can build strength, address critical dependencies and create value in strategic applications.

This is the purpose of this ECS Strategic Research and Innovation Agenda (ECS SRIA), jointly developed by the experts of the European ECS community, coordinated by the three industry associations: AENEAS, INSIDE Industry Association (formerly ARTEMIS-IA) and EPoSS. This tenth edition identifies the Major Challenges, necessary RD&I efforts and expected outcomes. The technology domains addressed range from micro- and nanoelectronics, smart electronics system integration (e.g. chiplets) via embedded and cyber physical systems to complex system of systems integration. It is an essential tool to drive the ECS research and innovation efforts in Europe with the ultimate goal of creating value, growth, jobs and prosperity.

0.1.1 The ECS SRIA: An agenda aligned with European priorities

ECS are the key technology, enabler and differentiating factor behind all mass applications and their innovations, serving a market of over 61 trillion Euro (see figure 0.1). Therefore, a very broad scope in the applications, in the design, the underlaying technologies, the requirements and in the manufacturing is addressed in this document, resulting in the identification of 72 Major Challenges.

They 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, and as shown in the major challenges table in Appendix B, the Major Challenges represent key factors for the achievement of **five Main Common Objectives**, which are aligned with the European Commission's strategic priorities:

1. **Boost industrial competitiveness**
2. **Ensure EU digital autonomy**
3. **Establish and strengthen sustainable and resilient value chains**
4. **Unleash the full potential of intelligent and autonomous ECS-based systems**
5. **Enable the ECS Engineering Ecosystem**

The SRIA is developed collaboratively by numerous technical experts from industry and academia, each contributing perspective shaped by their respective background and industrial areas of interest. Its purpose is not to prioritize specific areas of the electronics components and systems domains or individual research and innovation activities. Rather, it reflects a holistic view and collective vision for advancing electronics-based industries in Europe as a whole and along complete value chains.

The three authoring industry associations — AENEAS, EPoSS and INSIDE —, which together represent the whole European ECS R&I community, are committed to identifying and discussing intersections between political priorities and the broad spectrum of activities pursued by their members.

Objective 1: Boost industrial competitiveness through interdisciplinary technology innovations

Investing in the Research and Innovation topics described in this document will not only translate into a more competitive and sovereign European ECS value chain, but it will also boost European industrial competitiveness across all sectors.

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 embedded software, as well as cross-sectional technologies such as edge computing, artificial intelligence, high-speed connectivity, and cybersecurity.

As a result, ECS research needs to be interdisciplinary to benefit from the multiple available sources of innovation, as well as 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.

The European Chips Act has moved into implementation. Under the Chips for Europe Initiative, the Chips Joint Undertaking combines research and innovation with technology and engineering capacity building. Current implementation includes:

1. A European Design Platform providing access to design facilities, intellectual property libraries, Electronic Design Automation (EDA) tools and support services;
2. Five pilot lines for process development, test and experimentation, and small-scale production, linking research to near-industrial capabilities;
3. Capacity building for quantum chips and associated semiconductor technologies;
4. A European network of semiconductor competence centres. All Member States and Norway have established centres that provide access to expertise, training and Chips Act infrastructure.

These instruments connect collaborative research with process development, design, test and near-industrial experimentation. The ECS SRIA identifies the research, development and innovation bottlenecks that should feed this capacity and helps align upstream research with prototyping and industrial uptake. This role complements first-of-a-kind manufacturing investments under the Chips Act.

Objective 2: Ensure EU digital autonomy through secure, safe and reliable ECS supporting key European application domains

The benefits for European strategic autonomy of the development of innovative ECS technologies focused on security, safety, reliability, dependability and privacy will be discussed in the section “strategic advantages for the EU”. 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 Information and communications technology (ICT) and to ensure compatibility with EU values.

These innovative technologies will simplify the implementation of the European Strategy for Data[1,2], and ensure security, privacy-by-design and strategic autonomy all along the industrial and digital value chains.

Europe's strategic autonomy depends on capabilities across the ECS value chain and on reliable access to technologies that are critical for downstream industries. The Major Challenges therefore address secure, safe and reliable ECS for key application domains including:

- Aerospace, defence, security.
- Automotive, transportation.
- Machinery, robotics, electrical equipment, energy.
- Communications, computing.
- Energy generation, distribution and grids
- Healthcare and well-being

and other domains.

Defence, security and space now provide a stronger application pull for trusted and high-reliability electronics, advanced sensing and radio-frequency technologies, secure connectivity, resilient computing, autonomous functions and efficient power electronics. These needs cut across the existing technology and application chapters and are treated as cross-cutting drivers within the current SRIA structure.

European strategic autonomy in ECS depends on reducing critical dependencies while retaining access to global markets and technologies. Resilience therefore requires diversified and trusted supply chains, strong European capabilities and the ability to maintain essential functions during geopolitical, trade or supply disruptions. This requires:

- Strengthening European capabilities in semiconductor design, manufacturing, equipment, materials, embedded software and system integration where they are strategically relevant, meeting stringent security requirements.
- Diversifying sources and manufacturing options for critical components, materials and technologies, and improving visibility across the supply chain.
- Ensuring that critical digital and physical infrastructure can rely on secure, trusted and maintainable ECS throughout the product lifecycle.
- Using European strengths in specialised semiconductors, systems engineering and application integration to create competitive products and reduce single points of dependency.

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.

[1] https://ec.europa.eu/digital-single-market/en/policies/building-european-data-economy
[2] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021DC0118

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 achieve carbon neutrality right down to the final application/digital service.

Even in a changing geopolitical context, climate change remains an environmental and economic imperative that cannot be ignored.

Advances in ECS technologies are both a major enabler of the Green Deal for all ECS-based application fields, and a direct contributor through their significant impact on power and resource consumption of ECS manufacturing and use.

Furthermore, 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.

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 and 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. Physical AI extends this challenge to systems that perceive, reason and act in the physical world, where real-time behaviour, functional safety and verification become part of the AI-enabled function.

Europe's position in artificial intelligence also depends on the hardware and systems that make AI efficient, dependable and deployable. Research in semiconductors, memory, advanced integration, embedded and edge AI, and trustworthy engineering supports applications across the SRIA. Chapter 2.1 addresses the edge and embedded part of this continuum, while other chapters cover the enabling hardware, connectivity, software and engineering methods.

Objective 5: Enable the ECS Engineering Ecosystem

Modern ECS-based systems are too complex to deliver reliably without a coherent **end-to-end engineering ecosystem** that spans requirements, architecture, design, verification and validation, deployment/commissioning, operations and remote maintenance, and eventually recycling and evolution. Establishing such an ecosystem—grounded in systems-engineering best practice—improves quality, reduces time-to-market, and enables confident scaling from components to complex systems and systems-of-systems.

This objective promotes lifecycle integration through model-based and data-centric methods, including Model-Based Systems Engineering (MBSE) and an unbroken digital thread. Product information, analyses and decisions should remain consistent from concept to field operation. Interoperable toolchains and open interfaces support co-design across the computing continuum and modular hardware such as chiplets. Design platforms can provide shared access to intellectual property (IP), process design kits (PDKs) and design automation in secure environments. The Data Act adds concrete requirements for access to data from connected products and for interoperability. This reinforces the value of lifecycle data and digital threads in engineering practice.

In this sense, security, safety, reliability and sustainability are treated by design. Engineering processes should cover cybersecurity and functional-safety lifecycles from architecture through operation and maintenance. The Artificial Intelligence Act, Cyber Resilience Act and revised Product Liability Directive reinforce the need for traceability, secure update mechanisms and lifecycle assurance. Lifecycle-integrated verification and continuous assurance are central to dependable ECS.

Delivering this objective also depends on **human capital**: Europe needs coordinated education, up-/re-skilling, and hands-on training pathways that match real engineering workflows across the semiconductor and ECS supply chains. (Multiple recent European analyses highlight the skills gap and the need for joined-up action by industry, academia and governments.)

In practice, Objective 5 will:

- impact industrial **competitiveness** by simplifying life cycle management, and improves the quality of the engineering process, making it more cost-effective and agile.
- simplify and improve the **development** of trustworthy ECS technologies, products and applications.
- support **sustainability** and **resilience** that reduce lifecycle management costs, as well as ensuring the automation and continuity of operations.
- unleash 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.

- improve professional training and **education** by strengthening and developing new and specific skills.

By consolidating these capabilities, Europe will **simplify lifecycle management, raise engineering quality and agility, and reduce cost and risk**—thereby amplifying the impact of Objectives 1–4.

0.1.2 The ECS ecosystem: a key enabler of prosperity for Europe

The importance for Europe of the ECS ecosystem is twofold. It is a major contributor to European economic and political strength through employment, wealth creation and technological capabilities. At the same time, ECS enable services and infrastructures across most areas of daily life and industrial activity.

A ECS as a Strategic Enabler for Europe

Semiconductors are a large and rapidly growing global market, with worldwide sales of around USD 0.8 trillion in 2025. The ECS sector supports a substantial European skills and employment base. Around 1.3 million people work in the EU manufacture of computer, electronic and optical products, while the semiconductor sector itself accounts for roughly 380,000 professionals. Europe currently accounts for around 9–10% of the global semiconductor market, while the Digital Decade target remains 20% by 2030. Recent growth is strongly shaped by artificial intelligence infrastructure, advanced computing and memory, while electrification and connected products sustain demand across industrial sectors. For Europe, the relevant competitive position extends beyond chip manufacturing to equipment, materials, specialised semiconductors, embedded software and system integration.

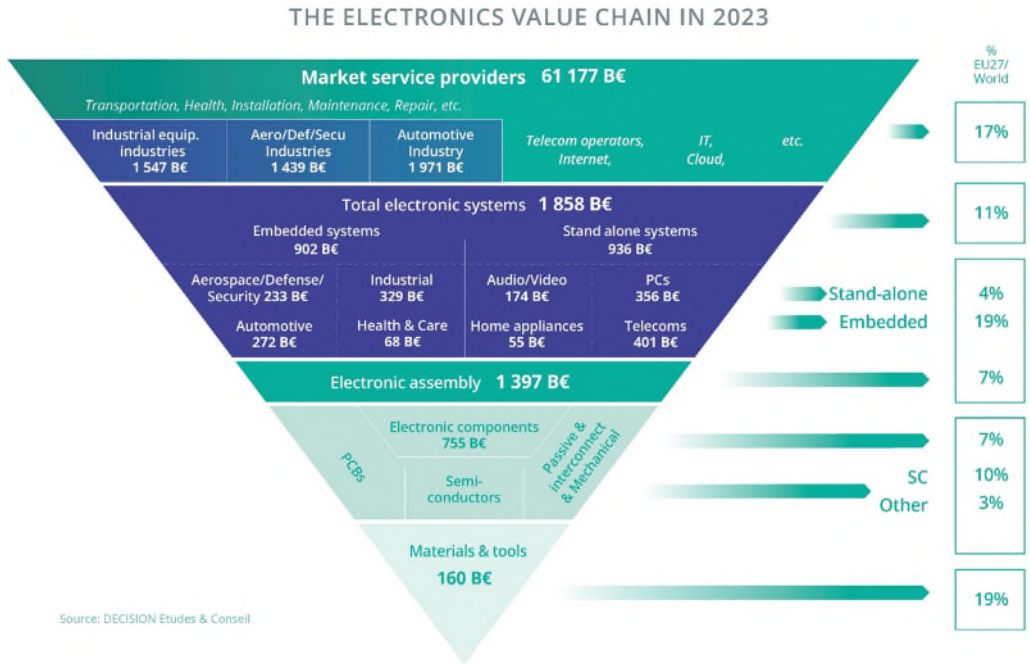

Figure 0.1 Process technology, equipment, materials and manufacturing is at the base of the digital value chain (Source: DECISION Etudes & Conseil) – 2023 market size numbers

These shifts also change the technical bottlenecks. Compute and memory bandwidth, advanced integration, power delivery and trusted embedded systems now matter alongside manufacturing capacity.

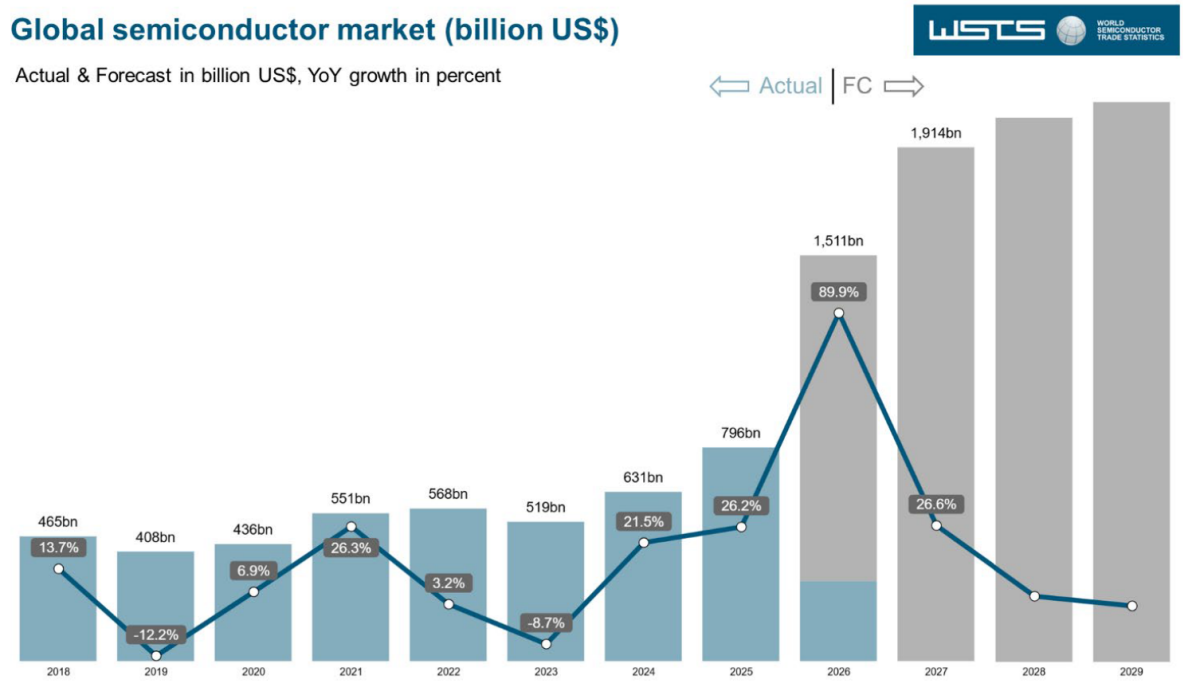

Figure 0.2 Semiconductor market evolution 2018 – 2029 (Source: WSTS)

Europe therefore needs competitive capabilities across complete ECS value chains and the sectors that depend on them. These capabilities support industrial productivity, secure digital infrastructure and resilience to supply disruptions.

Maintaining competitiveness of the European ECS value chain

Even though the European microchips manufacturing market share is only around 10 %, the European share of integrated products and electronic systems is much higher, for example in the automotive and telecom sectors. Many European companies master specialties technologies, including integration of those technologies into smart systems, combining hardware and software - including firmware and middleware -, which allow them to grab a relatively high share of the end-product value.

Systems-of-systems[3] (SoS) and their formalisation were originally conceived and studied in the defence domain, but they are (and will be) vital infrastructure for many other vertical domains. For example, the shift in the mobility sector towards electrification and autonomous mobility necessitates the adoption of systems-of-systems in e.g. vehicles and roadside infrastructure. Given current and

[3] 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. See full definition in the glossary.

future expectations of the market, investment in SoS research and innovation[4] is essential to European leadership in the mobility sector. Likewise, to remain at the state-of-the-art in embedded systems architecture and software Europe should continue to invest in this domain, despite fierce competition. From this perspective, the convergence between AI and edge computing - embedded intelligence - should be a top priority.

Europe is internationally known for high-quality products and strong systems engineering. European strengths in integration, validation and testing support safety, security and reliability under European and international standards. Mature engineering methods and toolchains help achieve these qualities with manageable effort and cost. This capability is especially valuable as ECS become more software-defined, connected and updateable throughout their lifetime, and it supports Europe's ability to demonstrate dependable behaviour at system level.

Europe should take benefit of its specific strengths, and of its ambitious plans - such as the "European Green Deal" - to make its ECS industry even more sustainable and competitive producing trustworthy products.

Sovereignty

European strategic autonomy in ECS calls for further collaboration between European companies and organizations. Design frameworks, reference architectures and integration platforms will lead to new design ecosystems. Integration platforms[5] 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 and Apple.

The same challenge is visible in Electronic Design Automation (EDA), where the leading platforms are provided mainly by non-European companies such as Synopsys and Cadence. European design capabilities in this area depend on access to trusted intellectual property, process design kits, toolchains and secure design environments. The European Design Platform can reduce barriers for start-ups, small and medium-sized enterprises and research organisations by improving access to design infrastructure and services. Open hardware and RISC-V add a complementary route, provided that industrial-grade tools, software, verification and long-term maintenance are available.

The Green Deal objectives will further drive the production of renewable energy and the large-scale adaptation of (bi-directional) battery electric vehicles, digitalization & electrification of industry, storage systems, even more local renewable electricity generation and the conversion of heating to heat pumps. Basis for the transition are along the European value chain leading edge technologies and system expertise in power electronics, control and securely connected energy systems. Consequently, Europe will have to modernize its energy grid towards a highly dynamic, blackout-protected energy infrastructure, also significantly reducing the dependency on imported fossil fuels.

[4] From Internet of Things to System of Systems – Market analysis, achievements, positioning and future vision of the ECS community on IoT and SoS, P. Azzoni, Artemis 2020.

[5] An integration platform is an ECS allowing the integration of different systems, applications and services into a single system. See full definition in the glossary

Advancements in ECS, particularly in edge AI computing and in mastering the integration task into its products, will substantially contribute to enabling European Industries to build systems with guaranteed quality properties. Europe's strengths in creating trustworthy dependable systems by high-quality system design ("made in Europe" quality) contributes to European strategic digital autonomy.

Resilience

Geopolitical fragmentation, export controls, concentrated supply chains and dependencies on critical materials, manufacturing capabilities and intellectual property now shape the resilience challenge for ECS. Europe needs diversified and trusted supply chains together with strong capabilities in design, manufacturing, equipment, materials, software and system integration. Existing instruments, including the Chips Act, Important Projects of Common European Interest and the Critical Raw Materials Act, support this effort.[6]

As stated in the Draghi report[7], investing in innovation is a necessary precondition to increase productivity and thereby contribute to competitiveness. New manufacturing models that will bring greater efficiency and more agile production processes need to be developed, and European manufacturing must be strengthened 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. Again, ECS innovations will play a key role here.

In semiconductor manufacturing specifically, 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 and second IPCEI on microelectronics, for example, have been 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] through the Digital Decade Policy Programme 2030 to strengthen Europe's position in advanced semiconductors and other key digital technologies.

Further, the EU can work with national governments and companies to create a true European foreign economic policy, to coordinate trade agreements and investments with external countries. In parallel, the EU should create clear incentives to cooperate more easily, and develop reliable societal emergency infrastructures. This will make European societies better prepared to deal with emergency and crisis situations.

Employment challenges

The European electronics industry is currently facing a **skill gap**. The European Chips Skills Academy (ECSA) estimates that the EU semiconductor ecosystem employed ~382,200 people in 2023 and, with production ramp-ups, could see ~250,000 job openings by 2030 (new roles plus replacements). Yet the graduate pipeline is projected to grow by only ~1% CAGR, yielding a talent shortfall of about **65,000 positions by 2030**, concentrated in hardware engineers, technicians, software engineers and data

[6] Semicon Coalition calls for reinforced Chips Act | Shaping Europe's digital future
[7] The Draghi report on EU competitiveness
[8] Europe's Digital Decade: digital targets for 2030 | European Commission (europa.eu)

specialists. Sufficient numbers of engineers with the right skills are crucial for Europe to compete with other regions and exploit the sector's true potential for the European economy. Faced with these challenges, Europe can play on two levers to develop a strategic advantage vs. other regions of the world:

- On the one hand, it must maintain and strengthen its traditionally strong and advanced **educational system**, and the presence of world-leading research institutes throughout the whole stack of competencies. 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 as EUROPRACTICE are essential in providing this access in an affordable manner. Likewise, continued investment in semiconductor-related studies, as intended under the Pact for Skills[9], is crucial to reversing the current trend of declining numbers of students.
- On the other hand, there is a need to drastically increase the **efficiency of engineering activities** throughout the whole design / develop / test / validation process by providing new tools that are able to handle new product features which in turn are enabled by usage of AI and other new technologies. Model-based and AI-supported technologies will contribute considerably to the increase in efficiency, the increase in capabilities, the mitigation of shortage in software engineering resources, and further improve overall software consistency and quality.

While effects will only be felt in the longer term, there is also a need for actions which will increase the number of students entering the STEM education pipeline, notably with “train the trainers” programmes which will develop the awareness of teachers at all levels – starting in primary schools – regarding the usefulness of science and engineering skills and the resulting employment perspectives.

While ECS is facing a skill gap, other industries are at risk of suffering job losses. For example, Europe’s automotive industry employs around twelve million people. Currently, the transportation sector is undergoing a fundamental and complex transformation across all modes. Its position is challenged by US information technology giants and aggressive and new agile Chinese automotive companies. The ECS community will contribute substantially to maintaining competitiveness, and therefore jobs, of the European car industry by using new technologies, components and systems to target areas like autonomous vehicles, electrified CO_2-neutral vehicles, Over-the-air (OTA) updates and new mobility concepts to reduce overall energy usage (e.g. mobility as a service).

Conclusion

The global digitalisation of society and industries is enabled by ongoing innovations in ECS. With its specific strengths Europe is well positioned to prevail in the fierce global competition. We are strong in embedded systems architecture and software, in embedded intelligence, in specialties

[9] https://employment-social-affairs.ec.europa.eu/policies-and-activities/skills-and-qualifications/working-together/pact-skills_en
https://employment-social-affairs.ec.europa.eu/policies-and-activities/skills-and-qualifications/working-together/pact-skills_en

semiconductors (Power, RF, sensors, FD-SOI, MEMS…), and in maintaining overall high quality, safety and security standards in ECS. Therefore, the European ECS market prospects are seen as strong. Further investments in the future of electronic components, modules and systems integration have 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 the microelectronic ecosystem with regards to heterogeneous integration.

To maintain leading positions in specific markets Europe must continue to invest in RD&I in strategic ECS technologies, including disruptive technologies like high NA lithography, 2D-materials, spintronics, quantum computing and related technologies, AI based development, design and verification methodologies, scalable platform technologies and differentiating capabilities by software. It must also secure its ECS manufacturing supply chain by identifying new materials and improving recycling, to decrease the dependency vis-à-vis non-EU-sourced rare materials. With strategic initiatives like the Green Deal, the Digital single market, the Pact for Skills, and the Chips Act, to name a few, the European Commission has already taken important steps to secure a healthy future for the ECS industry in Europe, and therefore for many ECS-enabled end-product industries. The ambition of the ECS Strategic Research and Innovation Agenda is to support, enable and amplify that effort, by:

- Strengthening industry involvement: Strategic R&D and manufacturing investments in disruptive technologies, needed to cope with the transition challenges of our society (digitalization and sustainability, EU sovereignty), as depicted in the ECS SRIA, need collaborative approaches for R&D and governmental support for lowering the risks for realization and implementation. Therefore, in particular industries with high R&D intensities addressing key enabling technologies to solve global challenges, such as Electronic Components and Systems (ECS), should be supported to grow;
- Providing guidance to join forces: For our continent with federal democratic structures and a high degree of individual required solutions, joining forces in a billion-market environment is the only viable approach to be well set-up for the future despite having limited resources. Collaborative RD&I projects are one of the main instruments to that effect in our federal eco-system.

B Technology-enabled societal benefits

Besides its economic weight per se, the strategic importance for Europe of the ECS ecosystem is further strengthened due to its role as the enabler of the digitalisation of our society.

Digitised services based on smart electronic components and systems (ECS) are becoming increasingly ubiquitous, penetrating every aspect of our lives. They also provide ever greater functionality, more connectivity and more autonomy. The benefits to society are numerous: safer traffic, less carbon emission and pollution, instantaneous access to information, convenience and cost saving in e-health,

more efficient factories, more social safety, and many more. In short, ECS-based applications and services are key to ensuring the stable growth and development of the European Union.

On the other hand, our dependency on ECS-based applications is also continuously growing. This reinforces people's concerns on – among others – the security of privacy and personal possessions (e.g. through cybercrime, cloud services, surveillance cameras), on personal safety (driver-assistance, e-health), and on the unclear impact of transformational technologies (AI, quantum technology). The societal concerns arising from these technologies need to be addressed. To achieve that, it is vitally important that these electronic systems are safe, secure and trustworthy. A human-centred approach is a key aspect of the EU's policy on technology development, and in line with fundamental European social and ethical values.

In the following pages, we examine in more details the societal benefits which ECS brings to Europe, and where R&I efforts are needed to ensure further gains

Smarter, more efficient society

Artificial intelligence (AI) and edge computing are now core technologies across the ECS stack. Processing is distributed over a continuum from deep-edge devices and edge systems to on-premise resources and cloud or high-performance computing (HPC). ECS research focuses on where functions should run and on the hardware/software co-design needed to meet latency, energy, data-protection, safety and resilience constraints. High-end computing infrastructure itself remains outside the ECS scope.

Embedded cyber-physical systems (ECPS), or IoT systems, provide data processing and intelligence on the site/edge, while improving security and privacy, and completely changing the way we manage everyday activities. ECPS also play a critical role in modern digitalisation solutions, quickly becoming nodes in distributed infrastructures supporting systems-of-systems (SoSs) for monitoring, controlling and orchestrating supply chains, manufacturing lines, organisation's internal processes, marketing and sales, and consumer products.

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).

Ongoing advancements in IoT systems will drive the further digitalisation of society, by bringing more smartness to human activities, like smart cities, smart transportation, smart grids, smart manufacturing, and pull the development of cyber physical systems and embedded systems-of-systems (SoS). A clear example is the introduction of 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, also offering timely delivery of goods and personnel. Another example is the integration infrastructures adopted in production, in order to meet customer demands locally. Here, the interoperability of SoS technologies across domains is an essential capability.

This evolution will in turn put high demands on the availability and reliability of high-speed, secure, low or guaranteed latency connectivity.

Another important trend is the emergence of open-source components which become the core building blocks of application software in many innovative domains[10]. Developers are being provided with an ever-growing selection of off-the-shelf possibilities, which they can use for assembling their products faster and more efficiently, where efficiency goes hand in hand with affordability and sustainability.

Healthier life

Europe's ageing population and shortages of healthcare staff are increasing demand for digital support across the care pathway. ECS improve efficiency and reduce development and maintenance costs of diagnosis and care equipment at the point of care, and enable continuous monitoring, connected diagnostics, assisted workflows and treatment at home, while preserving safety, privacy and clinical reliability.

The shift from hospital-centred care towards a hospital-to-home continuum requires reusable technology architectures that integrate sensors, wearables, implants, point-of-care devices, communication and AI-enabled functions. Personalised treatment and closed-loop systems create additional requirements for dependable data, interoperable devices and low-power operation.

Connected healthcare systems extend these capabilities across care settings. They can support remote monitoring, diagnosis and treatment, including for patients outside major clinical centres. The ECS research challenge is to integrate heterogeneous devices and data, support remote operation and updates, and maintain safety, privacy and reliability over long lifetimes.

Sustainability

Contribution of ECS technologies to sustainability are two-fold:

On the one hand, ECS are a major enabler of the Green Deal objectives as they foster sustainable and smart mobility; the supply of clean, affordable and secure energy, resource-efficient manufacturing, a healthy and environment-friendly food supply chain, healthcare transformation, as well as more efficient information systems.

To accelerate the shift towards sustainable and smart mobility, the mobility sector requires energy efficient mobility grade semiconductor devices, be it for vehicles or for the supporting infrastructure required for the charging of EV's. This needs to be complemented with middleware and embedded SW applications, which are often part of a cloud-to-edge continuum.

In the energy sector, the power grid architecture will be transformed into a multi-modal energy system architecture. It will comprise distributed renewable energy generation, energy conversion units for sector coupling, transmission and distribution grids allowing bi-directional power flow, and storage for all modes of energy (electric, thermal, chemical). 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) based on highly efficient and fast-switching semiconductor power devices and modules that enable real-time control of energy system

[10] More than 81% of produced software are consuming open-source code in products or services (https://github.com/todogroup/osposurvey/tree/main/2020)

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, finally, requires a sophisticated information and communication infrastructure including cloud services, IT security, and AI technologies.

Besides, ECS will be at the core of implementing new ways of manufacturing, to promote an environmentally friendly production and to develop building blocks in advanced automation and control, advanced sensors, digital twins, artificial intelligence, collaborative robotics, monitoring through value chains – that will allow for better accuracy and performance, better (predictive) maintenance and higher asset utilization. It is particularly important to ensure that design processes will cover the complete lifecycle of products for future ECS-based applications. Data must be collected to this aim, and used to enable continuous updates and upgrades of products, but also in-the-field tests of properties that cannot be assessed at design-, development- or testing-time. This will as well increase the effectiveness of validation and test steps by virtual validation methods based on this data.

Another major application sector for ECS is agriculture, where policies focus on preservation of landscapes, biodiversity, and environmental protection. This will require measurement and monitoring technology which is accurate, highly scalable, and secure. In addition to these environmental requirements, Smart Internet of Things (IoT) systems support productivity growth, access to clean water, fertile soil and healthy air for all, and help fighting against pests while preserving biodiversity and restoring the planet's ecosystems.

Healthcare digitization will enable the shift from hospital care to remote care at home, thus reducing travel-induced environmental impact, while personalized medicine will reduce waste in resources.

Finally, edge computing and embedded intelligence will allow to significantly reduce the energy consumption for data transmissions (e.g. to the cloud), will save resources in key domains of Europe's industrial systems, and will improve the efficient use of natural resources.

On the other hand, the ECS sector is focusing on improving its own energy performance and disposability of electronic components and reducing its environmental footprint by means of cleaner and greener production processes, more circularity and less energy and material consumption. These efforts are mandatory since the demand for ECS is set to grow considerably to serve environmentally sustainable applications, and we cannot allow this to translate into an equivalent increase in the resources consumed in their production and operation. This is also a prerequisite to decrease the dependency of the European ECS industry on rare, foreign sourced materials.

The sustainable manufacturing of semiconductors requires the continuation of significant R&I on new processes, manufacturing techniques, equipment and materials. Advances in the manufacturing of chips and packages in the coming years will strongly contribute to Europe's ambition to become climate-neutral by 2050. Some examples are:

- Device scaling - by moving into 3D for sub-3 nm node memory - and computing technologies will drive down energy consumption following the power, performance, area and cost (PPAC) scaling roadmaps.
- New embedded non-volatile memory technologies, including MRAMs, 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, or hybrid devices combining both (e.g., integration of magnetic materials with standard CMOS), will increase the energy efficiency of electric powertrains, energy storage, lighting systems, etc.
- Opportunities to reuse older CMOS nodes by integrating novel emerging technologies with standard CMOS; for example, spintronic devices allows to envision rich and complex functionalities, demonstrating that specifications can be met at these nodes, and in some cases, even surpass the current state-of-the-art performance of existing devices
- Improved integration technologies and miniaturisation will support sustainability of products and production technologies.

One key point of attention is the development and 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[11]) and minimization of critical raw materials (CRM) dependence. In particular, due to their unique physicochemical properties, PFAS are currently extensively used in both chip fabrication and for semiconductor manufacturing equipment and factory infrastructure. Research to identify alternative chemistries and to develop efficient abatement technologies for uses where no alternative can be found is therefore essential.

Beyond fabrication, sustainability has to be designed across the full ECS lifecycle. Life-cycle assessment (LCA), material traceability, repairability, condition monitoring, hardware and software upgradeability, lifetime extension, predictive maintenance, second-life use and recycling should be linked through lifecycle data. Feedback from operation and end-of-life can inform design and maintenance decisions, while low-power hardware and software reduce energy use during operation.

Moreover, eco-design has to consider re-use in a second life application, and the recovery of components and materials for recycling. Note that increased integration will cause the borders between components, modules and systems to become blurred: More diverse and complex materials will be used at each level, so that the dismantling of systems into their constituent components at the end of their useful life will become increasingly difficult, requiring significant R&I efforts to identify solutions to achieve circular economy. From 2027, battery passports are required for some types of batteries. This is only one example of how traceability, interoperable data and circularity requirements enter engineering workflows.

Finally, another lever to decrease the overall resource consumption of ECS is at the architectural level. Embedded intelligence for instance can provide 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, and reliability of applications and services. Above all, this new computing paradigm could significantly reduce environmental footprint by the introduction of ultra-low power and efficient computing solutions. There is plenty to explore on the trade-off between performances and power consumption reduction, and on managing complexity (including security, safety, and privacy) for embedded architectures to be used in different applications areas, which will spread the use of edge computing and artificial intelligence and their contribution to European sustainability.

[11] PFAS is a class of thousands of synthetic substances known as ‘forever chemicals’ since they do not break down in the environment. 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.

Privacy, Safety and Security

The efficiency and flexibility of embedded software, in conjunction with the hardware capabilities of ECS, allow to move various processing functions to local devices, such as voice and environment recognition, allowing for privacy preserving functionalities. AI also increase the capabilities to detect intrusions, thus reinforcing the protection of privacy.

Furthermore, the ever-improving detection capabilities of cameras and other long-range sensors (radar, lidar, etc…) combined with the development of AI at the edge is opening unprecedented opportunities for many safety and security-related applications that currently rely on human involvement, such as automated driving, security and surveillance and process monitoring.

Connected functionalities will extend the control and automation of a single system (e.g. a truck) 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.

Critical infrastructure in energy, transport, communications and industry combines connected physical assets with digital control. ECS must support secure low-latency communication, local operation under degraded network conditions, trusted updates and system-level monitoring. These are horizontal requirements across several application chapters.

Finally, one cannot ignore that the ever-increasing importance of ECS-based systems in our daily lives raise concerns regarding trustworthiness, privacy, safety and cybersecurity. Indeed, a degraded behaviour of cyber-physical systems or an incorrect integration among them, would affect vital properties and could cause serious damage. Shortcomings in those dimensions might even outweigh the societal and individual benefits perceived by users, thus lowering trust in, and acceptance of, new technologies. Ensuring high standards on safety, security, and reliability at affordable efforts and cost, require continuous R&I efforts on methods and tools for ECS architecture and design:

- Applying “quality by design” approaches for future ECS-based systems.
- Providing methodology, modelling and tool support to ensure end-to-end trustworthiness of new designs. This includes balancing trade-offs of quality aspects and ensuring tool-supported verification and validation (V&V) at the ECS level, providing methodology, modelling and tool support to validate safety of AI-based systems.

Connected society / social inclusion

The further integration of “smart everything” into “ubiquitous smart environments” will introduce large and very complex systems of systems with complex physical interactions. In this context the technology competence and innovation in the field of embedded and cyber-physical based SoS will be a critical asset.

ICT technologies have long been recognised as promoting and facilitating social inclusion, as well as digital inclusion (i.e. the ability of people to use technology). These aspects span dimensions as diverse as disaster relief, food security and the environment, as well as citizenship, community cohesion, self-expression and equality. One illustration is the use of AI to enhance conversational interfaces, improving the human-machine interface with reliable understanding of natural language.

0.2 PART 2 – WHAT? CONTENTS OF ECS SRIA 2027

0.2.1 Scope

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 0.4 with an example.

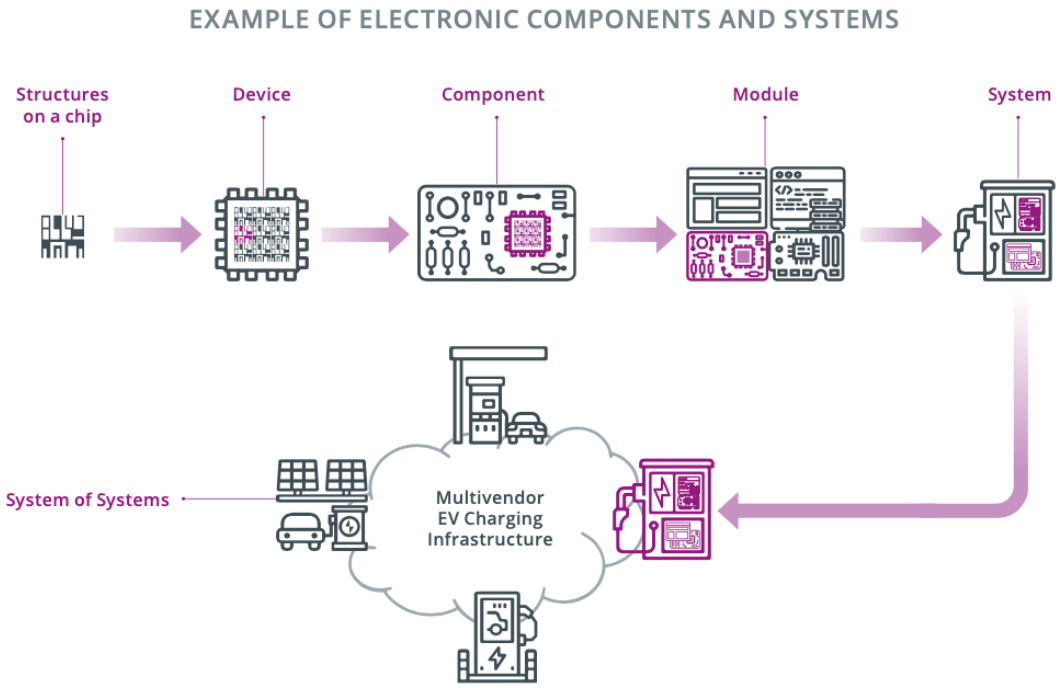

Figure 0.3 Different integration levels illustrated by the example of an EV charging infrastructure[12] (Source: Eurotech)

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

[12] Structure on a chip: elementary building blocks of an integrated circuit, such as a FDSOI or FinFET transistor, or more complex structures such as an embedded memory block.

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.

0.2.2 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.

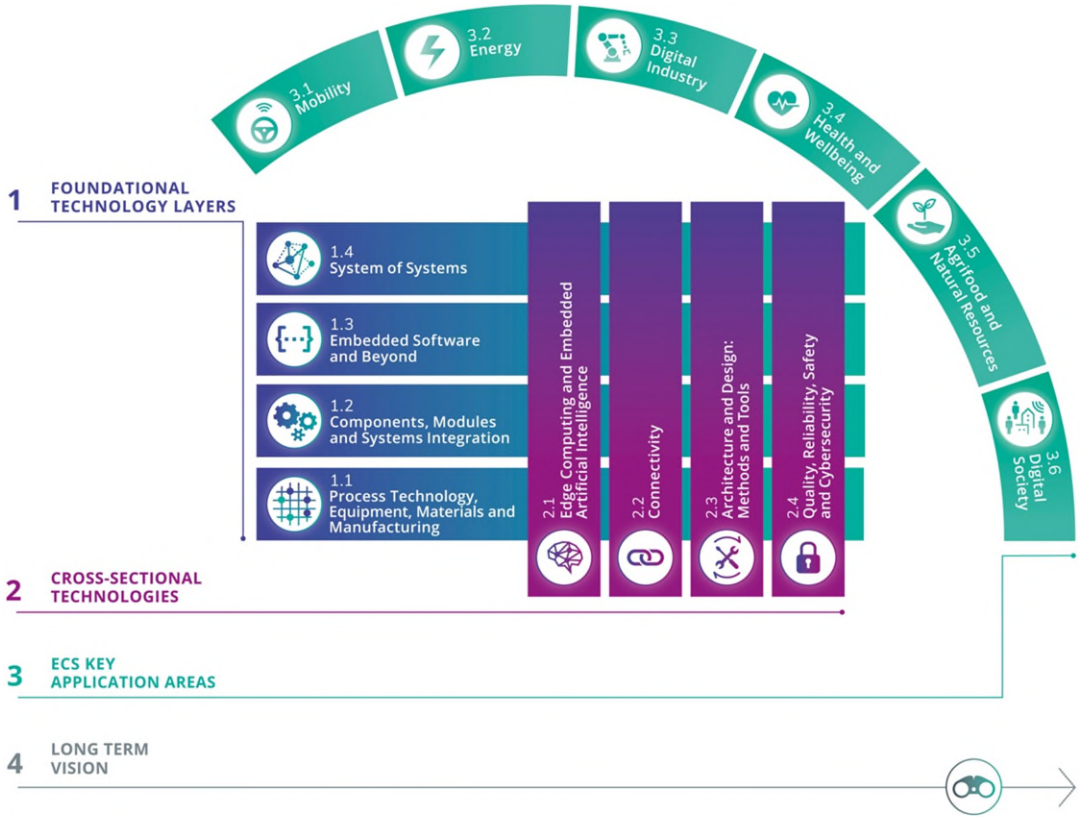

Figure 0.4 The structure of the ECS SRIA

The four Cross-Sectional Technology chapters address capabilities that span the foundational layers. Edge Computing and Embedded Artificial Intelligence now operate within a continuum from deep-edge devices and edge systems to on-premise resources and cloud or high-performance computing (HPC). The ECS focus is on hardware/software co-design, workload placement, connectivity and trustworthiness across that continuum; high-end computing infrastructure itself remains outside the ECS scope. Architectures and Design: Methods and Tools, together with Quality, Reliability, Safety and Cybersecurity, provide lifecycle-wide engineering methods across the stack.

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** chapters describe the challenges arising from specific ECS application domains that are key for Europe and identify the RD&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.

As for previous editions, the chapter editing teams have been reviewing their text with the goal to achieve greater conciseness, while of course eliminating outdated materials and providing new data.

0.2.3 The 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[13]. 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 6G 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)[14] in electronic packaging and integration, the IEEE International Roadmap for Devices and Systems (IRDS)[15] for the

[13] https://watereurope.eu/wp-content/ uploads/2019/07/Water-Europe-SIRA.pdf
[14] https://eps.ieee.org/technology/ heterogeneous-integration-roadmap/2019- edition.html
[15] https://irds.ieee.org/

semiconductor industry), and the RISC-V Roadmap of RISC-V International[16] and the European Working Group[17].

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.

0.2.4 New and growing trends

This revision focuses on technology developments that create clear ECS research bottlenecks across several chapters. The main shifts concern efficient artificial intelligence across the computing continuum, advanced and heterogeneous integration, optical and electrical interconnects, trusted open hardware, next-generation connectivity and dependable autonomous systems. Quantum technologies and beyond-CMOS concepts remain important, with maturity and time-to-application varying significantly by technology. The following sections therefore emphasise remaining ECS research needs rather than general technology descriptions.

A Chiplets

Chiplets are reusable integrated-circuit blocks designed to operate together within a package. They allow functions to use the semiconductor technology best suited to each function and then be combined through high-density interconnects.

Chiplet architectures can improve system economics and development flexibility by partitioning large designs into smaller dies, reusing validated IP and selecting the most suitable process technology for each function.[18][19]

For Europe, chiplets provide an opportunity to combine strengths in specialised semiconductors, photonics, sensing, power electronics, packaging and system integration within heterogeneous multi-die systems. Open interfaces and interoperable design and test flows are therefore important if chiplets are to develop from supplier-specific implementations into broader multi-vendor ecosystems.

The research focus is shifting from basic feasibility towards interoperable, trustworthy and economically viable multi-die systems.

Key bottlenecks are die-to-die interfaces and multi-vendor interoperability, known-good-die and test strategies, power delivery and thermal management, 2.5D/3D integration, system-level Electronic Design Automation (EDA), verification and validation (V&V), and security.

These issues link packaging and integration to architecture, software, connectivity and lifecycle engineering.

Chiplets manufacturing is addressed in Ch 1.2, while implications of chiplets are addressed in Ch 1.3, 1.4, 2.2 and 2.3.

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[16] RISC-V-Introduction-_-Aug-2021.pptx (live.com)
[17] https://digital-strategy.ec.europa.eu/en/library/recommendations-and-roadmap-european-sovereignty-open-source-hardware-software-and-risc-v
[18] John Lau, Chiplet Design and Heterogeneous Integration Packaging, Springer 2024
[19] Cadence PCB solutions, https://resources.pcb.cadence.com/blog/2023-all-about-chiplet-technology, consulted 25 July 2024

B Open-Source Hardware

Open-source hardware is hardware whose design is made publicly available so that anyone can study, modify, and further distribute the design, and/or freely make and sell hardware based on that design. The use of open-source hardware drastically lowers the barrier to design innovative SoCs. Indeed, this allows research centers and companies to focus their R&D effort on innovation, leveraging an ecosystem of pre-validated IP that can be freely assembled, modified, and customized for specific applications, whereas currently the cost of design of a set of IPs in-house is available to only few companies. And the use of alternative 3rd party IPs licensed by companies imposes constraints on innovation due to architecture. Open-source is also a sovereignty tool and avoids licensing IPs from foreign third parties, in a geopolitical context characterised by trade wars and export control restrictions.

Open-source hardware and RISC-V have moved beyond an academic trend. The main European challenge is its use for industrialisation: trusted and maintained intellectual property, coherent development tools and software, long-term governance, verification and certification.

This is particularly important when open hardware enters automotive, industrial, space and other safety- or security-critical products. Open ecosystems need documentation, testing, configuration control and product-lifecycle maintenance in addition to reusable intellectual property blocks.

The European strategy on open-source hardware should focus on application domains where there is a stronger impact, i.e. automotive, industrial automation, communications, health and aeronautics/defense. As these fields convey specific requirements (safety, security, reliability, power and communication efficiency…), the key differentiator between European core design efforts and existing players will be the attention given to the aforementioned requirements and also the extensibility with custom operations. Above all, a special focus should be placed on safety and security solutions, dealing with key aspects of collaboration, documentation, verification and certification in open-source communities.

A working group gathering European stakeholders was established in 2022. It drafted a technological roadmap starting with processors (RISC-V, beyond RISC-V, ultra-low power and high-end). The chiplet-based approach mentioned above is identified by the roadmap as a unique opportunity to leverage European technologies and foundries to create European HW accelerators interposers that could foster European More-than-More technology developments. Die-to-Die communication remains a missing link to leverage that approach, and its development in open-source is advocated by the working group.

The SRIA therefore treats open hardware as an ecosystem challenge spanning architecture, Electronic Design Automation, software, verification, certification and productisation. Open building blocks create value when they can be maintained and integrated into dependable industrial products.

C Quantum Technologies

Disruptive technologies, where market positions are not established yet, are level-playing fields where Europe has all its chances to gain leadership. Quantum technologies fall in that category and therefore their evolution and maturity are closely monitored by the ECS SRIA expert community. The importance of the technologies is identified in both the Chips Act and in the European Quantum strategy[20].

[20] Quantum Europe Strategy: Quantum Europe in a Changing World, COM (2025) 363 final, European Commission

Together with the European Quantum Flagship SRIA, these documents highlight areas of importance and overlap with the ECS SRIA:

- Technologies for dedicated quantum chips, required to fulfil the quantum challenges.
- Classical chips technologies for quantum (enabling technologies) required to support the industrialization and scaling of quantum technology.
- Systems combining these two for applications taking advantage of quantum technology.

Quantum technologies are very diverse in nature, encompassing quantum computing and simulation, quantum communication, and quantum sensing and metrology[21]. As application fields, they go beyond the scope of the ECS SRIA, but the community should prepare for using quantum technology in the applications that can benefit from quantum chip technologies, e.g. in navigation and timing using quantum sensors.

Quantum chip technologies include six major modalities: Superconducting circuits, semiconducting quantum dots, ion traps, photonics, neutral atoms and nitrogen vacancies in diamonds. All of these technologies have their specific chip technology development needs. The technologies combine traditional microfabrication technologies in Silicon and other substrates with novel primitives that use quantum physics on single electron/atom/ wavefunction level, with RF and optical control and readout. As an example, ion trap quantum systems combine RF electrodes for ion trapping for with optical control of trapped ions.

Quantum technologies use have special material needs, such as the use of isotopically pure Si, and specific processing needs, such as Al/AlOx/Al tunnel junctions with extreme requirements for dielectric tunnel barrier quality and thickness control. In integrated photonics, the needs of the quantum systems typically include extremely low losses and wavelengths in the visible range, from 800-900 nm as low as 300-400 nm, depending on the atoms or ions used.

The maturity of quantum technologies differs substantially. Quantum sensing is already closer to deployment in selected applications, including navigation, timing and biomagnetic measurements. Large-scale fault-tolerant quantum computing remains a longer-term objective.[22] For ECS, this makes enabling hardware and manufacturing capabilities more relevant than a single market forecast.

Across these maturity levels, the main ECS bottlenecks are process control and material quality, metrology, low-loss photonics, cryogenic electronics, control and read-out, reliable fabrication, interconnect and packaging:

- As there are still several candidates for becoming the standard quantum computing technology, 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.
- To achieve practical applications, reliable fabrication, connection, and read-out of qubits need to be developed.

[21] Strategy Research and Industry Agenda, Published in February 2024 by the European Quantum Flagship
[22] McKinsey & Company: Quantum Technology Monitor 2025

- The low temperatures, from milliKelvins to 4 K, at which many quantum systems are operated requires the development of cryogenic devices, to interface conventional electronics.

These maturity differences lead to quantum technologies remaining visible in the SRIA while placing most quantum-computing developments in the Long-Term Vision. Nearer-term enabling technologies remain linked to the relevant foundational chapters, in particular process technology, photonics, packaging, sensing and control electronics.

D Spintronics

Similarly to quantum technologies, spintronics (excluding MRAMs which are already at a commercial stage) belongs to the category of disruptive technologies, where market positions are not established yet and Europe has the opportunity to gain leadership. This is an emerging field that holds significant potential to become a key component of future energy efficient chips technologies. The high performance and ultra-low power consumption intrinsic of such technology, make it a very attractive solution to the increasing demands for computing power, notably with the growing market of AI. By combining processing, logic, sensing and storage on a unified platform, spintronic devices can advance technologies such as neuromorphic electronics, unconventional and quantum computing, and energy harvesting, significantly contributing to low-carbon footprint prospects. Europe is well positioned with world-leading institutes in the domain.

E Silicon Photonics

The growth of artificial intelligence, data-centre traffic and high-performance computing is raising bandwidth and energy requirements for interconnects. Photonic integration is therefore moving from long-haul and rack-level communication towards intra-datacentre, chip-to-chip and optical input/output links, where electrical interconnects face power and bandwidth limits.

Silicon Photonic Integrated Circuits (PIC), referred to as Si-photonics, is the technology that realizes photonic components and circuits on Si substrates using materials and fabrication process flows in the well-established microelectronic industry. Replacing electrons with photons to transmit data brings advantages including high-speed operation, low power consumption and high-capacity transmission. Building photonic integrated circuits (PICs) based on industry-standard Si platform promises additional merits, namely lower cost, high-volume manufacturing, large integration density, advanced functionality and high scalability.

Furthermore, Si-photonics, with their CMOS compatibility and small size, weight, area, and power consumption, have the capability of accommodating growing volumes of computer data arriving in real time and at very high rates in large-scale distributed computing systems. The wavelength and spatial multiplexing properties of optics are beneficially translatable to executing critical bandwidth and communications-intensive connections between increasingly parallel computational resources.

Benefiting from an ideal Si/SiO_2 interface and a large refractive index contrast, Si is an ideal platform for implementing passive optical devices such as low-loss waveguides, mode converters, and multiplexers/demultiplexers. Although Si is a centrosymmetric crystal and, thus, not an ideal material for optical modulators, high-performance modulators have been demonstrated. Efficient Ge- and SiGe-based photodetectors operating in the telecom bands are also selectively grown on Si-photonics wafers.

However, if Si can efficiently transmit, modulate, and detect light, its indirect band structure precludes efficient light emission. The achievement of on-chip light sources, using Ge alloys for instance,

represents a significant challenge in advancing the complete integration of silicon-based PICs. Therefore, III-V material (InP, GaAs) on-chip lasers are currently embedded in PICs using 2.5 and 3D heterogeneous integration. Monolithic integration of III-V materials is an attractive alternative due to its high integration density. However, it introduces a high density of crystalline defects, significantly degrading the laser's performance. Exploring methods of reducing these defects is paramount to advance monolithic integration toward high-density, large-scale silicon-photonic integration.

Similarly, for applications that require high-speed modulation, the properties of Si-based modulators are not sufficient. Hence, ferroelectric electro-optic materials such as, III-V semiconductors, $LiNbO_3$ and $BaTiO_3$ should be embedded in the PIC using heterogeneous integration (die-to-die, die-to-wafer, or wafer-to-wafer bonding). Also, improving the quality and performance of waveguides, passive and active photonics devices sometimes requires the introduction other dielectric materials such as nitrides.

Europe has strong capabilities across photonics research and the photonic integrated circuit value chain, while scaling manufacturing, high-volume packaging and integrated design workflows remains a challenge. For ECS, optical input/output, co-packaged optics and photonic interposers connect photonics directly to advanced packaging and AI infrastructure. Heterogeneous electronic-photonic integration and manufacturable optical packaging are central R&D needs. Sensing, LiDAR, quantum, biomedical and environmental applications remain important and broaden the required materials and wavelength range.

F Artificial intelligence topics in the ECS SRIA

Artificial intelligence now affects ECS in three closely related ways: AI runs inside embedded and cyber-physical systems; ECS hardware determines the efficiency of AI from the edge to large computing infrastructure; and AI is entering ECS engineering itself.

- ECS as enabler of AI: Embedded and edge AI are moving across the deep-edge, edge and on-premise parts of the computing continuum. Agentic and smaller specialised models extend the range of local functions. The central bottlenecks are energy and memory efficiency, data movement, real-time performance, privacy, safety, security and the ability to update systems over long lifetimes.
- AI as enabler of ECS: AI can support design-space exploration, software generation, verification and validation, test generation and lifecycle operations. These tools can improve engineering productivity, but their output still requires traceability, verification and domain-specific assurance, especially for safety- or security-critical systems.

Trustworthy AI in ECS is a system-level engineering problem. Research must address predictable behaviour, monitoring and fallback strategies, secure updates, training and validation data, and the interaction between learning components and conventional control functions.

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 at the same time as reaping the benefits of European AI.

These challenges connect Chapters 1.1, 1.3, 2.1, 2.3 and 2.4. Together they cover efficient AI hardware, embedded and agentic AI, AI-assisted engineering, and the verification and assurance methods needed for dependable deployment.

G Physical AI and autonomous systems

Physical AI brings artificial intelligence into robots and autonomous machines that perceive, reason and act in the physical world. The ECS research challenge is the closed loop from multimodal sensing through embedded or edge inference and real-time control to actuation, with dependable connectivity, energy efficiency, functional safety and verification and validation. Progress therefore depends on coordinated advances across sensors, compute, software, connectivity, power electronics and systems engineering, enabling new autonomous products and applications across the SRIA domains.

H Managing the energy demand – transition and AI

Electrification of mobility and industry, expansion of renewable generation and the growth of AI infrastructure are changing both electricity demand and power-system operation. AI infrastructure is now a distinct ECS demand driver because accelerators, high-bandwidth memory and large distributed computing systems raise requirements for logic, memory, interconnect, packaging and power electronics.

The system bottleneck is no longer only compute performance. Data movement and power delivery are becoming equally important. High-bandwidth electrical and optical interconnects, 2.5D/3D integration and advanced packaging reduce communication distances, while efficient power conversion must move closer to the point of load and remain within thermal and reliability limits.

Global data-centre electricity consumption is projected to roughly double from about 485 TWh in 2025 to around 950 TWh in 2030[23], with AI-focused data centres growing much faster than the total. This makes power conversion, cooling, grid integration and energy-efficient computing key ECS challenges. Wide-bandgap semiconductors, including silicon carbide (SiC) and gallium nitride (GaN), are important for efficient power conversion in data centres as well as mobility, renewable energy and industrial systems. This creates a common research agenda around device technology, packaging, thermal management, reliability and power-system control.

AI infrastructure also interacts directly with the energy system. Large computing sites need efficient and controllable power supply, while grid constraints and variable renewable generation increase the value of monitoring, forecasting and control. Europe has relevant strengths in power electronics, semiconductor equipment, advanced integration and system engineering. To keep the technology base in Europe and serve demand from European manufacturing, continued research and investment in the key technologies for future electricity demand are essential.

Device architecture, the excellence in achieving extremely thin wafer thicknesses, and for the wide bandgap technologies the move to larger wafer diameters are core technology capabilities in Europe which should be further strengthened to keep a significant manufacturing and knowledge share in Europe. Vision is to serve the energy transition with highest efficient, reliable, sustainable manufactured power electronics and be capable to have the system competence to design beyond

[23] IEA (2026), Key Questions on Energy and AI, IEA, Paris https://www.iea.org/reports/key-questions-on-energy-and-ai, Licence: CC BY 4.0

state-of-the-art power systems, for the renewables, electric mobility and for the powering of the AI data centers.

0.2.5 Further changes vs. previous edition

On top of these general trends, individual chapters also reflect the latest evolutions:

In Chapter 1.1, Process Technology, Equipment, Materials and Manufacturing, AI-related semiconductor technologies are strengthened across advanced computing, manufacturing and packaging, including AI-chip assembly and test. Spintronics is positioned more clearly across computing and sensing, while sustainability now explicitly addresses PFAS and other hazardous materials.

In Chapter 1.2, Components, Modules and Systems Integration, the three Major Challenges are retained, while advanced integration expands toward integrated photonics, co-packaged optics and flexible electronics, with stronger lifecycle sustainability.

Chapter 1.3, Embedded Software and Beyond, extends agentic AI from an engineering aid to a deployed software component. This adds requirements for secure integration, continuous monitoring and verification, lifecycle traceability, and resilience against model and software-supply-chain vulnerabilities.

In Chapter 1.4, System of Systems, runtime trustworthiness is strengthened by adding stability alongside safety and security. The revision also gives more weight to energy-aware distributed intelligence, autonomous operation and lifecycle management across edge-to-cloud infrastructures.

Chapter 2.1, Edge Computing and Embedded Artificial Intelligence, updates the fast-moving edge-AI landscape with small generative models, tighter memory constraints and embodied AI, while retaining its four Major Challenges.

Chapter 2.2, Connectivity, strengthens secure connectivity for Physical AI and European-controlled end-user devices, including low-latency, Integrated Sensing and Communication and quantum-safe requirements.

Chapter 2.3, Architecture and Design: Methods and Tools, strengthens AI-supported engineering across the lifecycle, moving towards agentic orchestration of design and verification while extending Digital Threads across the value chain.

Chapter 2.4, Quality, Reliability, Safety and Cybersecurity, separates hardware quality and reliability into distinct Major Challenges, raising the total to six, and updates cybersecurity and AI-safety requirements around current EU regulation.

Chapter 3.1, Mobility, is restructured more strongly around the Software-Defined Vehicle as an integrated European hardware–software platform. New emphasis is placed on strategic autonomy, reusable open software building blocks, hardware abstraction and virtualisation, and AI-supported verification and validation across the vehicle lifecycle.

Chapter 3.2, Energy, receives a focused update on energy-system resilience and the AI–energy nexus. It adds energy-autonomous sensing with embedded intelligence and reflects AI’s growing electricity demand and optimisation potential.

Chapter 3.3, Digital Industry, strengthens autonomous systems and robotics around Physical AI and robot foundation models. It adds the transition of advanced and anthropomorphic robots towards industrial deployment and frames European capability across the complete robot stack as a strategic sovereignty issue.

Chapter 3.4, Health & Wellbeing, shifts towards reusable ECS architectures and reference designs across distinct medical devices. It also strengthens multimodal sensing, digital twins, edge-enabled home care and emerging Bio-IT technologies.

Chapter 3.5, Agrifood & Natural Resources, is substantially refocused around climate change as a present operating condition for agriculture and ecosystems. The technology update strengthens AI-supported decision-making and adds Physical and embodied AI for robots, autonomous machines and drones acting directly in the environment.

Finally, Chapter 3.6, Digital Society, extends its ECS scope in two directions: distributed digital content-production workflows and financial infrastructure. It also strengthens consumer cybersecurity against fraud and identity attacks, linking trustworthy digital services more directly to European technology capability.

0.2.6 The ECS global timeline for Europe

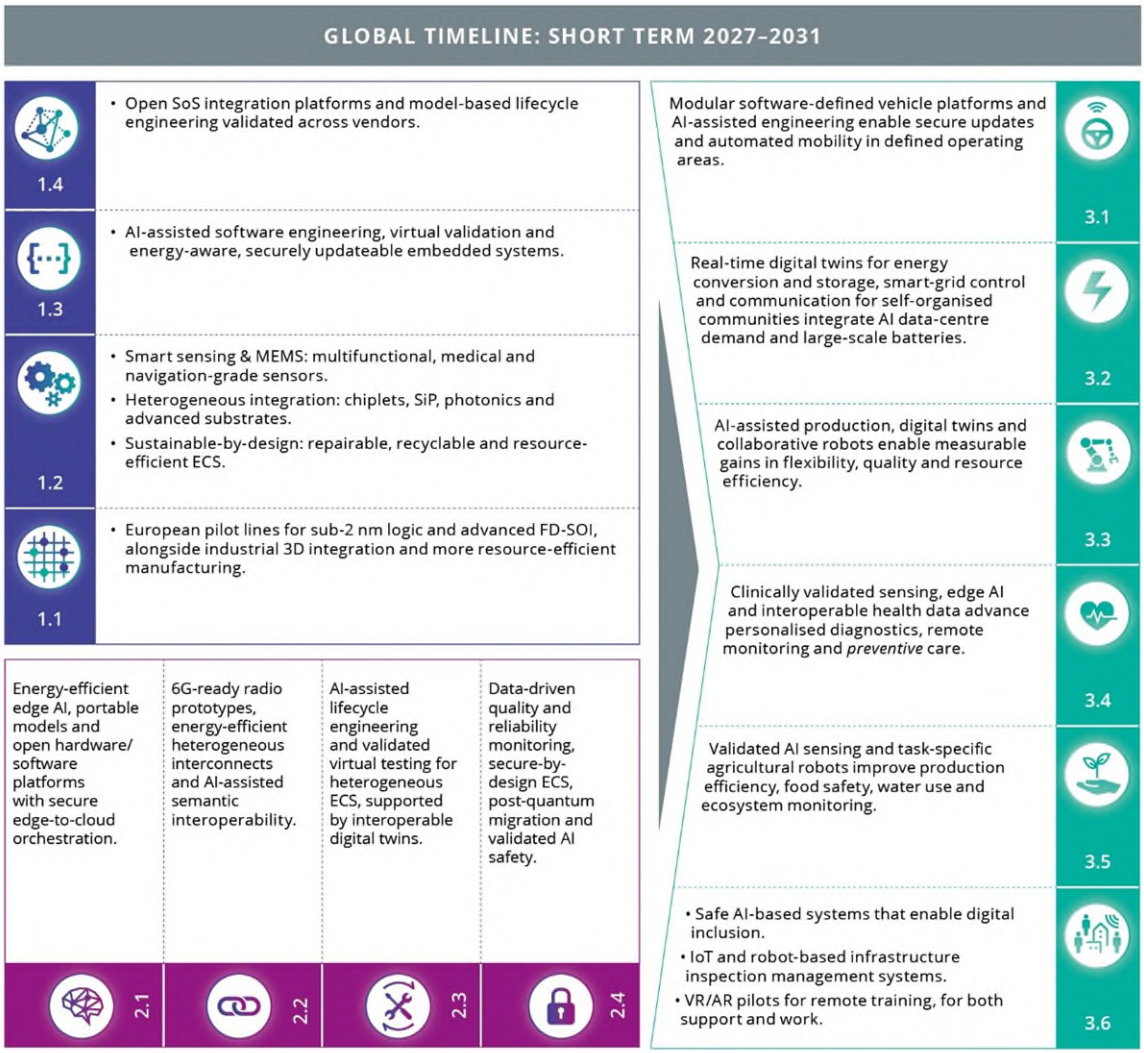
The 2027 ECS SRIA uses three planning horizons: short term (2027–2031), medium term (2032–2036) and long term (2037 and beyond). The horizons indicate when the chapters expect research results to reach advanced prototype or early commercialisation levels, while recognising that maturity differs by technology and application.

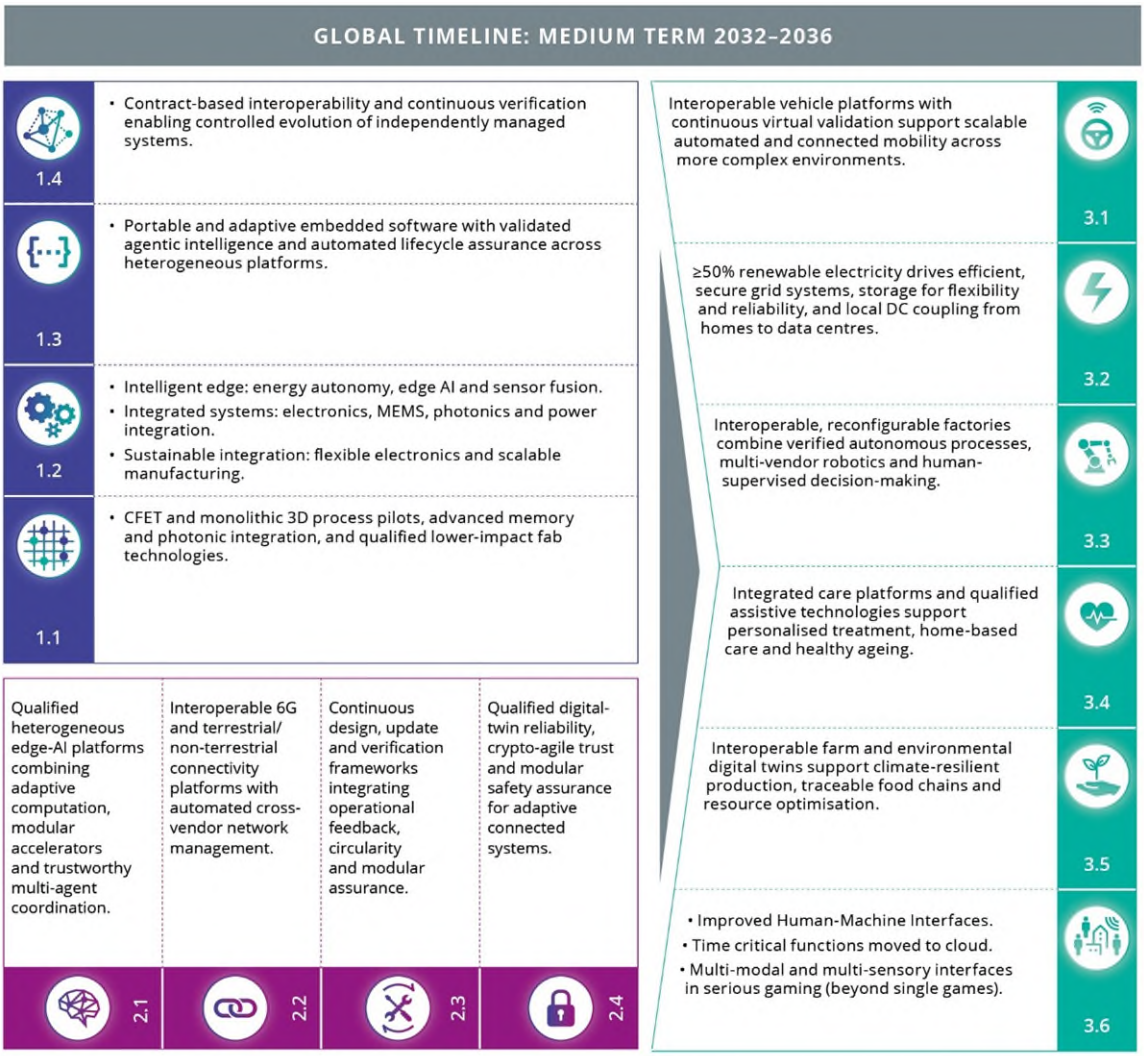
The following figures summarise the most salient milestones to be reached in the various domains covered by the ECS SRIA over the three time periods:

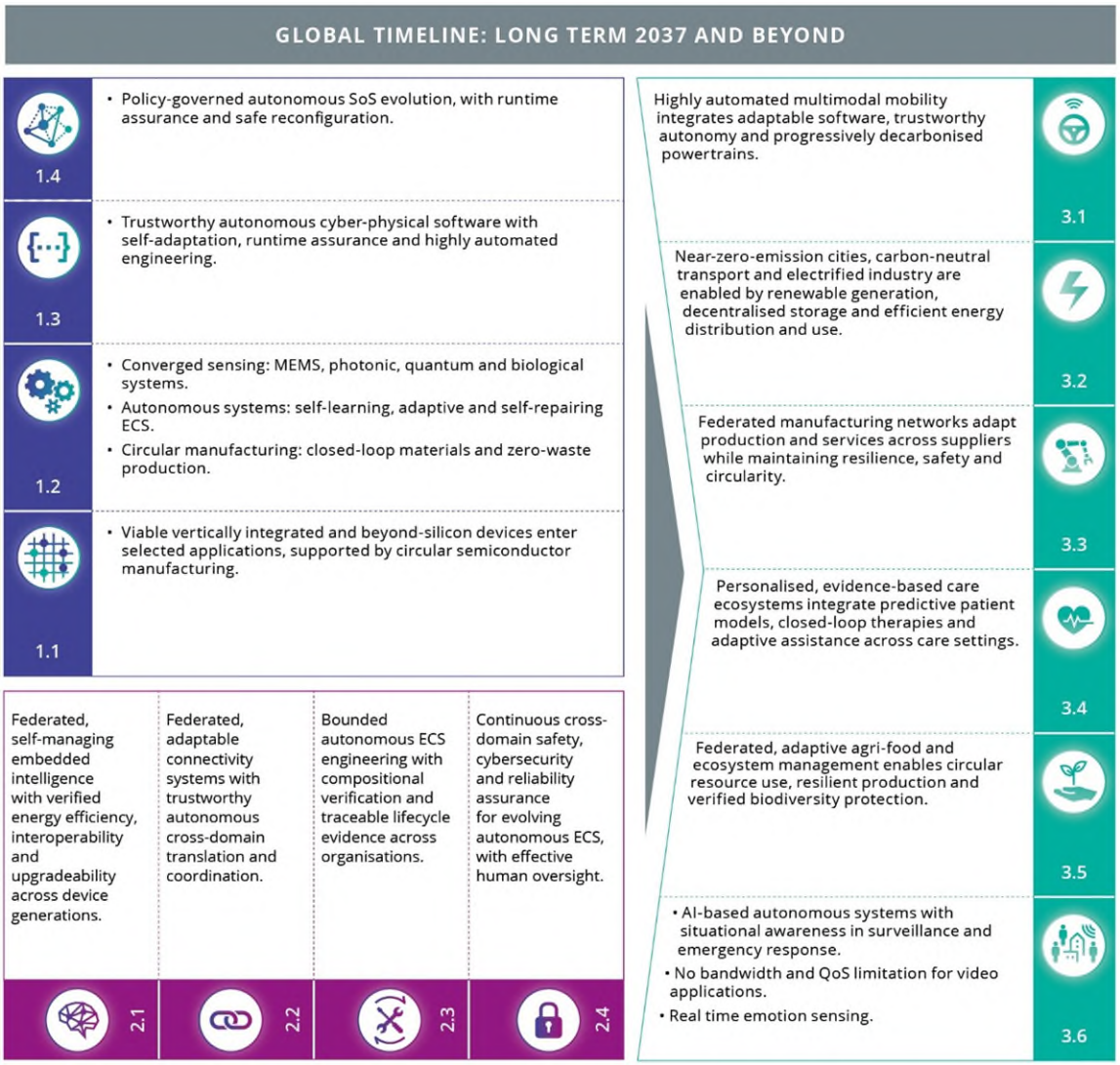
- Short term (2027–2031)
  Priorities are tied to technologies and engineering capabilities already approaching industrial validation or deployment.
- Medium term (2032–2036)
  Roadmaps remain sufficiently mature to identify expected capabilities, but technology choices and application requirements may still change.
- Long term (2037 and beyond)
  Milestones are prospective and indicate research directions rather than fixed deployment dates.

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.

Detailed timelines are maintained in the individual chapters, where assumptions and maturity can be updated with the required technical context. The Introduction therefore concentrates on the shared horizons and the dependencies between them.


GLOBAL TIMELINE: SHORT TERM 2027–2031
1.4
• Open SoS integration platforms and model-based lifecycle engineering validated across vendors.
1.3
• AI-assisted software engineering, virtual validation and energy-aware, securely updateable embedded systems.
1.2
• Smart sensing & MEMS: multifunctional, medical and navigation-grade sensors.
• Heterogeneous integration: chiplets, SiP, photonics and advanced substrates.
• Sustainable-by-design: repairable, recyclable and resource-efficient ECS.
1.1
• European pilot lines for sub-2 nm logic and advanced FD-SOI, alongside industrial 3D integration and more resource-efficient manufacturing.
Energy-efficient edge AI, portable models and open hardware/ software platforms with secure edge-to-cloud orchestration.
2.1
6G-ready radio prototypes, energy-efficient heterogeneous interconnects and AI-assisted semantic interoperability.
2.2
AI-assisted lifecycle engineering and validated virtual testing for heterogeneous ECS, supported by interoperable digital twins.
2.3
Data-driven quality and reliability monitoring, secure-by-design ECS, post-quantum migration and validated AI safety.
2.4
Modular software-defined vehicle platforms and AI-assisted engineering enable secure updates and automated mobility in defined operating areas.
3.1
Real-time digital twins for energy conversion and storage, smart-grid control and communication for self-organised communities integrate AI data-centre demand and large-scale batteries.
3.2
AI-assisted production, digital twins and collaborative robots enable measurable gains in flexibility, quality and resource efficiency.
3.3
Clinically validated sensing, edge AI and interoperable health data advance personalised diagnostics, remote monitoring and preventive care.
3.4
Validated AI sensing and task-specific agricultural robots improve production efficiency, food safety, water use and ecosystem monitoring.
3.5
• Safe AI-based systems that enable digital inclusion.
• IoT and robot-based infrastructure inspection management systems.
• VR/AR pilots for remote training, for both support and work.
3.6


GLOBAL TIMELINE: MEDIUM TERM 2032–2036
• Contract-based interoperability and continuous verification enabling controlled evolution of independently managed systems.
1.4
• Portable and adaptive embedded software with validated agentic intelligence and automated lifecycle assurance across heterogeneous platforms.
1.3
• Intelligent edge: energy autonomy, edge AI and sensor fusion.
• Integrated systems: electronics, MEMS, photonics and power integration.
• Sustainable integration: flexible electronics and scalable manufacturing.
1.2
• CFET and monolithic 3D process pilots, advanced memory and photonic integration, and qualified lower-impact fab technologies.
1.1
Qualified heterogeneous edge-AI platforms combining adaptive computation, modular accelerators and trustworthy multi-agent coordination.
2.1
Interoperable 6G and terrestrial/ non-terrestrial connectivity platforms with automated cross-vendor network management.
2.2
Continuous design, update and verification frameworks integrating operational feedback, circularity and modular assurance.
2.3
Qualified digital-twin reliability, crypto-agile trust and modular safety assurance for adaptive connected systems.
2.4
Interoperable vehicle platforms with continuous virtual validation support scalable automated and connected mobility across more complex environments.
3.1
≥50% renewable electricity drives efficient, secure grid systems, storage for flexibility and reliability, and local DC coupling from homes to data centres.
3.2
Interoperable, reconfigurable factories combine verified autonomous processes, multi-vendor robotics and human-supervised decision-making.
3.3
Integrated care platforms and qualified assistive technologies support personalised treatment, home-based care and healthy ageing.
3.4
Interoperable farm and environmental digital twins support climate-resilient production, traceable food chains and resource optimisation.
3.5
• Improved Human-Machine Interfaces.
• Time critical functions moved to cloud.
• Multi-modal and multi-sensory interfaces in serious gaming (beyond single games).
3.6


GLOBAL TIMELINE: LONG TERM 2037 AND BEYOND
1.4
• Policy-governed autonomous SoS evolution, with runtime assurance and safe reconfiguration.
1.3
• Trustworthy autonomous cyber-physical software with self-adaptation, runtime assurance and highly automated engineering.
1.2
• Converged sensing: MEMS, photonic, quantum and biological systems.
• Autonomous systems: self-learning, adaptive and self-repairing ECS.
• Circular manufacturing: closed-loop materials and zero-waste production.
1.1
• Viable vertically integrated and beyond-silicon devices enter selected applications, supported by circular semiconductor manufacturing.
Federated, self-managing embedded intelligence with verified energy efficiency, interoperability and upgradeability across device generations.
2.1
Federated, adaptable connectivity systems with trustworthy autonomous cross-domain translation and coordination.
2.2
Bounded autonomous ECS engineering with compositional verification and traceable lifecycle evidence across organisations.
2.3
Continuous cross-domain safety, cybersecurity and reliability assurance for evolving autonomous ECS, with effective human oversight.
2.4
Highly automated multimodal mobility integrates adaptable software, trustworthy autonomy and progressively decarbonised powertrains.
3.1
Near-zero-emission cities, carbon-neutral transport and electrified industry are enabled by renewable generation, decentralised storage and efficient energy distribution and use.
3.2
Federated manufacturing networks adapt production and services across suppliers while maintaining resilience, safety and circularity.
3.3
Personalised, evidence-based care ecosystems integrate predictive patient models, closed-loop therapies and adaptive assistance across care settings.
3.4
Federated, adaptive agri-food and ecosystem management enables circular resource use, resilient production and verified biodiversity protection.
3.5
• AI-based autonomous systems with situational awareness in surveillance and emergency response.
• No bandwidth and QoS limitation for video applications.
• Real time emotion sensing.
3.6

0.2.7 The ECS SRIA outline

The following diagrams 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”.

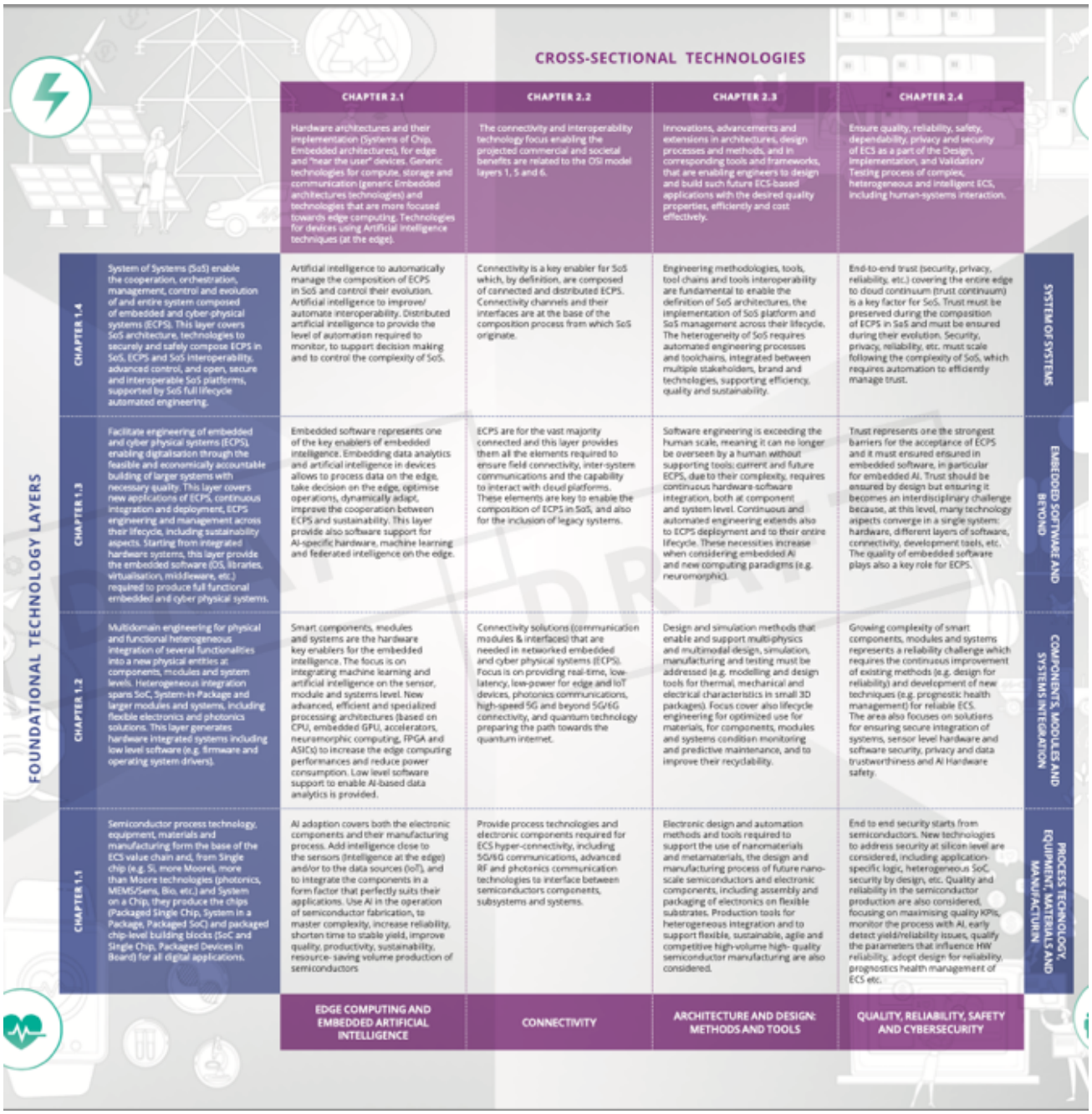


Figure 0.5 SRIA outline – 1 of 2



Figure 0.6 SRIA outline – 2 of 2

0.3 PART 3 - HOW? Navigating the ECS SRIA

As mentioned, the ECS covered by this document is very wide-ranging, and involves many technical disciplines in materials, processes, hardware and software. Therefore, most readers will only want to read those chapters that cover the disciplines of their interest, without being willing to go through all the technical details presented in the ECS SRIA.

For each technology and application domain it covers, the ECS SRIA identifies specific so-called **Major Challenges**, with a focus on the most critical aspects to be tackled from the perspective of innovation. The analysis of each Major 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.

The structure of all the **Foundational Technology** and **Cross-Sectional** chapters is identical. In the **Key Application Areas** chapters, the authors explore each domain with the application demands as 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 earlier releases of the ECS SRIA is now 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.

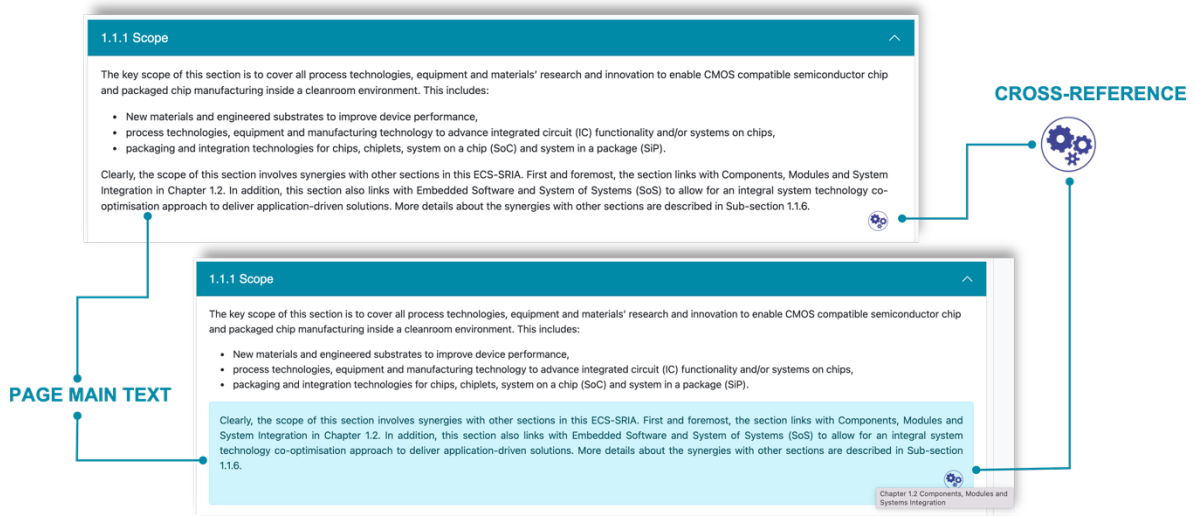


Figure 0.7 Cross Reference example

References within a text are indicated by small numerical markers embedded in the content, e.g. 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.

1

Strategic Research and Innovation Agenda

FOUNDATIONAL TECHNOLOGY LAYERS

1.1



Foundational Technology Layers

PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING

1.1 PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING

Semiconductor process technologies, 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 semiconductor IC manufacturing inside a cleanroom environment. This includes:

- New materials and engineered substrates to improve integrated circuit (IC) performance,
- Process technologies, equipment and manufacturing technology to advance IC functionality and/or systems on chips,
- Wafer level integration addressing a technology of packaging a die while it is still on the undiced wafer or bonded/attached to a wafer (D2W). Protective layers and electrical connections are added to the substrate before dicing.

Clearly, the scope of this section as indicated in figure 1.1.1 below 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.

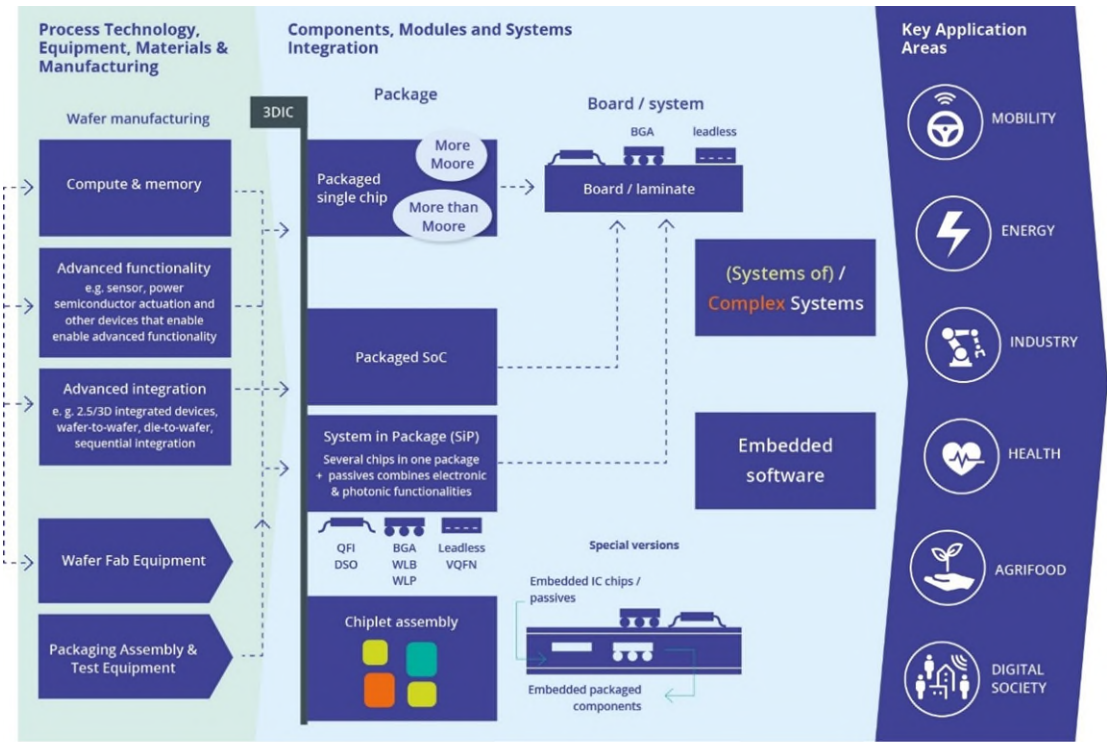


Figure 1.1.1 - The chip and packaged chip-level building blocks are the starting point for the other ECS-SRIA Chapters

1.1.2 Application breakthroughs

The main breakthroughs enabled by the technological advances discussed in this section permeate almost all aspects of our society.

Artificial Intelligence & Energy

In the last fifteen years, the amount of data created, captured, replicated and consumed each year has increased exponentially from about 2 Zetta-bytes (1 ZB= 10^{21} bytes) in 2010 to ~180 ZB in 2025, and is expected to grow to more than 2000 ZB in 2035. Data is becoming the "new oil" of the 21st century.

Therefore, all the application sectors described in §3 require access to AI models to process quickly and efficiently their own data. In order to be processed efficiently and support conclusions, decision-making and action, such data can require the use of large AI models. Conversely, the continuous expansion of AI, especially with advances in generative AI models, will be a strong catalyst for a data tsunami.

AI models use artificial and more often deep neural networks (ANNs and DNNs), which can contain trillions of parameters, to teach "computers" to process data in a way that mimics how the human brain sends signals and receives information. Just like our brain's interconnected network of neurons, ANNs are very schematically composed of alternating layers of artificial neurons, as computing units, and synapses, as memory units, with each layer of neurons driving those in the next layer through their synaptic "weight" connections, to finally solve a problem.

Deep ANNs (DNNs) are trained in order to determine the synaptic weights of each neuron layer using backpropagation methods for adjusting those weights using huge datasets. DNN training currently requires the use of:

- high-performance computing blocks that are designed for rapid parallel processing such as graphics processing units (GPUs), tensor processing units (TPUs), neural processing units (NPUs) and other dedicated chips. Their computing performance is enhanced by increasing the transistor density, and so, by scaling down the transistor dimensions (Moore's law).
- massive storage memories, such as stacked volatile DRAMs (High Bandwidth Memory-HBM), which are used for increasing the data transfer rate between the processing blocks and the main memory.

However, increasing the data transfer rate between the computing block and the DRAM array leads to very high energy consumption and long computing times, which strongly limits the use of conventional central processors (CPUs), typically used in PCs and smartphones, for processing very large DNNs.

Once DNNs are trained, they can be used to answer queries, the so-called inference process, which is also energy-intensive. To increase their accuracy, the DNN models can be further improved by adjusting the synaptic weights with new data arising from multiple queries.

Depending on the application and on its peculiarities in terms of energy consumption, latency for real-time analysis, data security and privacy, and on the size of the requested DNN model, data processing using AI can be performed either in the cloud, using AI-related data servers, or at the edge, as close as possible to the data sources (edge-AI) (see §2.1). Due to the current limited computing capabilities at the edge, "medium-sized" DNNs are trained in the cloud and can be downloaded to the edge-AI

processors for the inference process. For huge DNNs, both training and inference are performed in AI-related data servers.

Energy transition

Large DNNs can require data-centre-scale computing resources for training and inference, with correspondingly high energy consumption. By comparison, the human brain operates at an estimated power of around 20 W. Therefore, the semiconductor industry is investigating various ways to reduce the power consumption of processing large AI models. Concepts being studied include more energy-efficient devices and new computing architectures such as near-memory, in-memory, edge and neuromorphic computing.

Furthermore, the energy consumption of AI-related data servers can also be significantly reduced using:

- WBG power electronic devices, such as those used in electric vehicles, to reduce electrical losses between active devices and improve the sustainability of data servers.
- Si-based optical interconnects instead of Cu interconnects for interconnecting the constituent nanoelectronic devices.
- Advanced packaging or 2.5D-3D integration to reduce connection lengths and increase computing speed.

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 importantly -, electric vehicles, as well as increasing electric-vehicle 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 highly thermally conductive materials.

Communication

The exponential increase in internet traffic[1] sets demanding requirements on data communication technologies. New architectures and technologies will also be essential for the future development of 6G communications for improving the bandwidth and data transmission rate, while exhibiting lower latency and lower power consumption.

Optical interconnects enable higher bandwidth-distance products, higher bandwidth density, lower electromagnetic interference, and 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, including through co-packaged optics (CPO). These photonic capabilities range from silicon and heterogeneous III/V (membrane) photonics to potentially disruptive technologies such as nano-photonics, and 2-D materials or graphene-based photonics and 3D integration. Additionally, developments in novel computing paradigms such as photonic and quantum computing threaten to

[1] https://xenoss.io/blog/big-data-trends

make current security protocols insecure and will require the development of novel, future-proof cryptographic methods.

Sensors & edge AI

Other breakthroughs will concern adding intelligence close to the sensors (intelligence at the edge) and/or to the data sources (IoT), and integrating 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 make decisions independently, without connecting to a central processing unit (CPU). While local decisions will initially be supported by inference, there will be an evolution towards training on edge devices. Edge AI extends embedded computing, and contributes to cost-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 that needs 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 many emerging markets, 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.

Sensor and biosensor technologies will be extensively studied because their rapid, low-cost and highly sensitive capabilities 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. 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 in the use of advanced gas-sensing technology is breath analysis, which aims at non-invasive diagnostics by 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.

Defense & Space

Driven by the growing complexity of modern warfare, where electronic systems play a crucial role in communications, reconnaissance, and targeting, the need for enhanced electronic systems is increasing strongly in military and space applications. [2] In military applications, semiconductors are of utmost importance due to their ability to process and transmit vast amounts of data quickly and efficiently where real-time data processing, notably using AI, is essential for effective decision-making. They allow the development of high-performance advanced radar, navigation and communication systems, encryption technologies, missile guidance, weaponry, and electronic warfare. Semiconductors also enable miniaturization, which becomes a vital issue by making it possible to create smaller, lightweight military equipment without compromising any functionality.

Semiconductor applications in the defense and space domains require specific devices including, but not limited to radiation-hardened ("rad-hard") devices, RF chips (GaN monolithic microwave integrated circuits for RF power amplifiers, for instance), and opto-electronic technology, as well as components also exhibiting lower size, weight, power and cost (SWaP-C) compared to their civilian counterparts. Military applications also require advanced sensing technologies in order to give enhanced situational awareness and decision superiority in the battlespace, which significantly improve defence personnel survivability and mission success. The modern military depends on reliable, advanced optical sensors from the IR to THz range with high sensitivity, high speed, and high operating temperature for applications ranging from night-vision systems to precision-guided munitions, Intelligence, Surveillance, and Reconnaissance (ISR) drones, command and-control centers, and navigation systems for aircraft and ships. LiDAR applications for military and security include target recognition, target location, aim point selection, tracking, and weapon guidance.

Low-Earth-orbit (LEO) satellite constellations already represent a market with substantial demand for devices embedded on the satellites themselves or in ground terminals. Semiconductor chips for LEO satellites must be radiation-hardened, power-efficient, reliable, and high-performance to operate in the demanding space environment. Technologies span from radiation-hard microprocessors and FPGAs to specialized RF and power management ICs. Innovations in materials, design, and integration continue to drive advancements in satellite capabilities, size scaling towards nano-satellites and overall cost-effectiveness.

Semiconductor chips used in base stations related to LEO satellite communication systems have distinct requirements and characteristics compared to those onboard satellites. These ground-based systems are crucial for uplink/downlink communication, signal processing, network management, and interfacing with terrestrial networks. Semiconductor chips for LEO satellite-related base stations focus on high-performance signal processing, RF front-end efficiency, network management, and scalability. They leverage advanced CMOS, GaN, and SiGe technologies to meet the demands of modern satellite communication integrated with terrestrial networks. Flexibility, power efficiency, and support for evolving standards are key drivers in chip design for these ground stations.

[2] IPC, 2025, Securing the Electronics Value Chain – The Blind Spot in the European Union's Defence Agenda?

Bio & health

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.

The advanced sensors required for next generation health and life sciences analytical equipment will also contribute to realizing next generation healthcare, including advanced scientific understanding of disease and the development of more effective treatments. Similar innovative sensor technologies will also enable improvements in the performance of analytical equipment used in materials science, including battery and hydrogen energy ecosystems, and the semiconductor industry resulting in more effective research, development and manufacturing, including yield and quality control.

Quantum sensing

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 quantum coherence and/or quantum entanglement, to measure a physical quantity – ideally with improved accuracy, stability, 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 optical 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 and microscopy**: imaging of molecular structure such as proteins.
- **Communications: Signal reception and amplification** for radar communication; calibrating electrical standards to support 5G/6G.
- **Navigation: Providing high-accuracy positioning;** 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.

Flexible electronics

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.

1.1.3 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, in-memory, neuromorphic, photonic and quantum computing concepts.
  Materials and substrates, process modules and integration technology for novel devices and circuits for advanced computing and AI, memory and in-memory computing concepts based on nano-electronic, photonic, spintronics, quantum or other technology.
- **Major Challenge 2:** Novel sensor, actuation and other devices that enable advanced functionality.
  Materials and substrates, process modules and wafer level integration technology for novel devices and circuits that enable advanced functionality: sensing including quantum sensing, actuating, power conversion, connectivity, etc.
- **Major Challenge 3:** Advanced integration solutions.
  Advanced integration including 2.5/3D integrated devices at wafer level, wafer-to-wafer (W2W) or material on wafer (sequential integration) or dies bonded/attached to a wafer (D2W), etc.
- **Major Challenge 4:** Advanced wafer fab equipment and manufacturing solutions.
  Equipment and manufacturing technologies for processing wafers in fabs from leading edge nodes to differentiated technologies and for advanced functionality devices, including new materials or unconventional geometry and heterogeneous integration technology options.
- **Major Challenge 5:** Advanced packaging, assembly & test equipment solutions.
  Equipment solutions to enable assembly and testing of a wide range of IC's from AI chips, logic and memory to advanced 2.5/3D integrated devices.
- **Major Challenge 6:** Sustainable semiconductor manufacturing
  Solutions to reduce greenhouse gas emissions, water & gas consumption and use of hazardous materials such as PFAS.

1.1.3.1 Major Challenge 1: Advanced computing, in-memory, neuromorphic, photonic and quantum computing concepts

Semiconductor process technology and integration actions will focus on the introduction of new materials and substrates, process modules and integration technology, 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 computing in servers for AI, ML and Gen AI data processing, edge computing/AI, and ultra-low power data processing at the IoT node level up to the highest possible performance. In order to lower the energy consumption of data transmission and processing, currently investigated computing approaches such as in-memory and neuromorphic computing, or quantum computing (to solve

classically unsolvable problems), will require the development of new materials, process modules and their integration in computing systems.

1.1.3.1.1 State of the art

The obvious solution for transistors with increased electrical performance is the use of fully depleted devices. The industry has adopted three integration methods: FDSOI CMOS, FinFET and Gate All Around (GAA) CMOS devices. In chip design it is now recognized that these transistor integration methods enable complementary roles depending on the level of system requirements, i.e., cloud-based services, edge computing or extreme-edge device functionality.

FDSOI is a 2D technology based on a thin buried oxide (BOX) layer under the CMOS channel. FDSOI exhibits several advantages, such as reduced leakage current in standby mode and higher tolerance against soft errors compared to traditional structures. FDSOI is perfectly suited for ultra-low-power IoT, automotive, edge AI and 5/6G SoCs. The leading companies currently produce 18 nm and 22nm FDSOI-based chips. The pilot line on FDSOI will develop 10 and 7nm FDSOI technology nodes to allow a further reduction in energy consumption, while increasing its information-processing performance thanks to the integration of embedded non-volatile memories, RF modules and 3D-integration options.

The 3D-based FinFET and GAA devices provide high current drive, and hence higher speed, low leakage and, most importantly, less wafer area per transistor than the classic 2D metal–oxide–semiconductor field effect transistor (MOSFET) technology. These new devices are designed and processed to deliver better performance for applications in high-growth markets such as hyper-scale data centres, AI and ML, autonomous vehicles and power-efficient SoCs for the most demanding computer applications. The international industry value chain is pushing production beyond the 2 nm node by moving towards more 3D-stacked FET architectures, and requires solutions to materials and process-integration challenges (High-NA EUV, 3D-integration for instance) to realise these novel devices.

Scaling further has recently been demonstrated to be possible via the introduction of CFET (complementary FET) or 3D-stacked FET devices. CFET devices are a key contender for sub-2 nm process technologies.

The CFET architecture is an evolution of a Gate-All-Around (GAA) architecture, where the nFET and pFET are stacked vertically rather than side by side. Its fabrication requires new schemes for metal wiring and the power rails used to power the device. CFET is a key contender for the sub-2 nm technologies.

Two CFET manufacturing integration schemes have been proposed – one that grows the pFET and nFET together in a monolithic manner and the other that grows them sequentially. The monolithic approach involves stacking nFET and pFET channels vertically on a single substrate, creating a complex but compact device with a shared gate. It offers better performance and lower cost. However, extremely high aspect ratio (HAR) etching is needed for monolithic integration, which is a challenge. In the sequential approach, n-type and p-type transistors are created on separate substrates, which are then bonded together to form the device. This allows more flexibility in nFET and pFET channel materials. However, a very accurate nFET-pFET alignment is needed and the manufacturing cost is higher.

The sub-2nm advanced System-on-Chip pilot line NanoIC deployed by the European Chips Act will enable R&D on this technology to reach higher maturity, including design enablement that will offer

access to European manufacturing and the design industry. Access to the NanoIC pilot line will boost the competitiveness of SMEs and start-ups and will also strengthen the EU's position in the value chain, increasing resilience and maintaining relevance in the world race of addressing the ever-increasing user needs and societal challenges

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 ML and Gen-AI. Near-memory and in-memory computing are new 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 and organic interposers allow 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 SoIC and "CoWOS" technology).

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, active devices are placed vertically on top of each other. This is commonly done in the field of CMOS image sensors and HBM (High Bandwidth Memory) DRAM stacks. These 3D integration technologies use TSV technology in the active die, in combination with high-density die-to-wafer or wafer-to-wafer interconnect technologies. This greatly increases the number of functional interconnects per die area on the functional chips. 3D-interconnect pitches below 5 µm and even down to 400 nm 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.

The amount of data processed in the cloud, the development of Internet-of-Things (IoT) applications, and growing data privacy concerns force the transition from cloud-based to edge-based processing. Limited energy and computational resources at the edge push the transition from traditional von Neumann architectures to In-memory Computing (IMC), especially for machine learning and neural network applications. IMC also uses the intrinsic properties and operational principles of the memory cells and cell arrays, by inducing interactions between cells such that they can perform computations themselves. IMC aims to improve the energy efficiency of artificial/deep neural networks (ANN/DNN) hardware realizations by computing weighted-sum tasks in the memory arrays, for instance.

In an ANN chip, the neuron/synapse states are encoded as digital bits, clock cycles or voltage levels, while in a spiking neural network (SNN) chip, information is encoded into spike timing, to mimic

biological brain operations. SNN hardware realizations are engineered to seek ultra-low power consumption and run at relatively low frequencies to emulate realistic biological behaviours; this is referred to as neuromorphic computing.

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 evolved into monolithically integrated 3D NAND, using the third dimension for scaling, and DRAM is currently following the same path. This will require innovation in DRAM select-transistor channel materials (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 and neuromorphic 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 TSVs 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 part of the main memory subsystem, and as embedded memories. New memory devices and technologies are currently being investigated that can both store data at high densities and lower cost, and present other benefits that will help computation with new in-memory computing paradigms: fast access time, long data retention, multilevel-to-analog capability and/or high endurance. The main emerging NVM technologies to allow in-memory computing architectures and embedded memories are: (i) phase-change memory (PCM), Threshold Change memory (TCM) ; (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), RAM (FeRAM) and tunnel junctions (FTJ); (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 non-volatility in main memory, and enabling new functionalities for computing systems outside von Neumann architectures.

Thanks to its optimal compatibility with CMOS technology, Silicon Photonics is becoming a key material platform enabling technology for high-speed connectivity in data centres. In the near future, Photonic Integrated Circuits (PIC) can also bring significant changes to high-performance computers and unlock the full potential of AI by resolving the transmission bottleneck of electronics.

Photonic processors that compute with photons instead of electrons display some extraordinary properties, such as an ultra-wide communication bandwidth, ultra-high processing frequency, and ultra-low energy consumption. Additional dimensions for multiplexing the light field, such as wavelength and spatial mode, enable multithread processing with almost no extra computing overhead, leading to significant acceleration compared with traditional electronic computers.

By combining the high bandwidth and parallelism of photonic devices, photonic neural networks (PNNs) have the potential to be orders of magnitude faster than state-of-the-art electronic processors while consuming less energy per computation. PNNs aim to leverage high-speed optical devices to

mimic essential computing primitives (neurons and synapses) and connect them into a neural network (ANN/SNN) with highly parallel and dense optical interconnects.

The goal of neuromorphic photonic processors is not to replace conventional computers, but to enable applications that require low latency, high bandwidth and low energy consumption and are currently unreachable by conventional computing technology.

Photonic processors have light sources, passive and active devices. Nowadays, more than 10 companies produce PICs worldwide, mainly based on SOI wafers. However, there is no commercial fabrication platform that can simultaneously offer devices for light generation, optical amplification, wavelength multiplexing, photo-detection, and transistors on a single die. State-of-the-art devices in each of these categories use different photonic materials (SiN, Ge, InP, GaAs, 2D materials, etc) with incompatible fabrication processes (SOI, CMOS, FinFETs).

Energy efficient and fast switching optical and electro-optical materials are needed for non-volatile photonic storage and weighting (synapses), as well as high-speed optical switching and routing, with low power consumption. Neural non-linearities are already possible on mainstream platforms using electro-optic transfer functions, but new materials promise significant performance opportunities. Phase change materials (PCMs), graphene and ITO-based modulators can also be utilized for implementing non-linearities (neurons).

On-chip optical gain and power will require co-integration with active III-V (InP or GaAs) lasers and semiconductor optical amplifiers. Current approaches involve either III-V to silicon wafer bonding (heterogeneous integration) or co-packaging with precise assembly (see also Chapter 1.2). Quantum dot lasers are another promising approach as they can be grown directly onto silicon, but fabrication reliability does not currently reach commercial standards. Co-integrating CMOS controller chips with silicon photonics to provide electrical tuning control/stabilization and robust packaging for preventing PIC temperature fluctuations will be critical.

The past decade has seen an explosion in efforts to develop quantum computers that could revolutionize the fields of physics, medicine, biology, AI, finance and cryptography by exponentially speeding up certain computational domains. While such demonstrations certainly mark an essential technological milestone, tasks accomplished at such an unimaginable speed do not necessarily imply the commercialization of quantum computers in the short term. To ensure the continued progression of quantum technologies over the next decade, advances in materials and fabrication processes are required for quantum computing hardware, following a path similar to the transistor technology scaling that enabled the evolution of digital computing.

1.1.3.1.2 Vision and expected outcome

Driven by market demand on the one hand for advanced high-performance computing, AI/ML, and on the other hand for mobility, edge AI and IoT devices, the advanced Si technology roadmaps for both FinFET/GAA 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, photonic 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), Threshold Change RAM, STT- MRAM, FeFET, FeRAM, FTJ, Electro-Chemical RAM (EC-RAM)) to the demonstration level in the IoT infrastructure (from servers, through the edge, to nodes).

New markets will require storage class memory to bridge the performance gap between DRAM and NAND Flash. Edge AI and IoT applications will require low-power embedded devices and cloud computing with more mass-storage space. The standard memory hierarchy is challenged. Indeed, learning algorithm requirements will dramatically increase the requirements on memory densities, access bandwidth and endurance on one hand, while new functionality such as multilevel-to-analog non-volatile memory cells are required to allow an efficient in-memory computing approach like ANN, from direct matrix vector multiplication to CNN or spike neural architectures. Simultaneously, advanced interconnect, System on Chip (SoC) integration 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 architectures is a strength to foster and build upon in Europe.

Furthermore, the downscaling of photonic components (light sources, modulators, photodetectors, optical phase shifters…) and their integration on CMOS platforms would lead to photonic neural networks (PNNs) for overcoming the current memory bottleneck. Such PNNs are expected to achieve orders-of-magnitude improvements in energy efficiency and throughput compared to ANNs and SNNs. Hence, the intimate collaboration between the strong EU electronic and photonic communities would enhance EU leadership in this domain.

One of the current major issues for most of the developed quantum technologies is their future scalability. For example, quantum computing error rates multiply as scale increases, and creating large numbers of qubits that are stable enough for long enough is extremely challenging. Collaboration between quantum “laboratories” and the EU electronic industry is essential for strengthening the EU position in quantum computing.

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.

1.1.3.1.3 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.

1.1.3.1.4 Key focus areas

This challenge includes the following key focus areas:

Topic 1.1

- Explorations of the scaled Si technology roadmaps of the 2 and 1 nm nodes including FinFET/Trigate and stacked gate-all-around horizontal or vertical nanowires, Forksheet-, complementary FET architectures, next-generation 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.

Topic 1.2

- Exploration and implementation of materials beyond Si (SiGe, SiC, GaN, Ge, InGaAs, InP, functional oxides, 2D material heterostructures, CNT and nanowires).
- 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.

Topic 1.3

- 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.
- New photonic integrated circuits (PICs) for a further improvement of optical I/Os for enabling compute, memory, and networking ASICs to communicate with dramatically increased bandwidth, lower latency and at a fraction of the power of existing electrical I/O solutions.
- In the longer term, Photonic Neural Networks (PNNs) could bring the benefits of photonics over electronics (energy efficiency, low latency, higher bandwidth, parallelism…) to AI/ML.

Topic 1.4

- Long-term challenges such as steep slope switches (tunnel FET, negative capacitance FET, nanoelectromechanical systems / NEMS), spin-based transistors, and alternative high-performance switches.

Topic 1.5

- New embedded non-volatile memory (e-NVM) technologies to enable local AI processing and storage of configuration data, which decrease data transmission volume and 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.

Topic 1.6 Materials-related challenges

- 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.
- Material innovations to merge different photonic materials (SiN, Ge, SiCOI, InP, GaAs, $LiNbO_3$, $LiTaO_3$, $BaTiO_3$, 2D materials, etc) with common semiconductor fabrication processes (SOI, CMOS, FinFETs).

1.1.3.2 Major Challenge 2: Novel sensor, actuator, power components and other devices that enable advanced functionality

Materials and substrates, process modules and wafer level integration technology for novel devices and circuits that enable advanced functionality: sensing - including quantum sensing, actuating, power conversion, connectivity, etc.

1.1.3.2.1 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” for the past 20 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.

For IoT applications, logic and RF functions are combined, but not with the highest efficiency required by the ultra-long lifetime of unattended objects. Energy harvesting schemes, often based on photovoltaics, do exist, yet are not always able to provide the required energy supply for self-contained, low-volume and low-cost sensor nodes.

Smart optical (including non-visible radiation), 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 or other coated materials. 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, with demanding concentration ranges, selectivity and stability requirements. 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 devices, and photonics. Please note that in the previous sentence

“quantum sensing” means sensing using individual quantum objects and their entanglement. 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 the more conventional light sensing techniques, sensors are often based on the absorption of a given semiconductor species, which leads to a rather broad but limited energy range. Emerging techniques tailor the wavelength range through either confinement of the sensing element (“quantum dots”) or the combination of different materials in the same stack. The question of wavelength selection, in case a further wavelength selectivity is needed, for instance to address both the visible and near infrared bands, is usually addressed by stacking different sensing elements and optical filters of various principles.

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, and are becoming dominant in some sectors, like high-power electric motors... 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 some GaN devices are produced on silicon substrates, but the technologies 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 to the transition to 200 mm and then from 200 mm to 300 mm substrates where possible and where volumes justify it. This is essential for future integrated logic and power management functions using technologies combining logic and power transistors. Besides 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 toward larger diameter substrates – leading to increased power densities and lower costs to support the transformation in the energy systems with Si-based power semiconductors. In some cases, the power dissipation of the devices - which remains high despite their better efficiency - is a real challenge and needs to be addressed both at device and wafer level and at the packaging level (see also Chapter 1.2).

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 both substrate diameters, 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. For example, BiCMOS brings advantages over some III-V technologies for some applications, leveraging the capability to integrate digital functions. However, it cannot compete with GaN when very high power is required, while GaN cannot compete with BiCMOS for products requiring mixed-signal functions. New RF technologies delivering high output power and efficiency like RF GaN (GaN-SiC as well as GaN-Si) and other III-V based materials - such as InP - could overcome these limitations. Those technologies have to be considered either stand-alone or in combination with either RFCMOS

or BiCMOS using heterogeneous integration. In the field of communications, the integration of photonics technologies with electronics is gaining commercial ground. Further advances in efficient source integration, 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, either by using light interaction with the signal to be measured outside the PIC and sensing the effect of this interaction within the PIC or by using the PIC as an actuator, for instance by implementing optical (phased array) antennae.

In optical communications, the intrinsic capability of light waves to transmit signals with low latency and power dissipation, at ultra-high 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, which is part of Silicon 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 addition to substrate progress, a host of innovations will be necessary and are expected to boost silicon photonic integrated circuits (PICs). Among those are new generations of active devices including the heterogeneous integration of active devices (sources, modulators) or passive components and detectors (mainly for sensing), for example for wavelengths outside the communication frequencies. They involve new materials and integration techniques.

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) are 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 areas can be identified where the merging of novel flexible devices and adapted Si electronics creates progress beyond the state of the art.

1.1.3.2.2 Vision and expected outcome

Depending on the application, the advantages of More-than-Moore (or SoC) technology are size, performance, cost, reliability, security and simpler logistics. Therefore, this approach 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.

For example, concerning thermal imagers, 300 mm capabilities, sub-90 nm nodes and advanced integration technologies are key to developing sensors that satisfy market requirements. Sub-90 nm nodes for digital IC are mandatory for adding functionalities to thermal imagers and reducing their pixel pitch. Hybrid bonding between micro-bolometer thermal imager wafers and artificial intelligence (AI) chips on more advanced nodes will be required for edge image processing, while the most advanced 3D stacking technologies are only available on 300 mm platforms. Advanced photolithography processes are required for advanced-node CMOS processes but also for achieving high yields during the MEMS above IC part of the process of small pitch devices (<12 µm). Indeed, the

features to be defined for small pitches cannot be defined reliably with 200 mm photolithography tools.

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 and ultra-wide bandgap materials, III-V semiconductor compounds, 2D materials (e.g. graphene, transition metal dichalcogenides, van der Waals layered materials...), 1D (e.g. nanowires, carbon nanotubes) and 0D (e.g. nanoparticles, quantum dots) materials, metal oxides, organic semiconductors, ferro- and piezoelectric, thermoelectric and ferro- and antiferroelectric thin films or heterostructures, materials with specific properties (for optics: dielectrics, bi-refringent, phase change materials which can also be used for conductivity change properties, for electromagnetic properties: low permittivity, etc.), metamaterials and metasurfaces. Obviously, safety and environmental aspects should also be taken into consideration.

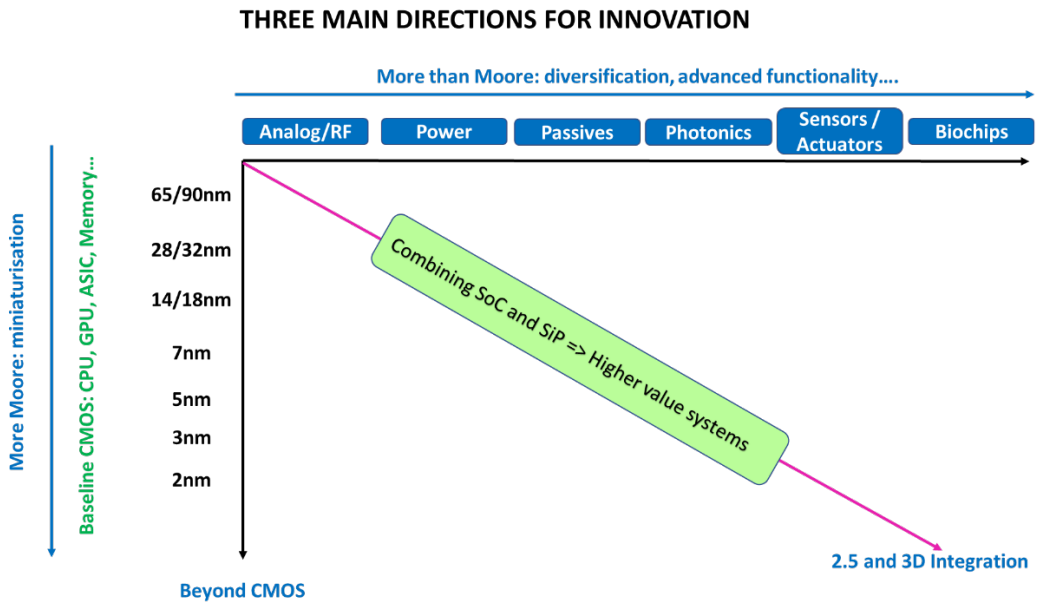


Figure 1.1.2 Diversification of applications, continued miniaturisation and integration on chips and in package leads to higher value systems (Source: IRDS)

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 Europe's position in specific design concepts and architectures, especially when used in combination with re-use IP and third-party IP blocks to secure fast time to market.

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 and sensing), much more efficient power management, higher integration of passive devices, photonics circuits and options, novel and more efficient displays and electronics, this list being non-exhaustive. A key element 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 an 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, and also InP which provides a further challenge to GaN in that it cannot be grown on Si).

1.1.3.2.3 Key focus areas

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

Topic 2.1: 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:

- Logic integration with RF, magnetic, optical or sensor technologies.
- Integration of lasers and detectors within a silicon photonics platform.

Topic 2.2: Advanced sensor and actuator technologies:

- Mechanical sensors and actuators (e.g., acceleration, gyroscopes, microphones and micro-speakers).
- 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, etc…).
- Physical sensors (magnetic, optical, including non-visible radiation, RF).
- Multispectral or highly sensitive optical sensors.
- Transmitter/receiver technologies for applications such as lidar and active phased array imaging.
- Biomedical and biochemical sensors.
- New, more efficient displays, in particular micro displays.
- Environmental protection technologies for audio MEMS and integrated technologies for enhanced robustness against the external environment for MEMS-based audio devices.
- Materials for energy harvesting (e.g., perovskite solar cells, piezoelectric thin films) and storage (in particular using high energy density storage materials, e.g. perovskites, ferroelectrics and relaxors), micro-batteries, supercapacitors and wireless power transfer – specifically for portable IoT applications.
- A more integrated “materials-to-systems” perspective linking materials, devices, system architectures and embedded intelligence, for enhancing the performance of functional sensing materials (chemical, optical or other)

Topic 2.3: Advanced power electronics technologies (Si-based, BCD, SiC, SiC-on-pSiC, GaN, GaN/Si, GaN/SiC, 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.
- Power devices and modules for highly demanding automotive, industrial and energy infrastructure applications.
- Substrates towards larger diameters to serve greater future demand for cost-sensitive power solutions.
- High-power and -energy density capacitors (e.g., snubber, DC-Link) with high voltage rating (> 400 V) based on ferroelectric/antiferroelectric materials (e.g., perovskites).

Topic 2.4: Quantum sensor technologies:

Technologies used for the next generation of quantum sensing include neutral atoms, trapped ions, magnon condensates, coupled oscillators, spin qubits, superconducting devices, and photonics

- 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 colour centres as sensitive elements.
- Superconducting circuit sensors based on SQUIDs, flux qubits and charge qubits.
- Sensors based on photon entanglement using nonlinear optical media.
- Quantum magnonics sensors exploiting the coupling with photons, phonons and qubits…

Topic 2.5: Advanced RF and photonics communication technologies to interface between semiconductor 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) via:

- New energy-efficient RF and mm-wave integrated device options, including radar (building on e.g., SiGe/BiCMOS, FD SOI, CMOS, GaN or other III-V compounds, PIC).
- Development and characterisation of new RF cryogenic electronics for Quantum Information Processing (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, nano-photonics, spintronic and optical interconnections, photonics-enabled device and system options into a CMOS-compatible manufacturing flow.
- Magnonics provides potential solutions to challenges in radio frequency (RF) communication systems from the perspective of minimized power dissipation/consumption and direct RF signal processing.

1.1.3.3 Major Challenge 3: Advanced integration solutions

Advanced integration including 2.5/3D integrated devices at wafer level, wafer-to-wafer (W2W) or material on wafer (sequential integration) or dies bonded/attached to a wafer (D2W), etc.

By splitting the chip into smaller, functionally distinct, physically separate parts, 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. One drawback is that the design and testing strategy needs to be entirely revised in order not to lose the yield advantage, and that assembly costs (as collective as possible) and yields must also be mastered. This is the key overarching challenge of this approach.

1.1.3.3.1 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, enabled by advances in integration technology. This is the so-called System in Package (SiP[3]) approach.

To maximise the benefits from ICs made of small geometry nodes, below 40 nm typically and certainly at 7 nm and below, there has already been a move toward more advanced methods, to manage complexity in the most cost-effective way. These advanced integration methods involve technologies such as flip chip, but also - depending on the use cases - wafer-level packaging, fan-out wafer-level packages without substrate interposers and complex 3D structures with TSVs, micro-bumps and thin dice.

The functional diversification of technologies, where digital electronics meets areas such as analog, photonic and MEMS technologies, has been advanced through the assembly of heterogeneous elements. For example, in today's power stages in automotive powertrain applications, power modules integrate several dice in parallel. Similarly, 5G networks are enabled by advanced RF functionality, often combining a photonic interface with in-package integrated logic and memory functionalities. Semiconductor materials encapsulated in packaging technology have already moved from being largely silicon-based or based on III-V compounds for photonic or high-power RF applications, to more advanced SiC and GaN compounds. For packaging, the industry has moved towards environmentally friendly lead (Pb) and halogen-free moulding compounds. For wire bonding, a similar move from aluminium and gold towards copper and silver wiring has been made. Furthermore, flip-chip attachment has transitioned to lead-free bumps inside the package, while BGA interfaces use lead-free balls between the package and the board.

1.1.3.3.2 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, optical, power management, energy harvesting and storage – into a SiP.

[3] SiP related technologies are fully decribed in the chapter 1.2

Depending on the application and type of system, the key drivers and parameters to be improved can be the density of contacts, the parasitics, the integration of passives - including antennae -, the thermal dissipation, the optical quality, the number of dice to be integrated either horizontally or vertically, the ability to handle various environmental conditions including extreme temperatures or resistance to chemicals, etc. It is becoming increasingly clear that the overall performance of the system is dependent not only on the semiconductor technologies but also - and sometimes to an equal extent or even predominantly - on the integration technology.

Advanced integration 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) and display technologies used in AR/VR. Depending on the application, heterogeneous integration technology can provide a better compromise between available functions, performance, cost and time to market.

System integration technologies are a key enabler for European industry, including for instance the essential field of energy transition with power management devices, but also including longer-term developments such as 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 into advanced electronic systems in a competitive and reliable way. All application domains addressed by the ECS agenda will benefit from innovative integration technologies.

Moreover, component carriers also known as Integrated Circuit (IC) Substrates represent a large 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, high-interconnect density computing solutions. Due to increasing functionality and chiplet integration, FC-BGA substrates are facing many challenges not only in terms of miniaturization but are also becoming central elements for thermal management in advanced computing systems.

Integration of the above functionalities in miniaturised packages and (sub)SiP requires 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.

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, e-NVM, 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 optimal technologies at lower cost per function and assembled using high-density 3D interconnect processes. In other words, for each application or system the SoC / SiP trade-offs and partitioning have to be revisited in the light of the respective evolutions of base technologies.

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.

For the reasons above, Electronic Design Automation for 3D integration needs to be explored much further and constitutes a very challenging domain as described in Chapter 2.3.

1.1.3.3.3 Key focus areas

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

Topic 3.1: Advanced Si interconnect technologies and materials:

- Interconnect technologies that allow vertical as well as horizontal integration: this includes process technologies for vertical interconnects, such as TSV, through-encapsulant via (TEV), through-glass via technologies and micro-bumps, and copper/copper bonding, as well as process technologies for horizontal interconnects such as thin film technologies for redistribution on chips.
- 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.
- New materials to maximize package thermal-dissipation efficiency (Flip Chip Thermal Enhanced BGA) are required for very demanding computing applications in extreme conditions, e.g., automotive and space environments.
- New materials such as Al bumps from electroplating could solve reliability issues and ensure advanced CMOS-compatible integration.
- Power electronic substrates will benefit from thick Al layers fabricated by novel electroplating technologies, and other thermal redistribution techniques.

Topic 3.2: Specific sensing, actuation and display technologies.

- Solutions for advanced optical functionalities on wafer, either for sensors (visible, NIR, infrared), for PIC, or for AR/VR, near-eye and head up displays, or any optical system.
- Specific solutions for the signal conditioning of other sensors (mechanical, physical, chemical…)
- Increasing functionality in IC Substrates for high-efficiency power delivery including voltage regulator circuitry and integrated capacitances and other passives.

Topic 3.3: 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 (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 need for interaction between system design and technology with a significant impact on electronic design automation (EDA) tools.

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 six Major Challenges in this section are strongly connected.

1.1.3.4 Major Challenge 4: Advanced wafer fab equipment solutions

This is about equipment and manufacturing technologies for processing wafers in fabs from leading edge nodes to differentiated or mature technologies and for advanced functionality devices, including new materials or unconventional geometry and heterogeneous integration technology options.

The semiconductor equipment and manufacturing sector in Europe provides the global market with best-in-class equipment to enable the research, development and 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, etching, cleaning and wafer handling.

1.1.3.4.1 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 require dedicated long-term investment in high-tech equipment solutions. Enabled by current deposition, lithography, etch, processing and metrology tools and their performance, the 3 nm technology node is in production by market leaders, solutions for 2 nm node are planned for 2025[4], and even Angstrom nodes[5] are being explored.

For the production of miniaturised and reliable More-than-Moore electronic 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.

1.1.3.4.2 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 1 nm, the alignment accuracy of successive layers, referred to as "overlay" or, in another definition, "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.

[4] TSMC 2nm Update: N2 In 2025 (anandtech.com) 3nm Technology - Taiwan Semiconductor Manufacturing Company Limited (tsmc.com)
[5] Intel Demonstrates Breakthroughs in Next-Generation Transistor... Intel Accelerated

In the realm of cutting-edge technology, the advent into new nodes necessitates the development of novel materials. These materials are either integrated into the structure to enhance electrical properties or utilized as sacrificial elements to facilitate the creation of intricate 3D shapes. The precision in material deposition is becoming increasingly critical, requiring meticulous control over where materials are applied, their thickness, and whether they are deposited on horizontal or vertical surfaces.

The introduction of those novel materials, for example superconducting or ferromagnetic materials, requires the consideration of contamination control. Detection and removal of metal contamination need to be taken into account at the fab-equipment level when moving on to monolithic integration into a CMOS environment, especially for leading-edge 300 mm semiconductor manufacturing.

The importance of metrology and inspection of 3D structures in the future cannot be overstated. This holds for both FEOL/BEOL as well as in advanced packaging and all the way to electronic systems. Since optical or electron microscopy-based methods are running out of steam, methods that can see into 3D structures, whether advanced transistor structures, interconnects or stacked chips, are highly needed. In addition, these methods have to be fast and provide high-resolution data.

The semiconductor industry is driven by the dual goals of boosting productivity and slashing energy and water consumption. Wafer fabs are striving to process more wafers per hour without increasing power usage through enhanced equipment throughput, real-time optimization of production flows and streamlined processes. Despite variations in throughput across different equipment types—such as lithography's DUV throughput at approximately 295 wafers per hour whereas throughput in deposition might take up to a few minutes for single wafer processes—there is a universal push for higher throughput and yield, alongside refined process control to minimize additional steps and reduce defective wafers. This pursuit has led to the development of more sophisticated equipment in patterning, processing and metrology, with kWh/wafer serving as a pivotal metric for sustainable innovation.

The increasing technical complexity calls for more efficient design and production methods. At factory level, solutions based on advanced mathematics, statistics or AI should enable broader integration across current domains. Advanced data modelling and analysis techniques, combined with generative AI, should rapidly enable smarter detection of deviations (whether in process or product quality, equipment or global production performance) together with faster reaction thanks to AI-augmented troubleshooting and guided analysis.

The intricate nature of future semiconductor manufacturing equipment requires a substantial increase in skilled labor for design and realization. Without advancements in efficiency, the local labor market may fall short in providing the necessary expertise, potentially slowing down innovation and affecting profit margins. Here too, generative AI should be instrumental in mining existing knowledge repositories to support knowledge transfer to new generations. New methods will have to be developed to ensure the efficiency of this transfer and the sustainability of European know-how. While the use of generative AI should also enable the integration of this knowledge into software assistants or copilots and eventually autonomous systems, techniques will have to be developed to ensure that the system will stay in (human) control.

Automation trends like Industry 4.0 and 5.0 are reshaping manufacturing, demanding greater data exchange and secure integration of design data into production processes. This evolution aligns with the Smart Industry roadmap.

Environmental considerations are also at the forefront, with efforts to eliminate toxic substances such as PFAS-containing materials and SF_6 gas from equipment and processes. Companies are committed to ambitious NetZero goals, focusing on enhancing energy, water, and material efficiency while exploring recycling opportunities for gases like hydrogen and carbon dioxide, as well as processed materials and consumables. Collaborations with equipment and materials suppliers are key to these initiatives, which include refurbishing and reusing components.

Overall, these developments pose significant challenges to the global semiconductor industry across various domains but also present opportunities for European equipment vendors and their supplier networks.

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 the world's leading semiconductor device and component manufacturers. Internationally developed roadmaps such as the International Roadmap for Devices and Systems (IRDS) will also be taken into consideration[6]. Currently, leading integrated device manufacturers (IDMs) are forecasting a continuation of the technology roadmap following the traditional Moore's law at least until 2036[7], which corresponds to at least four new generations after the current technology node.

All-in-all, this represents a major challenge to the international semiconductor industry in the areas of lithography, material innovation, processing, assembly, process control, analysis and testing, as well as an opportunity for the well-positioned European equipment vendors and their network of suppliers.

1.1.3.4.3 Key focus areas

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

Topic 4.1 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.
- Deposition and etching equipment for novel materials to be integrated into a conventional CMOS line, for example for ferromagnetic, ferro- and antiferroelectric, superconducting or 2D materials
- In-line wafer inspection and analysis for process control, defect detection, contaminant control, etc.
- Multi-dimensional metrology (MDM) and inspection for sub-2 nm node devices that combine the full spectrum of physical tools and data processing techniques.

[6] https://irds.ieee.org/

[7] https://www.electronicspecifier.com/products/design-automation/how-long-will-moore-s-law-last/#:~:text=How%20long%20will%20it%20last,the%20year%20traditional%20approaches%20collapse.

- Metrology & inspection methods that can see into 3D structures, whether advanced transistor structures, interconnects or stacked chips, are highly needed. In addition, these methods have to be fast and provide high-resolution data.
- In-line metrology equipment is indispensable for the semiconductor manufacturing industry, providing real-time control, enhanced efficiency, and reduced waste. In the future, it will enable the quantification of hazardous materials and the development of new tools to monitor PFAS and other emissions in real-time.
- Thin film processes including thin film and atomic layer deposition, beam line and plasma ion implantation for doping and material modification, and corresponding equipment and materials, able to support the growing use 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.

Topic 4.2: Wafer fab equipment for differentiated and/or mature technologies

- 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 material substrates of up to 200 mm, or 300 mm in the future.
- 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), which will also require new manufacturing logistics and technologies (e.g. panel moulding).
- 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).

Topic 4.3: Automated manufacturing technologies including fab robotics and wafer transport & handling are required to enable IC-fabs with interconnected tools to support flexible, sustainable, agile and competitive high-volume semiconductor manufacturing

- Enable flexible line management for high-mix and distributed manufacturing lines, including lines for fabrication and deposition of advanced functional (nano) materials.
- Develop infrastructure technology to interconnect systems from various companies and support anticipation, configuration, optimization, etc.
- Implement 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, preserve knowledge and master complexity.

- Apply Productivity Aware Design (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.
- Doubling semiconductor manufacturing in Europe in 2030 also means evolving and upgrading the installed base through incremental approaches, which will necessarily mean increased complexity. Managing such hybrid factories will require advanced decision support and diagnosis techniques leveraging GenAI, Retrieval Augmented Generation (RAG) and integrating existing human knowledge and know-how.
- Developing 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).

Topic 4.4: Sustainable semiconductor manufacturing

- 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 recycling of water and other chemicals.
-

1.1.3.5 Major Challenge 5: Advanced packaging, assembly & test equipment solutions

Semiconductor packaging and assembly equipment refers to the machinery and tools used in the process of packaging and assembling integrated circuits (ICs) and other microelectronic devices. Packaging is a crucial part of semiconductor manufacturing as it protects the semiconductor die, connects the chip to a board or other chips, and conducts heat dissipated by the components it contains. It affects power, performance, and cost on both macro and micro levels. The equipment includes various types of machinery from wafer dicing and encapsulation (or moulding) of the die into a plastic package, through wire bonding (thermocompression, ultrasonic and stitch bonding) and wireless bonding (quasi-monolithic, hybrid bonding), to package marking and labelling equipment.

Semiconductor test equipment is used to evaluate the functionality and performance of semiconductor devices, such as integrated circuits (ICs), during and after the manufacturing process. This equipment is essential for ensuring that the devices meet the required specifications and quality standards before they are shipped to customers. The main types of semiconductor test equipment include Automatic Test Equipment (ATE), Wafer Test Equipment, In-Circuit Test (ICT), etc. These tools are crucial for detecting defects, ensuring reliability, and maintaining high yield rates in semiconductor manufacturing.

1.1.3.5.1 State of the art

The current state of the art in semiconductor packaging and assembly equipment is highly advanced and includes several key technologies that have emerged over the past two decades. Current advanced packaging technology uses sophisticated methods to aggregate components from various wafers, creating a single electronic device with superior performance. It is particularly important for applications like 5G, autonomous vehicles, IoT technologies, and virtual/augmented reality, which require high-performance, low-power chips capable of processing large amounts of data. [8] 3D integration techniques such as 2.5D, 3D, fan-out, and system on-a-chip (SoC) packaging have been developed to supplement traditional wire-bonding and flip-chip technologies. These methods allow for higher density and performance by stacking chips vertically or integrating multiple chips into a single package. In the specific case of chiplets, the approach involves designing chips in a modular fashion that can be integrated with other types of chips to create a complete system. It allows for more flexibility in design and can lead to improvements in performance and power efficiency.

Yet, while reducing the complexity of design, 3D integration - when done at large scale - should considerably increase the complexity of production and supply chain management. Integrating multiple chips in a single package will introduce a new level of complexity in assembly lines which will have to synchronize multiple flows, both internally (bringing the right quantity and quality to the machine) and externally, i.e., at supply chain level, across various front-end facilities or even companies. Designing and operating robust supply chains will require digital twins operating at a much wider scale.

The current state of the art in semiconductor test equipment is characterized by several key advancements. Machine Learning has been integrated into test systems to analyze large volumes of test data in real-time. This allows for the detection of subtle defects or performance deviations that might be missed by traditional methods. Similarly, Machine Learning algorithms predict when automated test equipment (ATE) is likely to fail, enabling proactive maintenance to minimize downtime. With the rollout of 5G networks and the proliferation of IoT devices, test equipment providers have developed innovative solutions to meet the demands for higher data rates, lower power consumption, and greater reliability and availability.

These advancements in packaging and test equipment have helped ensure that semiconductor devices meet the necessary quality and performance standards. This is critical for the reliability and functionality of modern electronics. As the industry continues to evolve, we can expect further innovations in semiconductor packaging, assembly and test equipment to enhance performance, reduce costs, and improve reliability.

1.1.3.5.2 Vision and expected outcome

The development of EU microelectronics must proceed in parallel with the development of EU equipment required for its packaging, assembly and testing. EU-headquartered packaging, assembly & test equipment industries should be strongly supported in order to ensure sovereignty of EU-manufactured microelectronics. Ideally, any EU microelectronic product should be manufactured and tested using only EU equipment.

[8] https://www.mckinsey.com/industries/semiconductors/our-insights/advanced-chip-packaging-how-manufacturers-can-play-to-win

The future developments in semiconductor packaging and test equipment are expected to focus on several key areas which may reshape the industry. [9]

As devices become smaller and more complex, advanced packaging technologies like system in-package (SiP) and 3D stacking are becoming important. The advanced multichip packaging approach integrates multiple semiconductor components into a single package, which is well-suited for applications such as mobile devices, automotive computing, and generative artificial intelligence (GenAI). It aims to improve performance and time-to-market while reducing manufacturing costs and power consumption. High-Density Fan-Out, 2.5D IC, and 3D IC Packaging Technologies are becoming increasingly crucial for future data-centric applications. To maximize the benefits from ICs fabricated in nodes of 7 nm and below, the equipment will need to enable complex 3D structures with Through Silicon Vertical Interconnect Accesses ("TSVIA"), micro-bumps and thin dies, as well as wafer-to-wafer bonding, to speed up production of 3D ICs.

Packaging equipment must be modified to meet the decreasing feature sizes and increasing precision requirements of advanced packaging. This may lead to the introduction of packaging equipment in the front-end part of semiconductor manufacturing and, hence, increased requirements for contamination control.

Further equipment developments include functional diversification of technologies, where digital electronics meet the analog world, using advanced assembly/packaging of heterogeneous chiplets, chips, sensors and/or smart antenna components. It should be noted that these trends are closely related to the trends formulated for (front-end) wafer-fab equipment, including the creation of silicon vias and backside power distribution networks.

An ongoing focus is on enhancing the functionality of heterogeneous systems by combining "traditional" semiconductors with photonic components or chiplets and on addressing high-speed component transfer by the assembly industry, with ambitious goals of developing transfer capability of up to 1 million components per hour (without physical manipulation) by 2028.

Besides this technological frontier, other trends for assembly equipment will also play a role. For example:

- Factory automation to increase product reliability with multi-faceted device inspections, sorting and advanced tracking and tracing as well as data storage throughout the production lines.
- Product developments for highly specialized applications such as power modules, medical applications, organ on chip devices, communication and agrifood.
- Development and application of 3D printing technology in heterogeneous integration, covering materials, process and equipment.

The future developments for semiconductor test & inspection equipment are anticipated to be influenced by several emerging trends and technological advancements. Building on the existing state of the art, further integration of AI and Machine Learning will play a significant role in transforming test engineering and the connected equipment. They will enable real-time analysis of extensive test data, identify subtle defects, and optimize test patterns to reduce test durations and enhance efficiency. As devices become smaller and more complex, new testing strategies and specialized test fixtures will be developed to access intricate device connections and ensure quality and performance

[9] https://www.bcg.com/publications/2024/advanced-packaging-is-reshaping-the-chip-industry

in advanced packaging technologies. Test equipment designers will also need to explore and integrate innovative approaches to enable improved wafer-level testing & inspection to catch defects early in the manufacturing process, which is crucial for maintaining high standards of quality.

Future advanced-node semiconductor manufacturing will require a much broader palette of materials, covering almost all elements of the periodic table. Appropriate testing tools are not yet available for this and, given the existing strong ecosystem of test-tool makers in the EU, this highlights an opportunity to increase EU competitiveness by developing key technologies to address this challenge.

These advancements by the EU high-tech equipment industry will help ensure that semiconductor devices meet the necessary quality and performance standards, which is critical for the reliability and functionality of modern electronics.

1.1.3.5.3 Key focus areas

Topic 5.1: Packaging & 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.
- A transition from equipment optimised for high-volume manufacturing of large batches of the same package to 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.
- Equipment solutions to handle glass substrates and enable Through Glass Vias and glass plating.

Topic 5.2: Test and inspection equipment:

- In-line and off-line technologies for the Testing, Validation and Verification (TV&V) of heterogeneous chips and SiP with an ever-increasing number of features and ever-decreasing feature sizes to tackle the challenge of failure localisation in these highly complex (packaged) chips.
- Characterisation and inspection equipment for quality control at multiple levels and different scales of semiconductor structures, films and components.
- Test tools to include characterization technology for a wide range of materials used in future semiconductor technology nodes

1.1.3.6 Major Challenge 6: Sustainability of semiconductor manufacturing

The semiconductor industry is living a paradox. On the one hand, continuous advances in chip capabilities are propelling the global effort to reduce carbon emissions through electrification and energy efficiency improvements in devices and all types of equipment. On the other hand, semiconductor manufacturing causes significant emissions itself and is responsible for large CO2 and greenhouse gas (GHG) outputs. As an example, the carbon footprint of ICT was evaluated at about 1200–2200 $MtCO_2$ eq. in 2020, or equivalently 2.1%–3.9% of the world greenhouse gas (GHG) emissions. A significant part of this footprint, i.e., between 360 and 660 $MtCO_2$ eq., is attributed to the semiconductor-manufacturing phase[10].

At the same time, the semiconductor manufacturing industry must respond to the unprecedented demand for semiconductors across the industry for major emerging technologies such as AI/ML, Gen. AI, IoT, EVs and 5G/6G networks. This demand may double in the next four to six years. Therefore, reducing CO2 and GHG emissions in semiconductor manufacturing is of utmost importance for the semiconductor industry.

In addition, or coupled with CO2 and GHG emissions, semiconductor manufacturing is resource-intensive in terms of energy, water, chemicals and raw materials. Moreover, the use of energy, water and other resources by the semiconductor industry continues to increase as wafer processing becomes more complex and as the industry expands production worldwide.

Furthermore, the semiconductor industry uses PFAS-containing materials in numerous critical applications. They are primarily utilized in the photolithography process to facilitate the smooth transfer of patterns onto the semiconductor substrate. PFAS stands for per- and polyfluoroalkyl substances, known as “forever chemicals” (PFAS have lifetimes in the thousands of years), and refers to synthetic chemical compounds that contain multiple fluorine atoms attached to an alkyl chain. The broad definition of PFAS by the Organisation for Economic Co-operation and Development encompasses more than 10,000 unique chemicals. Because of human health and environmental factors associated with the persistence, bioaccumulation and toxicity of several PFAS, legislative and regulatory efforts worldwide are seeking to initiate restrictions that could limit the use of PFAS-containing materials.

1.1.3.6.1 State of the art

For decades, the ECS community has made significant efforts to enhance the energy efficiency of electronic components for computing and sensing thanks to aggressive improvements to circuit design, component integration, and software, as well as power-management schemes and integration of specialized accelerators. However, the flip side is that higher energy efficiency does not necessarily translate to lower CO_2 and GHG emissions from semiconductor manufacturing processes.

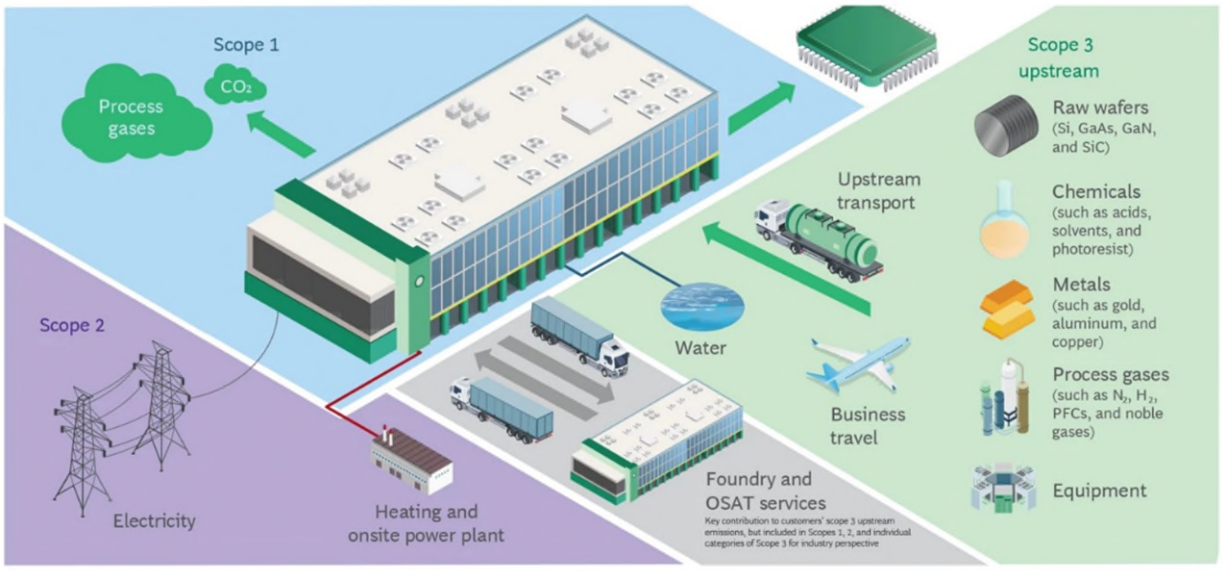
According to the GHG Protocol, there are three types of GHG emissions (Fig. 1.1.3):

- Scope 1 – direct emissions from business operations and manufacturing.
- Scope 2 – indirect emissions including those from power plants to meet business energy requirements

[10] T. Pirson et al. 2023, “The Environmental Footprint of IC Production: Review, Analysis, and Lessons From Historical Trends”, IEEE Trans. on Semicon. Manuf. 36, 1, 56-67

- Scope 3 – emissions including all other indirect emissions in a company's value chain; upstream emissions are those generated by suppliers or their products, while downstream emissions are related to the usage of products containing semiconductors during their lifetime. Scope 3 downstream emissions are nearly independent of the semiconductor-manufacturing phase.

In a typical semiconductor fab, 35% of GHG emissions fall into the Scope 1 category, compared with 45% for Scope 2, and 20% for Scope 3 upstream[11].



Source: BCG analysis.

Note: Si = silicon; GaAs = gallium arsenide; GaN = gallium nitride; SiC = silicon carbide; N_2 = nitrogen; H_2 = hydrogen; PFCs = perfluorinated compounds; OSAT = outsourced semiconductor assembly and test.

Figure 1.1.3 GHG emission sources from semiconductor manufacturing

With about 80% of semiconductor manufacturing emissions falling into either scope 1 or scope 2 categories, semiconductor manufacturing lines control a large portion of their GHG emission profile. 85-90% of scope 1 emissions arise from fluorinated process gases used during wafer etching and cleaning, and chamber cleaning, while 10-15% originate from the use of fluorinated heat-transfer fluids. These gases, which include perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), NF3, SF6 and N2O have high global-warming potential (GWP) as well as a long atmospheric lifetime. Moreover, their emissions rise as node size shrinks. According to the sixth assessment report of the Intergovernmental Panel on Climate Change, GWP100 values (defined as a relative GWP value for the period of 100 years with respect to CO_2) of CF_4, C_4F_8, NF_3 and SF_6 are 6630, 10200, 16100 and 23500, respectively.

To reduce PFC emissions, several strategies, such as alternatives, process optimization, recycling/recovery and abatement, have been attempted.

The use of alternative materials to PFCs is expected to reduce PFC emissions by employing environmentally benign chemistries with low GWPs. However, finding relevant alternative materials will require significant R&D efforts. Process optimization through increasing the efficiency of PFC-consuming processes by adjusting process parameters, such as temperature and chamber pressure,

[11] "Keeping the semiconductor industry on the path to net zero", McKinsey & Company November 2022

can reduce PFC usage and, correspondingly, PFC emissions. Recycling/recovery and abatement of PFCs from exhaust streams can also control PFC emissions.

Scope 2 emissions, which represent the highest proportion of GHG from semiconductor companies, are linked to the energy required to run their extensive production facilities. The sources of these emissions include the following:

- Tool fleets containing hundreds of manufacturing tools, such as lithography equipment, ion implanters, and high-temperature furnaces. Their energy consumption accounts for the largest share (39%) of a typical semiconductor fab[12].
- 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.

As the node size of chips continues to shrink, energy requirements at production facilities are expected to rise significantly. Indeed, the energy consumption for manufacturing a 28 nm and a 3 nm 300 mm wafer has been modelled to be 400 and 1400 kWh, respectively[13]. The facility energy was not included in this model.

Lowering greenhouse gas emissions is one of the semiconductor industry's most complicated challenges due to the energy needed to make chips and the unique requirements of the manufacturing processes. This complexity is further increased as the semiconductor industry must also expand globally to meet the growing demand for chips.

Semiconductor manufacturing is also extremely water-intensive and requires large volumes of ultra-pure water to avoid the contamination of electronic devices. A typical semiconductor manufacturing facility uses 7.5 to 15 million litres of ultra-pure water per day, and it takes about 6,000 litres of city water to create 3,800 litres of ultrapure water. In response to prolonged droughts and increasing demand for semiconductors, the semiconductor industry is focusing on new ways to recycle, reduce, and reuse the water used in their production. New advancements in water treatment have emerged to allow semiconductor manufacturers to recover and reuse wastewater and remove targeted contaminants. They allow manufacturers to reach a water recycling rate, defined as the ratio between the recycled water and the total water use (which is the sum of recycled water use and water intake), ranging from 12 to 70%[14]. However, since the demand for semiconductors will grow strongly in the coming years, the semiconductor industry must improve the water recycling rate, especially in water-stressed countries.

[12] S-C. Hu et al. 2020, "Energy savings approaches for high-tech manufacturing factories", Case Studies in Thermal Engineering 17, 100569

[13] M. Garcia Bardon et al., "DTCO including Sustainability: Power-Performance-Area-Cost-Environmental score (PPACE) Analysis for Logic Technologies," 2020 IEDM, San Francisco, CA, USA, 2020,

[14] Wang Q. et al. 2023, "Water strategies and practices for sustainable development in the semiconductor industry", Water Cycle 4, 12–16

Given its carbon-fluorine chemistry, PFAS-containing materials offer a unique set of surface-tension properties, stability and chemical compatibility that many semiconductor applications require. The following paragraphs highlight key uses and challenges of PFAS in each of the application groupings, which are critical to the semiconductor industry:

- **Photolithography materials containing PFAS are critical components** used within photoacid generators in chemically amplified resists and bottom antireflective coatings, top antireflective coatings, surfactants, barrier layers, photo-imageable polybenzoxazoles and polyimides for dielectric and buffer coat applications, and photoresist applications. The amount of PFAS consumed in each technology node depends on the number of masks used and the complexity of the multi-patterning steps.
- **Wet chemistries** are applied within semiconductor manufacturing for cleaning, stripping, wet etching, chemical mechanical planarization, metal plating, and to facilitate other processes. Most wet chemistry applications do not contain PFAS. However, there are some applications that rely on PFAS materials for specific performance requirements. Examples of these applications include - but are not limited to - post-plasma photoresist strip, high aspect ratio collapse mitigation, selective film inhibition, wetting of low surface energy substrates, and specific parts cleaning.
- **Dry etching and deposition processes:** Perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) are essential gases for directional etching and cleaning of silicon compounds. Additionally, fluorinated organometallic compounds are essential for the deposition of metal-containing films. Some PFCs and HFCs are part of the PFAS category such as CF_4, C_2F_6, C_4F_8 and C_3F_8.
- **Heat Transfer Fluids** (HTFs): Many semiconductor-manufacturing processes entail physical and chemical processes that require precisely controlled temperatures, and thus are highly reliant on HTFs. In both cooling and heating applications, fluorinated HTFs (F-HTFs) help ensure the ability to provide the precise temperature control required in specific manufacturing operations within the semiconductor fabrication process.
- **Semiconductor manufacturing and related equipment** and infrastructure articles. Semiconductor manufacturing facilities and the manufacturing equipment and infrastructure within them contain a multitude of articles. An article is any object made from one or more substances and mixtures which during production is given a special shape, surface or design that determines its function to a greater degree than its chemical composition, whether on its own or in an assembly with other articles, substances and mixtures. PFAS-containing articles include those made of a fluoropolymer, articles coated or painted with a fluoropolymer, or other PFAS-containing materials (such as oligomers) and those made of non-PFAS polymers containing PFAS processing/machining aids or additives. Many semiconductor manufacturing applications require the use of PFAS-containing articles for safety, contamination control, resilience and other factors.
- **Pump fluids and lubricants**. Semiconductor manufacturing relies on the extensive use of robotics, automation and vacuum systems to achieve nanometre-scale precision. The use of lubricants, many of which need to be fluorinated, is essential to the precision and reliability of these systems.

Due to the extremely wide range of individual PFAS and their respective use cases in the semiconductor manufacturing process, timeframes for finding and deploying alternatives can be very long, even in best-case scenarios. Depending on the use case, an alternative that has the same functionality must first be invented and tools and/or process facilities must be adapted before the

alternative can be qualified and deployed. As an example, some alternatives are currently being developed to substitute PFAS in HTFs, in working fluids for vacuum pumps and in some equipment components. However, no alternatives to PFAS are available in photoresists, developers, antireflective coatings, rinsing solutions, wet and dry etching[15].

The short-term approach to reducing or even preventing emissions of PFAS from the semiconductor industry is to remove PFAS-containing materials from fab water, solvent wastes, gases and chemical vapours.

1.1.3.6.2 Vision and expected outcome

Since GHG emissions from a typical semiconductor fab arise from its power/energy consumption, identifying strategies for reducing power consumption in a semiconductor manufacturing line is essential. Process optimization is one approach to reduce energy consumption. It requires close collaboration between chip manufacturers, R&D labs and tool suppliers by simultaneously optimizing yield and energy consumption during the least energy-efficient process steps. Similarly, such collaborations should also help equipment suppliers to manufacture more energy-efficient equipment and materials.

As the energy and water consumption of a typical semiconductor manufacturing line depend on the number of process steps, and evolve proportionally[16], reducing the energy consumption through process optimization should also lower the water consumption. However, the most convenient approach to lower the water intake of the semiconductor industry is to enhance the current water recycling rate in order to reach a rate higher than 70% in the coming years.

The semiconductor industry faces significant challenges in securing a stable supply of critical raw materials due to factors such as geopolitical tensions, trade restrictions, and environmental regulations. Consequently, it is essential to reduce the use of these materials in semiconductor fabs and increase the use of recycled metals, aiming for 25% metal recycling by 2030.

Finding alternative gases for replacing PFCs will be long and costly, because only a few green solutions are currently viable alternatives to currently used gases. It seems to be easier to find alternatives for fluorinated gases for cleaning processes (pre-clean, seasoning, chamber cleans) than for dry etching. Looking for such viable alternatives will require close collaboration across the semiconductor supply chain from R&D labs and chemical suppliers to the semiconductor manufacturers.

Hence, over the short to mid-term, the current solution to decrease GHG emissions from fluorinated gas usage is the implementation of abatement systems to contain and decompose the problematic compounds. The current abatement efficiency in a semiconductor manufacturing line typically ranges from 20 to 65%[17]. This abatement rate should be enhanced in the short term. This will remain the case until alternative gases with fewer emissions are available, or until gas recycling is widely adopted.

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[15] Lay D. et al., “A guide to PFAS in electronics”, ChemSec H2020 Project No. SA22171340

[16] Wang Q. et al. 2023, “Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation”, Water Cycle 4, 47–54

[17] S. Jones “IEDM 2023 – Modeling 300mm Wafer Fab Carbon Emissions”, https://semiwiki.com/semiconductor-services/techinsights/340325-iedm-2023-modeling-300mm-wafer-fab-carbon-emissions

Gas recycling is another approach for reducing GHG emissions from the semiconductor industry. It consists of capturing unutilized process gases and by-products through various means, such as membrane separation, cryogenic recovery, adsorption, and desorption. The captured gases can then be refined into pure process gases that can be used again, potentially reducing process-gas emissions. For this lever to become economically viable, researchers will need to address major challenges related to the separation of process-gas outflows and purification.

To achieve a circular economy in semiconductor manufacturing in the long term, it is essential to rethink existing business models and processes. For example, additive techniques can be developed to optimize resource usage in fabs. Moving towards additive manufacturing means shifting from subtractive to additive processes where appropriate and reducing resource use, for example in hybrid electronics combining a ULP chip with a disposable electronics part made using additive manufacturing.

Concerning PFAS, the semiconductor industry recognizes the need for and is undertaking additional R&D to:

- Characterize the human health and environmental risks associated with PFAS-containing materials used in the industry.
- Develop analytical methods to characterize PFAS-containing materials.
- Evaluate PFAS releases to air and/or water.
- Identify, test and implement substitutes to either eliminate PFAS-containing materials, or substitute PFAS-containing materials with those having lower human health or environmental risks.
- Evaluate and test abatement technologies to capture or destroy PFAS-containing materials before their release to the environment.

1.1.3.6.3 Key focus areas

Topic 6.1: Semiconductor manufacturing line:

- Enhanced water recycling rate including the full removal of PFAS from wastewater.
- Enhanced efficiency of gas abatement systems for reducing GHG and PFAS emissions in the atmosphere.
- Optimized process steps for reducing the energy consumption of the least energy-efficient steps, while maintaining high manufacturing yield.

Topic 6.2: Equipment and material suppliers:

- Improve energy efficiency of the equipment.
- Implement re-use of parts/modules for equipment maintenance and servicing.
- Reduce the use of PFAS-based materials in equipment production.
- Find viable alternatives to PFAS for etching and layer deposition.
- Find alternatives to PFAS for photolithography resists and wet chemistries.

Topic 6.3: Sustainable materials

- Materials recycling
- Lead-free ferroelectrics and piezoelectrics
- Replacement of critical raw materials in ferroelectrics and piezoelectrics

- Optimise usage of Critical Raw Materials
- Development of new chemicals to replace hazardous materials (PFAS)

1.1.4 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 the IEEE's IRDS[5], in which European academia, RTOs and industry are participating. For system integration, the International Electronics Manufacturing Initiative (iNEMI)[18] 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 continuously evolving. The timelines below are high-level derivatives from these global evolutions, and follow the structure of the six 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 production lines will involve 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 Productivity Aware Design or the improvement of robustness of the manufacturing processes, will get due attention to enhance competitiveness.

[18] https://roadmap.inemi.org/ir/

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
Major challenge 1: Advanced computing, in-memory, neuromorphic, photonic and quantum computing concepts	**Topic 1.1:** Extensions of the scaled Si technology roadmaps High-performance, ultra-low-power 3D integration	Volume scaling of nanosheet/GAA logic beyond the initial 2 nm generation, including backside power delivery. European sub-2 nm and 10 nm FD-SOI pilot platforms with industry-accessible process/design validation.	Further angstrom-class logic scaling; CFET device and process maturation with design enablement, subject to qualification. Advanced FD-SOI and sequential/monolithic 3D integration in pilot platforms.	Industrial adoption of CFET-derived and vertically integrated device architectures where viable. Beyond-Si channel options subject to proven yield, reliability and cost.
	Topic 1.2: Exploration and implementation of unconventional devices based on materials beyond Si	High-Ge SiGe and alternative interconnect materials in advanced-node process development. Early CMOS-compatible 2D-material device and integration demonstrators.	Pilot integration and validation of Ge/III-V channels and selected 2D materials where they offer a measurable advantage.	Potential manufacturable 2D-channel and other beyond-Si device platforms, conditional on process control and reliability.
	Topic 1.3: Novel device, circuit and systems concepts, such as for near/in-memory, neuromorphic, optical and quantum computing	HBM and hybrid-bonded logic/memory integration at industrial scale. Near-memory accelerators and application-specific in-memory-computing demonstrators.	More mature in-memory/neuromorphic pilots using emerging memories; greater 3D logic–memory integration. Photonic computing remains application-specific and subject to validation.	Selective commercial neuromorphic/photonic processing where energy and system benefits are demonstrated. Scalable quantum computing remains conditional, not a dated commercial milestone.
	Topic 1.4: Long-term challenges such as steep-slope switches, spin-based transistors and alternatives	Research test structures for steep-slope, 2D/CNT and spin-based switches; no defensible broad TRL 8–9 milestone.	Device-level benchmarking and manufacturing/reliability validation of promising alternatives (e.g. TFET, NCFET, 2D FET).	Niche deployment of alternative switch concepts only if performance, integration, yield and lifetime outperform CMOS.
	Topic 1.5: New eNVM technologies	Wider qualified use of production eMRAM/eRRAM and phase-change memories at selected nodes. Pilot arrays for compute-in-memory and multilevel storage.	Qualified next-generation MRAM, FeFET/FeRAM and ReRAM variants in selected edge and memory-centric applications. System-level in-memory compute pilots.	Potential scalable VCMA-MRAM, ECRAM and ferroelectric-tunnel-junction platforms, subject to endurance and yield.
Major challenge 2: Novel sensor, actuation and other devices that enable advanced functionality	**Topic 2.1:** Application-specific logic integration	Expanded deployment of established 18/22 nm FD-SOI with embedded memory/RF; 10 nm FD-SOI pilot validation and design enablement.	10/7 nm-class FD-SOI pilot maturity and application-driven integration of logic, memory, RF and power functions.	Further FD-SOI scaling and heterogeneous functionality only where technically and commercially justified.
	Topic 2.2: Advanced sensor and actuator technologies	Smaller, lower-power imaging, inertial, chemical and biomedical sensors; heterogeneous sensor/CMOS integration. Improved field robustness and low-power autonomous sensing.	Qualified multimodal sensor systems integrating local intelligence, microfluidics and energy autonomy. Greater photonic and quantum-sensor integration for selected uses.	Highly selective nano/biosensing and complex monolithic sensor–compute integration if reliability and manufacturability are proven.
	Topic 2.3: Advanced power electronics technologies	Industrial scale-up of existing 200 mm SiC and first 300 mm GaN power-wafer products. Improved high-voltage, high-efficiency power devices and integration.	Broader qualified 300 mm GaN power production; vertical GaN and larger-diameter SiC where cost and yield permit. Higher-temperature smart power integration.	Potential niche power devices based on ultra-wide-bandgap materials (e.g. Ga_2O_3, AlN, diamond), conditional on reliability.
	Topic 2.4: Quantum sensing technologies	Broader qualification and deployment of chip-scale atomic and solid-state quantum sensors; European atomic/photonic pilot integration.	Smaller, lower-cost and better integrated atomic, spin and photonic sensor modules with qualified performance.	Advanced entanglement-enhanced and multi-parameter quantum sensing, subject to demonstrable system benefits.
	Topic 2.5: Advanced RF and photonics communication technologies	5G-Advanced RF/mm-wave devices and 6G component demonstrators aligned with IMT-2030 standards. Broader SiGe/BiCMOS, RF-SOI, GaN and silicon-photonics integration.	6G RF technologies in expanding deployments; more efficient RF/photonic co-integration and advanced mm-wave front ends.	Specialized sub-THz/THz and heterogeneous photonic–electronic RF platforms as viable applications emerge.

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
Major challenge 3: Advanced integration and solutions	**Topic 3.1:** Advanced interconnect technologies	Industrial chiplet integration with advanced substrates, TSVs, hybrid bonding and thermal management. Fine-pitch die-to-wafer bonding in pilot lines; optical-interconnect packaging.	Higher-yield, finer-pitch chiplet and 3D interconnect manufacturing with co-designed power, thermal and optical interfaces.	Scalable active photonic interposers and deeper heterogeneous integration where cost and reliability are validated.
	Topic 3.2: Specific power, sensor and RF application technologies	Qualified packaging for high-voltage SiC/GaN modules and mm-wave RF. Advanced optical coupling and thermal management for sensing and photonics.	More integrated THz, photonic and wide-bandgap modules; robust packaging for high power density and harsh conditions.	Highly integrated cryogenic quantum-interface packages and novel thermal materials where application maturity warrants.
	Topic 3.3: 3D integration technologies	Wider industrial adoption of high-density 3D chip stacking and hybrid bonding; chip–package–board co-design and STCO.	Multi-tier logic–memory 3D systems with higher yield, testability and system-level technology co-optimisation.	Transistor-level sequential/monolithic 3D integration only after thermal-budget, yield and interconnect challenges are resolved.
Major challenge 4: Advanced wafer fab equipment solutions	**Topic 4.1:** Wafer fabrication equipment	Equipment for post-N2 nanosheet logic and angstrom-class processing, including High-NA EUV qualification. Pilot tools/metrology for finer-pitch 3D bonding and backside processing.	Tools for angstrom-class device manufacture, emerging CFET processes and higher-density 3D integration. Advanced in-line 3D metrology and process control.	Equipment for potential post-CMOS and vertically integrated devices when viable process flows are validated.
	Topic 4.2: Wafer fabrication equipment for differentiated and/or mature technologies	Equipment supporting 200 mm SiC manufacturing and 300 mm GaN power pilots. Improved substrate handling, metrology and differentiated-device processing.	Qualified production equipment for larger-volume wide-bandgap, novel non-volatile memory and heterogeneous platforms.	Scalable equipment for emerging materials and device categories subject to robust industrial demand.
	Topic 4.3: Automated manufacturing technologies	Fab-wide data interoperability, AI-supported defect detection and predictive maintenance. Standardised interfaces for robotic maintenance and digital-twin validation.	Human-supervised autonomous fab operations with closed-loop optimisation and auditable agent-based workflows.	Progressively self-optimising and interoperable fabs; autonomy subject to validated safety, yield and operational reliability.
Major challenge 5: Advanced packaging, assembly and test equipment solutions	**Topic 5.1:** Packaging and assembly equipment	Higher-throughput assembly for chip-to-wafer hybrid bonding, chiplets, HBM and complex 2.5D/3D packages. Growing industrial use of co-packaged-optics assembly and photonic integration.	Higher-throughput heterogeneous assembly, fine-pitch bonding and optical packaging with validated yields.	Scalable photonic interposer, waveguide and advanced multi-material assembly where economically justified.
	Topic 5.2: Test and inspection equipment	Known-good-die, wafer-level and package-level inspection/test for multi-die 2.5D/3D systems. Testing of fine-pitch hybrid bonding and optical interfaces.	Integrated test, inspection and failure localisation for multi-tier 3D and co-packaged optical products.	Non-destructive, high-resolution inspection and embedded self-test for highly complex photonic/electronic stacks.
Major challenge 6: Sustainability of semiconductor manufacturing	**Topic 6.1:** Semiconductor manufacturing line	Measured reductions in fab energy, water and process-gas intensity; expanded ultrapure-water reuse. Qualified abatement and PFAS removal from relevant waste streams.	Industrial deployment of higher-efficiency gas abatement, recovery and resource-circulation systems with verified results.	Broader circular-fab material and heat flows, subject to proven process safety and product quality.
	Topic 6.2: Equipment and material suppliers	Lower-energy tools, repair/refurbishment and real-time monitoring of fluorinated emissions and PFAS. Pilot alternatives for selected hazardous chemistries.	Qualified lower-impact consumables and equipment materials; better real-time monitoring, reuse and abatement.	Substitution of technically difficult hazardous materials only where qualified alternatives retain performance and safety.
	Topic 6.3: Sustainable materials	Increased recovery of semiconductor-relevant strategic materials; lower-hazard materials qualified in feasible use cases.	Industrial use of recycled strategic materials and validated substitutes for selected PFAS and critical-material applications.	Further replacement of hard-to-substitute substances and closed-loop recovery where technically and economically feasible.

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) depend on physical and functional integration (PFI): the ability to combine several functions into new components, modules and systems (CMS). PFI turns separate technologies into compact, reliable, manufacturable and application-ready smart systems. It is therefore a strategic capability for maintaining and strengthening European competitiveness in smart systems. While many PFI solutions are application-specific, the materials, technologies and manufacturing processes behind them should be standardized, interoperable and reconfigurable wherever possible.

As smart systems evolve, heterogeneous integration becomes essential at all levels, from semiconductor systems-on-chip (SoCs) to systems-in-package (SiPs), larger modules and complete systems. Chapter 1.1 focuses on semiconductor technologies, material families and on-chip systems. This chapter addresses integration beyond that scope, including complementary functional and structural materials, additive manufacturing, flexible and structural electronics, photonics, and advanced assembly and packaging methods.

Heterogeneous integration is used here in its broadest sense. A component may be a chiplet, die, MEMS device, passive or active part, assembled package or functional module that is integrated into a higher-order component, module or system. Advanced packaging provides the technologies, processes and competences to connect such diverse elements physically, electrically and functionally in a cost-efficient and environmentally sound way, so that the resulting system can interact safely and reliably with its application environment.

Smart CMS technologies link foundational technologies such as semiconductors and interconnection with the application domains described in the application chapters. By integrating intelligence, sensing, communication, actuation, energy management and control into compact devices, and by supporting event-driven, neuromorphic and AI-enabled processing paradigms where appropriate, they enable adoption across mobility, health, industry, communication, security and environmental applications. Embedded software, AI and System-of-Systems aspects are considered where they directly affect integration, packaging, test, reliability, autonomy or lifecycle performance.

Design, production, assembly and test methods for CMS must therefore be developed with quality, reliability, repeatability, scalability and sustainability in mind from the start. This includes circular economy principles, a reduced CO2 footprint, life-cycle considerations and efficient use of resources.

Mastering integration across CMS levels is a core European strength. Strengthening this capability will help Europe translate technological breadth into reliable, sustainable products, resilient value chains and competitive markets, including high-volume applications where sovereignty, manufacturability and time-to-market are decisive.

In addition, Europe must address volume-driven technological sovereignty by strengthening end-to-end capabilities from concept and design to manufacturing, production capacity and industrialization. High-volume and dual-use markets, including intelligent mobility, drones and counter-drone systems, require short time-to-market, resilient and interoperable supply chains and circular-economy approaches such as closed-loop recycling and sustainable sourcing across material families.

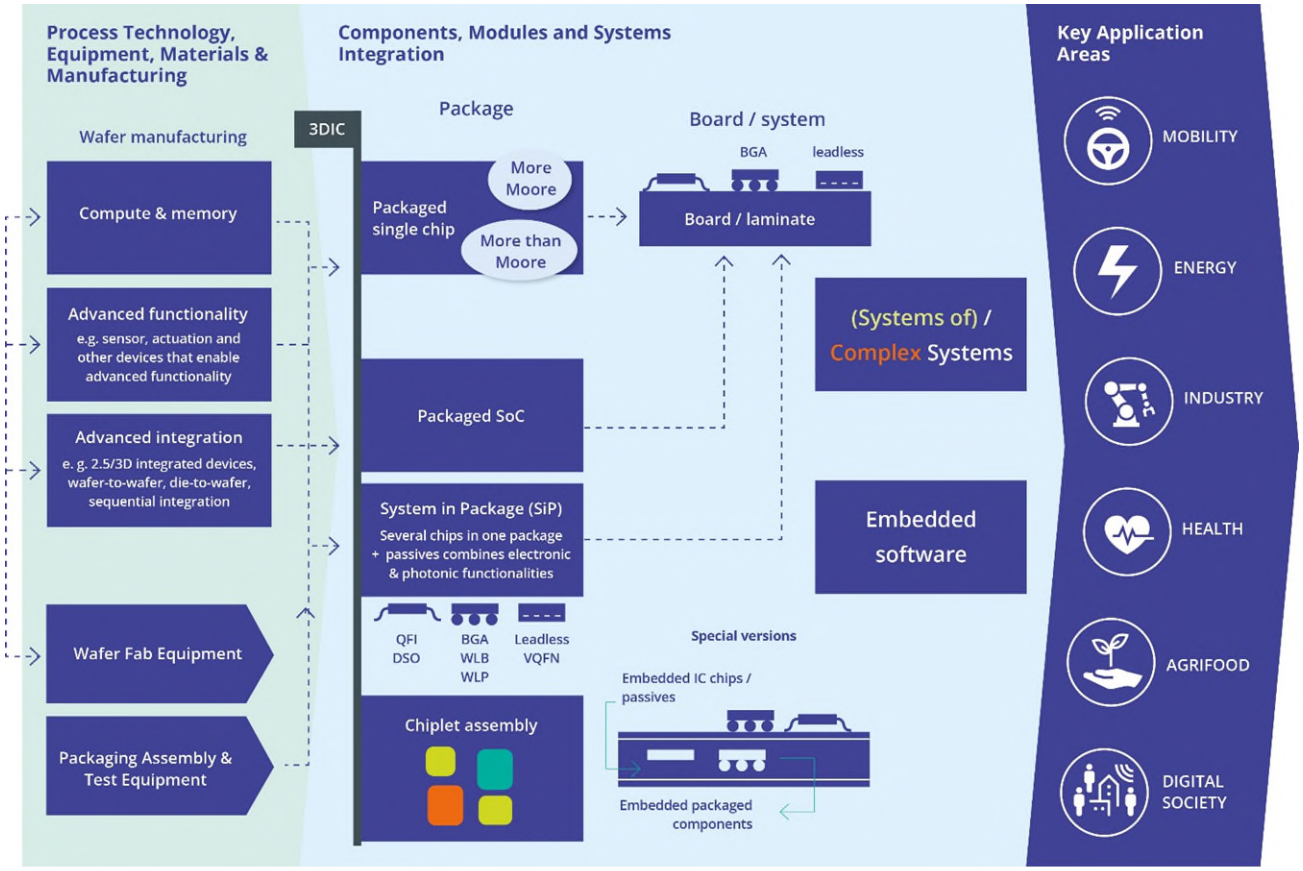

Figure 1.2.1 The Components, Modules and Systems Integration Chapter focuses on physical and functional integration of devices and components into subsystems and systems, using sustainable and efficient materials and integration processes.

1.2.2 Application breakthroughs

Future smart CMS will combine more functions, materials and integration levels in smaller and more demanding form factors. Their application impact will come less from individual components than from the ability to integrate sensing, processing, communication, actuation, energy management and protection into reliable systems.

Digitization across edge-IoT, mobility, telecommunications, healthcare, industry and critical infrastructure increases the need for cyber-resilient long-term storage, secure firmware and boot media, extended operational lifetime and adaptability to changing operating conditions.

These application breakthroughs share a common need: compact, reliable, low-power and often autonomous systems that integrate multiple functions under demanding physical, regulatory and lifecycle constraints.

- Communication and data infrastructure, including 5G, 6G, non-terrestrial networks, time-sensitive networks, navigation, localization, optical integration and fiber-network components.
- Mobility, transport, logistics, buildings and microgrids, where autonomous and zero-emission systems require fast response, efficient power conversion, robust sensing and reduced human error.

- Healthcare, life sciences and human-centric systems, moving from diagnostics toward prevention, therapy, rehabilitation, personalized medicine and smart systems in, on or around the body.
- Industry, infrastructure and remote monitoring, including Industry 4.0, structural health monitoring, harsh environments and unattended systems with edge decision-making and power autonomy.
- Environment, agriculture and resource efficiency, including sensing for smart agriculture, livestock, aquaculture, manufacturing, workplaces, homes and urban areas.
- Imaging, audio and immersive systems for security, healthcare, digital industry, precision agriculture, food production, VR/MR/AR and digital society.
- Space, security and dual-use applications requiring miniaturized, radiation-hardened, ultra-reliable and secure electronic, photonic and packaging solutions.
- Circularity and repair, including repair indexes, repair processes, self-monitoring, fault tolerance and condition evaluation as the basis for new service and business models.

1.2.3 Major Challenges

The following Major Challenges are identified:

- **Major Challenge 1: Functionality.** Enable new sensing, actuation, processing, communication and energy functions through novel materials, device concepts and miniaturized CMS architectures.
- **Major Challenge 2: Advanced & Heterogeneous Integration.** Combine diverse components, materials and technologies into reliable, manufacturable, resilient and cost-effective modules and systems through packaging, co-design, test and scalable manufacturing platforms.
- **Major Challenge 3: Sustainability.** Design CMS and their integration processes for reduced environmental impact across the full lifecycle, including resource efficiency, repairability, reuse, recycling and circular business models.

1.2.3.1 Major Challenge 1: Functionality

1.2.3.1.1 State of the art

Physical and functional integration (PFI) develops the elements and methods needed to integrate more functions into CMS in the most effective form factor. Smart CMS combine electronic, mechanical, magnetic, photonic, fluidic, acoustic, radio-frequency, biological, chemical and quantum principles. They integrate sensors, actuators, energy devices, processing units, transceivers, antennae and interconnections through approaches such as mainstream silicon, MEMS/NEMS, MOEMS, integrated photonics and large-area electronics.

PFI goes beyond the compact monolithic SoC approaches supported by the semiconductor technologies covered in the **Process Technology, Equipment, Materials and Manufacturing** Chapter. It addresses System-in-Package (SiP) implementations integrating technologically diverse components using various platforms and processes, including integrated circuit carriers, PCBs, additive manufacturing on flexible or hybrid substrates, and co-packaging of optics and electronics.

PFI also requires co-design with embedded software, embedded AI accelerators and modular architectures, because functionality increasingly depends on the interaction of hardware, data and control. This chapter addresses these aspects only where they shape physical integration, hardware

architecture, test, reliability, energy autonomy or lifecycle performance; broader software topics are covered in the Embedded Software chapter.

1.2.3.1.2 Vision and expected outcome

Future smart CMS must be resilient and operate reliably outside controlled laboratory conditions: in harsh industrial environments, in vehicles, infrastructure, space, consumer devices and in or around the human body. Their value will come from combining functions that sense, decide, communicate, actuate and manage energy within strict limits for size, cost, power, reliability and lifetime.

Energy, performance and form factor define the main design envelope. Portable and distributed IoT devices require ultra-low-power operation, energy harvesting or long service intervals; power electronics must manage high current density, high voltage and thermal stress; and consumer, medical and industrial systems demand dense interfaces from chiplets and packages to modules and connectors. Heterogeneous integration, advanced packaging and careful thermal design are therefore not add-ons but core system architecture choices.

MEMS/NEMS/MOEMS technologies remain central functional building blocks for miniaturized sensing and actuation. They enable compact inertial sensors, pressure sensors, microphones, particle sensors, micro-mirrors, print heads, tunable lenses, ultrasound transducers and piezoelectric RF devices. New materials such as ScAlN, spintronic sensor concepts and CMOS-compatible post-processing extend performance while preserving manufacturability. This is particularly important for medical diagnostics, consumer health and point-of-care systems, where smaller, smarter sensors can reduce complexity and shorten time to results.

Silicon-based mmWave and terahertz components add further modalities for high-resolution imaging, spectroscopy, radar sensing and ultra-high-capacity communication. Their strategic relevance lies in scalable, miniaturized transceivers and sensor modules that can be co-integrated with electronic, photonic and AI-enabled subsystems for healthcare, industrial inspection, security, 6G communication and autonomous systems.

Integrated photonics enables energy-efficient sensing, transmission and computing functions with high throughput and low latency. At cloud level, it supports optical interconnects and circuit switching for data centres; at edge level, it enables compact photonic sensors, optical interconnects, co-packaged optics for HPC and AI systems, and lightweight processing close to the data source. Its contribution is strongest where electronics alone can no longer meet bandwidth, latency or energy-efficiency requirements.

The main integration challenges for photonics are co-design, thermal management, hybrid integration and packaging. High-bandwidth electro-photonic systems, high-pixel-count sensors, displays, 3D imaging and smart glasses require standard solutions for integration, testing, qualification and regulatory use. Future packages will therefore have to combine optical, electrical, thermal and mechanical requirements in one design space.

Consumer electronics and portable devices are strong drivers for compact, high-volume integration, but much of the related manufacturing capacity is located outside Europe. Europe must therefore strengthen its own capabilities in advanced packaging, flexible electronics and heterogeneous integration. Flexible, stretchable, structural and 3D electronics enable thinner, lighter and more adaptable systems for displays, wearables, smart surfaces, HMI, antennas, lighting and embedded sensors or actuators.

IoT sensor nodes illustrate the system-level challenge. They combine sensing, actuation, processing, wireless communication, energy storage and harvesting in small, often unattended devices. To scale beyond niche deployments, they need low-power components, reliable energy autonomy, thermal management, energy-aware network architectures, reconfigurability and fault-tolerant operation for long-term monitoring applications such as civil infrastructure, industry, logistics and environment.

Electronic Control Units (ECUs) are a practical example of PFI at system level. They combine dense electronics, sensing, processing, cybersecurity, communication and health management, and therefore benefit from miniaturization, generative design, AI-supported diagnostics, scalable architectures and robust heterogeneous integration.

Future CMS will also need efficient local computation. Low-power processors, neuromorphic and in-memory architectures, distributed AI, sensor-level processing and data fusion can reduce data traffic and support local decisions. These functions require equally reliable low-loss interconnection, packaging and hardware-software co-design. For AI-driven and data-intensive systems, compute, memory and interconnect must therefore be treated as one coupled design problem, because data movement, bandwidth and latency increasingly limit system efficiency.

This is particularly relevant for AI workloads and large models, where GPU utilization, data movement, memory access and interconnect bandwidth can become the dominant system bottlenecks. Future CMS architectures must therefore address compute, memory and interconnect together, including optical and electrical interconnects within and between chips, packages, modules and systems.

New functionality also depends on materials beyond conventional semiconductor technology, including ceramics, polymers, glass, inks, functional materials, rare and precious metals, hybrid substrates and novel CMOS-compatible post-processing layers. The strategic challenge is not only to introduce new materials, but to ensure process compatibility, environmental compatibility, reliability and scalable manufacturing across packages, PCBs, additive processes and SiP technologies.

Spintronics can contribute ultra-low-power sensing, memory, logic and neuromorphic functions by exploiting electron spin rather than charge alone. Its integration relevance lies in low-power magnetic sensing, edge AI, memory-compute concepts and potential links to quantum and neuromorphic systems.

Quantum technology adds another More-than-Moore modality for sensing, computing and communication. Its industrial use depends less on isolated quantum devices than on enabling technologies such as precision control, low-noise readout, cryogenic or compact cooling, advanced packaging, photonic integration and scalable semiconductor-compatible manufacturing.

The following key focus areas cover the multimodality of ECS beyond semiconductor technology. They combine physical integration platforms with the functions that integrated systems must deliver: sensing, actuation, communication, energy management, local processing, reliability and scalable manufacturability.

1.2.3.1.3 Key focus areas

- Sensing, imaging and actuation:
  - Integrated MEMS/NEMS, MOEMS, micro-optics and CMOS-based sensors and actuators for compact, multifunctional CMS.
  - Biomedical, environmental and industrial sensing for vital signs, biomarkers, gases, volatiles, allergens, residues, particles, hazardous substances, radiation, materials research and semiconductor manufacturing.
  - Advanced imaging and light-based sensing, including SWIR, VIS-NIR CMOS image sensors, lidar, radar, sonar, X-ray, magnetic resonance, hyperspectral imaging, OLED-under-display sensing, smart displays and dedicated UV-to-IR light sources.
  - Silicon-integrated mmWave and THz sensors for scalable, low-cost, lightweight and miniaturized imaging, spectroscopy and radar modules in industrial, biomedical, security, automotive and space applications.
  - Quantum and spintronic sensors, including single-photon and TMR-based devices, where cryogenic or CMOS/edge-AI integration enables high sensitivity and low-power operation.
  - Novel materials and hermetic miniaturized packages for reliable sensing and actuation, including 2D materials, CNTs, nanowires, metamaterials, metallic glass, cellulose nanofibers and other CMOS-compatible functional materials.
  - Sensor fusion, virtual sensors, self-powered sensors (e.g., piezoelectric or microfluidic devices) and event-based ultra-low-power sensing for condition monitoring, prognostics, health management and anomaly detection.
  - Deployable, low-cost and low-power chemical and environmental sensing modules, including printed, optical, electrochemical and hybrid approaches with long-term stability, calibration, selectivity, drift compensation and edge-AI support.
  - Scalable sensing platforms for indoor air quality, environmental monitoring, agri-food, health, water management and energy-system monitoring, with attention to environmental interferences and long-term calibration strategies.

- MEMS technology:
  - CMOS- and GaN-compatible piezoelectric thin films, including ScAlN, for MEMS sensors, actuators and RF functions.
  - Acoustic piezo-MEMS, pMUTs, acoustic RF filters above 6 GHz and audio MEMS with integrated amplification and active noise cancellation.
  - MEMS for medical devices, point-of-care diagnostics, consumer health and continuous monitoring in everyday devices.
  - MEMS pumps and force-generating MEMS for precise liquid and gas transport, active cooling of highly integrated circuits, in-ear audio systems, lab-on-chip diagnostics, environmental analytics and medical dosing applications.
  - Navigation-grade inertial sensors, high-acceleration sensors and tactile MEMS for robotics, autonomous systems and harsh-environment applications.

- Integrated photonics:
  - Active photonic materials and devices, including lithium niobate, indium phosphide, III-V materials and silicon photonics for higher bandwidth, lower latency and lower energy consumption.

  - Waveguides, meta-lenses, tunable lenses, filters, holograms and beam-shaping components from UV to mid-IR.
  - High-speed modulators, optical transceivers, optical circuit switching, programmable photonic meshes and neuromorphic or quantum photonic systems.
  - Microbolometers, integrated optics, displays, optical engines and sensors for VR/MR/AR, mobility, safety, agriculture and digital society.
  - Quantum PICs with integrated sources, manipulation and detection, including compact single-photon components and broadband or programmable light sources.

- Flexible, stretchable and structural electronics:
  - Wearable, conformal and structural systems that integrate sensing devices, power sources, displays, antennas, actuators and touch surfaces on flexible or stretchable substrates.
  - Functional materials, inks, transparent conductors, barriers, dielectrics, organic and inorganic semiconductors, perovskites and sustainable substrates for flexible electronics and additive manufacturing.
  - Hybrid integration of bare chips or discrete components on flexible and stretchable wiring substrates, including 3D and structural electronics based on LDS, moulding and novel substrates such as TPU and PDMS.
  - Patch-type, surface-integrated and conformable electronic systems that embed sensing, actuation, heating, connectivity, energy harvesting and local processing directly into polymer, composite, textile or elastomeric components.
  - Reliability, qualification and design-for-manufacturing of structural and conformable electronics under mechanical deformation, thermal cycling, humidity, UV exposure, cleaning or washing, vibration, ingress, electromagnetic interference and long-term field operation.
  - Interface engineering, adhesion between functional layers and structural substrates, compatibility with industrial polymer processing, repairability, recyclability and end-of-life separation for deployable and conformable systems.

- Communications:
  - Module-level high-speed wireless and photonic communication, including new frequency bands, beyond-1 Tb/s photonic modules, 5G, 6G and non-terrestrial network front ends.
  - Low-latency, low-power in-package, module-level and system-level communication for edge and IoT devices.
  - Energy- and application-aware communication architectures that adapt between edge, gateway and cloud, supported by secure over-the-air updates to extend device lifetime.
  - Reliable operation in harsh environments through EMI mitigation, robust components and secure communication concepts, including spintronic and magnonic approaches where appropriate.

- Energy and thermal management:
  - Low-power and low-loss modules for sensing, actuation, processing and communication.

  - Multi-source power architectures, energy harvesting, storage and energy-autonomous sensor modules with context-aware digital control based on realistically sized devices using real-life ambient energy levels.
  - Power management components for harsh environments, including high temperatures, vibration, biocompatibility, ingress protection and EMI in industrial, automotive, medical and space environments.
  - Thermal management for photonics, RF, industrial and quantum systems, including active cooling, integrated cooling and compact cryogenic solutions.
  - Non-toxic and lightweight materials for energy sources, harvesters, electrodes, electrolytes and storage devices.

- Information processing and control:
  - Edge AI, sensor-level processing, data analysis and machine learning at sensor, module and system level.
  - Security, privacy, data reliability and hardware-software co-design for low-level communication, visualization and security functions.
  - Self-diagnosis, self-monitoring, self-learning and self-repair features at component, module and system level.
  - Low-power computing, in-memory computing, neuromorphic and spintronic concepts for data analysis close to the source.
  - Electronic Control Units as practical integration examples combining sensing, processing, communication, cybersecurity, prognostics, health management and scalable heterogeneous packaging.

1.2.3.2 Major Challenge 2: Advanced & Heterogeneous Integration

1.2.3.2.1 State of the art

The global electronics industry is shifting toward smaller, more efficient and highly reliable systems that integrate multiple functions in reduced footprints. Advanced packaging, heterogeneous integration and system-in-package (SiP) technologies now shape not only consumer electronics, but also mission-critical systems for harsh, long-lifecycle and safety-relevant environments. Heterogeneous integration must increasingly be considered as a continuous system stack spanning chip, package, advanced IC substrate, high-density PCB and module levels.

The international state of the art is defined by four connected trends:

- High-density substrates and interconnects based on organic, silicon and glass platforms.
- Wafer-level packaging, 2.5D/3D integration and chiplet architectures for scalable heterogeneous systems.
- High-speed electrical and optical interconnects for AI, HPC, RF and communication applications.
- Thermal, mechanical and reliability co-design supported by simulation, digital twins, new heat-spreading materials and embedded cooling.

Heterogeneous integration combines logic, memory, RF, photonics, MEMS, power devices, quantum elements and biological or chemical functions into one system. This expands the design space but also couples thermal, electrical, mechanical, optical and electromagnetic effects. Multi-physics simulation, digital twins, interoperable design tools and shared material data are therefore becoming essential design infrastructure.

For chiplet-based systems, organic IC substrates, glass-core substrates, redistribution layers, silicon bridges and organic interposers are not merely implementation options; they determine die-to-die connectivity, bandwidth, latency, signal integrity, power delivery and manufacturability. Power delivery networks within packages, including embedded voltage regulators and closely integrated power devices below or around power-hungry processors and accelerators within innovative and adaptive power architectures, are therefore becoming key differentiators for future AI and HPC systems.

Chiplet integration can be realized through several packaging concepts, including silicon interposers, polymer-based redistribution-layer substrates, organic interposers or direct chiplet integration on organic substrates. These options directly influence die-to-die connectivity, achievable line/space and via dimensions, manufacturability, yield and system reliability; for selected applications, organic interposers and fine-structured organic substrates can replace silicon-based interposer or bridge concepts at lower cost and with improved manufacturability.

Glass-core IC substrates are another emerging development direction. Compared with conventional organic substrates with glass-fiber reinforcement, glass-core substrates can provide increased stiffness, thinner build-ups and improved coefficient-of-thermal-expansion matching to silicon interposers and ICs, which is important for advanced heterogeneous integration.

Europe has strong positions in advanced packaging for harsh environments, power electronics, photonics, flexible electronics and quantum technology packaging. Its opportunity lies in mastering integration for demanding, long-lifecycle and reliability-critical applications while building scalable pilot lines, common design-to-manufacturing methods, testing capabilities and skills.

1.2.3.2.2 Vision and expected outcome

The vision for Advanced & Heterogeneous Integration is to turn diverse technologies into smaller, more efficient, sustainable and interoperable systems. Advanced packaging is no longer merely an enclosure or interconnection task; it becomes the system architecture that connects electronics, photonics, MEMS, power, quantum and sensing functions into manufacturable smart systems.

Europe’s ambition is to become a global leader by building an integration ecosystem that:

- links research, design, manufacturing, reliability testing, sustainability, training and industrial deployment;
- bridges the gap between prototypes, pilot lines and cost-effective production;
- serves both high-volume markets such as telecom, automotive and consumer electronics, and low-volume, long-lifecycle markets such as industrial sensing, aerospace and defence based on a circular economy.

Achieving this vision requires four coordinated capability blocks:

- Infrastructure and pilot lines for open prototyping, small- and medium-volume production and distributed manufacturing across Europe.
- Co-design tools and methods based on Design-to-X principles, multi-domain simulation, digital twins, shared material databases and early manufacturability checks.
- Materials, packaging and reliability capabilities for sustainable substrates, functional materials, thermal management, sensing, energy harvesting and harsh-environment operation.

- Skills, SMEs and ecosystem coordination, including training, hands-on access to pilot lines, targeted SME instruments and focused international cooperation.

The expected outcome is a resilient European integration ecosystem that can deliver reliable, sustainable and competitive systems from lot-size-one to volume manufacturing, with zero-defect ambitions and strong environmental performance.

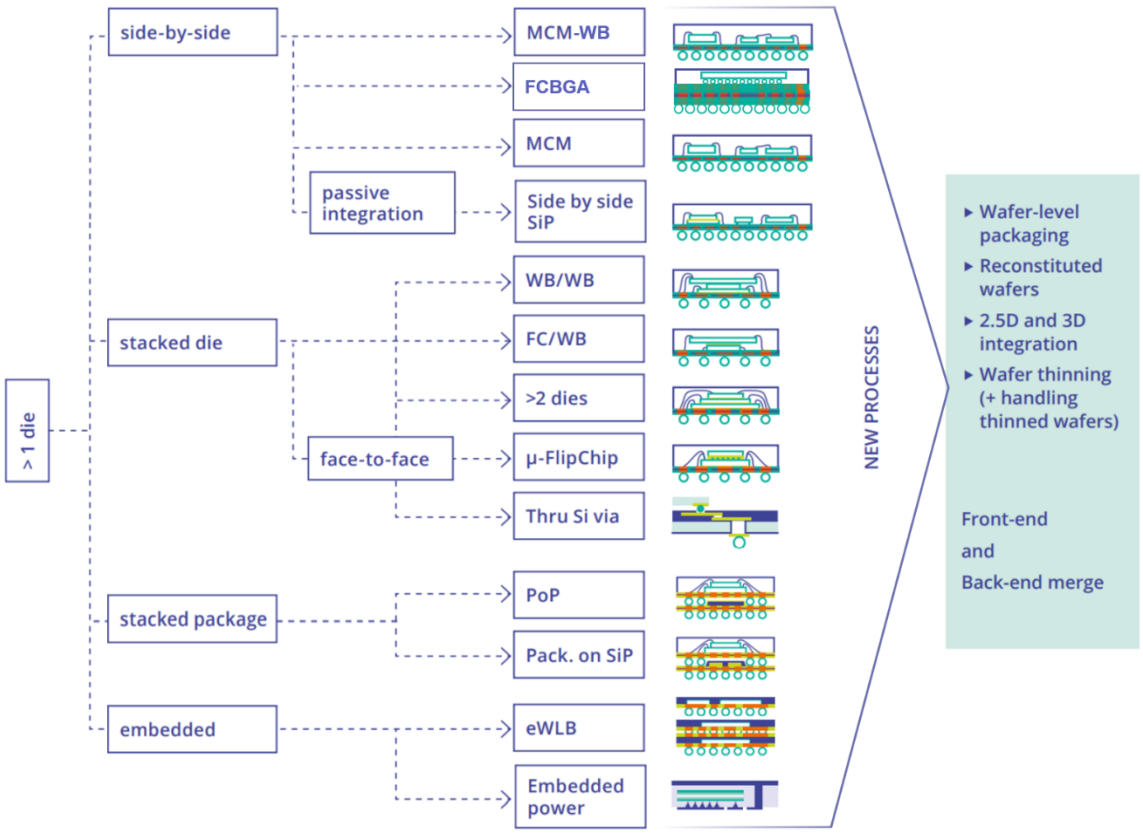

Figure 1.2.2 System-in-Package (SiP) examples. The convergence of front-end and back-end processes enables diverse heterogeneous integration options. (Source: Andreas Grassmann – Infineon – 3D Systems Summit)

1.2.3.2.3 Key focus areas

The key R&D priorities span five connected domains. Each domain should be treated less as a standalone technology field and more as part of a common integration capability: design, package, manufacture, test and scale heterogeneous systems reliably.

- Advanced Packaging and SiP Technologies
  - Heterogeneous 2.5D/3D and chiplet integration of electronics, memory, RF, MEMS, power, photonics, sensing, quantum and energy functions into miniaturized and robust systems.
  - Substrates, redistribution layers, silicon bridges, organic interposers, glass-core substrates and fine-pitch interconnects for high-density electrical, optical and power routing with low warpage, high reliability and scalable manufacturability.

- Packaging as an active functional element, including antennas, sensors, embedded heat spreaders, thermoelectric surfaces, photonic interfaces and energy sources.
- Package-level power delivery networks, embedded voltage regulators and integrated power devices for efficient supply of AI accelerators, HPC processors and other power-hungry components.
- Power, RF, THz and photonic packaging for high-frequency, high-power and high-bandwidth applications, including antenna-in-package and co-packaged optics.
- Reliability, inspection and health monitoring, including contamination control, hermetic sealing, built-in self-test, self-repair concepts, failure analysis and AI-supported pre-assembly inspection.
- Design-to-manufacturing and Lab2Fab methods, including digital twins, common process ontologies, Process Design Kits, early Design Rule Checks and transfer from research pilot lines to industry.
- A federated data-space ecosystem for semiconductor integration, enabling data-driven services, shared process understanding, trusted material data and the ground-work for future industrial data spaces.

- Discrete Power Packaging and Power Modules

  Power packaging and power modules must deliver higher power density, better thermal management and stronger reliability in smaller footprints. Demand is driven by electrification, energy systems, automotive applications, industrial equipment and AI-related power delivery.

  - Miniaturized 3D and heterogeneous power modules that integrate active and passive components for high-current and high-voltage delivery.
  - Advanced joining, interconnect and module manufacturing processes such as copper or silver sintering, Cu wire/ribbon/clip bonding, laser welding, transfer moulding and additive manufacturing.
  - Sustainable substrates, die attach, encapsulation and high-performance thermal interface materials combined with integrated cooling, including microfluidics and double-sided cooling.
  - Low-inductance interconnects, busbars, embedded planes and chip-to-chip or chip-to-die bonding for high-frequency wide-bandgap devices.
  - Durable packages for high thermal and electrical cycling, especially in automotive, grid, industrial and AI data-centre applications.
  - GaN, SiC and ultra-high-voltage device and module concepts, including intelligent gate drives, traction inverters, grid applications and scalable European back-end manufacturing capacity.
  - Requirements-driven multi-physics design methods and modular, automated manufacturing concepts for economically viable power modules.

- Integrated Photonics and Co-integration with Electronics
  - Electro-photonic system integration that combines PICs with high-speed RF electronics, MEMS/NEMS/MOEMS sensors and advanced packaging for compact sensing, communication and computing modules.
  - Wafer-level photonic-electronic integration for smart emitters, detectors, optical interconnects and scalable electro-optical IC carriers.

  - Heterogeneous integration of active optical materials and components, including III-V semiconductors, ferroelectrics and ultra-low-loss waveguides, onto silicon and other PIC platforms.
  - Low-loss fiber coupling, high-precision placement, bonding and alignment processes to make photonic packaging manufacturable and reliable.
  - Integration of non-electrical optical functions such as waveguides, holographic and diffractive optics, reflective light guides, freeform optics and metasurfaces for compact displays, HMD-type devices and optical sensing systems.
  - Quantum PIC integration, including single-photon sources, detectors, manipulation circuits and quantum photonic functions for communication, sensing and computing.
  - Multi-domain co-packaging for RF, photonics, sensing and computing functions, including thermal, electrical, optical and mechanical co-design.

- Flexible Electronics
  - Ultra-thin and conformable vertical form factors, including miniaturized matching networks and flexible silicon substrates for 3D integration.
  - Large-area electronics fabrication using submicron processes, advanced printing, nanoimprinting and roll-to-roll-compatible manufacturing.
  - Automated, high-accuracy assembly, interconnection and testing for flexible, stretchable and structural electronics.
  - Non-fossil, organic, biocompatible, recyclable, biodegradable and compostable substrates for wearable, implantable, ingestible and other sustainable devices, with design-for-disassembly and material recovery considered from the outset.
  - Adhesives, bonding materials and interconnection methods for reliable integration of rigid components, bare dies and flexible substrates.
  - Embedded antennas, photovoltaics, energy storage, magnetics, heat spreaders, displays, sensors and actuators in flexible or structural systems.

- Quantum Systems
  - Packaging and integration of semiconductor electronics, integrated photonics and superconducting devices for cryogenic and ultra-low-noise environments.
  - Interfaces between room-temperature control systems and cryogenic quantum components, including low-loss interconnects and scalable signal routing.
  - Wafer-to-system integration methods for scalable quantum modules, including bonding, assembly and packaging routes compatible with industrial manufacturing.
  - Cryogenic electronics, including cryo-CMOS and multiplexing ASICs, to move control and readout circuits closer to quantum devices.
  - Compact cryogenic cooling and thermal management concepts for quantum systems.
  - Quantum PIC integration for communication, sensing and computing, including single-photon sources, detectors and manipulation circuits.
  - Advanced packaging for ion-trap and solid-state quantum systems, including photonic integration, UHV/cryo-compatible assembly and scalable RF or DC control.

- Manufacturing Methodology, Characterization, and Testing
  - Automation and customization of CMS integration for scalable production, smaller lots and lot-size-one manufacturing.
  - Industry 4.0 design-for-manufacturing methods using production data feedback loops, process modelling and digital twins.

- Zero-defect integration supported by advanced inspection, in-line testing, self-monitoring and high-resolution metrology for complex 3D packages.
- Shared material property databases, standardized ontologies and materials-by-design approaches for simulation, reliability and functional or structural components.
- Low-energy selective joining and assembly methods that protect sensitive components during heterogeneous integration.
- Embedded self-powered sensors for lifetime monitoring, provenance tracking, authenticity validation and predictive maintenance.
- Federated data-space concepts for semiconductor manufacturing and integration, linking pilot lines, design tools, process data, material-property databases and data-driven services across the ecosystem.
- Transfer methods from research and pilot-line environments to manufacturable, standardized and scalable industrial integration processes.

1.2.3.3 Major Challenge 3: Sustainability

1.2.3.3.1 State of the art

Global e-waste already exceeds 50 million tons per year and is projected to keep growing. Europe has a comparatively strong position in documented e-waste collection and recycling, supported by EU and national policy frameworks, but increasing CMS integration makes circularity more difficult. The more tightly components, materials and functions are integrated, the harder they become to repair, separate and recycle unless circularity is designed in from the start.

Many ECS products, especially in industrial and infrastructure applications, remain in use for decades. Their design must therefore anticipate future requirements for repairability, upgradeability, lifecycle reconfigurability, material substitution, traceability and recyclability even when final regulations are not yet known.

Regulatory and methodological frameworks such as the Eco-design Directive, the Circular Economy Action Plan, Digital Product Passports, Life Cycle Assessment, Product Environmental Footprint and Organization Environmental Footprint provide the basis for more transparent and measurable sustainability decisions.

For ECS, sustainability must cover the full value chain: material sourcing, design, manufacturing, assembly, operation, maintenance, repair, reuse, recycling and recovery. This makes eco-design a system-level integration task, not an end-of-life add-on.

Extending product lifetimes is one of the most effective levers for reducing environmental impact. It requires modularity, repairable architectures, software and hardware updates, condition monitoring, low-power operation and design strategies that allow valuable components and materials to remain in productive use for as long as possible.

1.2.3.3.2 Vision and expected outcome

The vision is to make sustainability a design constraint for ECS from the initial concept to end-of-life. Circular economy principles, eco-design, Safe-and-Sustainable-by-Design and the 9R framework should guide choices on materials, architectures, manufacturing processes, operation, repair, reuse, recycling and recovery. Life Cycle Assessment (LCA) and related methods should identify environmental hotspots early and verify whether design decisions actually reduce impact.

Future ECS products should therefore be developed around five sustainability capabilities:

- Circularity and eco-design, using sustainable materials, low-carbon manufacturing and reliable environmental data for LCA, PEF, PCR and EPD.
- Sustainable materials and processes, prioritizing non-fossil, recyclable, biodegradable or compostable options and reducing hazardous substances, critical raw materials, energy, water and emissions.
- Durability, modularity and repairability, including upgrades, easy dismantling, material separation, spare parts availability, condition monitoring and lifetime extension.
- Traceability and operational sustainability, supported by Digital Product Passports, product indexes, predictive maintenance, retrofitting and second-life use.
- Circular business models that make repair, reuse, remanufacturing, recycling and recovery economically attractive across the ECS value chain.

Integration processes and design tools should enable dismantling, material separation, recycling and urban mining instead of locking valuable materials into inseparable assemblies. Multifunctional components should therefore be designed for high recyclability and, where possible, second-life use.

Battery systems illustrate this challenge. Reuse and recycling must cover packs, modules and cells, while reducing material use and improving recovery rates for valuable materials.

Smart battery modules and battery-integrated sensing are important examples of this direction. Embedded and distributed sensing at cell, module and pack level, including temperature, pressure, strain, swelling, humidity, gas, current distribution and interconnect degradation monitoring, can support safer, more efficient and more circular battery systems across different chemistries and second-life use cases.

The expected outcome is an ECS ecosystem in which sustainability is measurable, designable and economically viable: products consume fewer resources, last longer, can be repaired or upgraded, and keep materials in productive use for as long as possible.

1.2.3.3.3 Key focus areas

- Eco-design of ECS to promote circularity:
    - Substitute hazardous substances and critical raw materials where feasible, including RoHS- and REACH-relevant materials such as PFAS, and apply Safe-and-Sustainable-by-Design principles to material and process choices.
    - Use recyclable, biodegradable, compostable and non-fossil materials from sustainable sources.
    - Increase functionality with fewer materials through compact, modular and material-efficient designs.
    - Assess environmental impact during design using LCA and related frameworks, supported by certified data for LCA, PEF, PCR and EPD.
    - Develop design, fabrication, integration, recovery, reuse, repairability and disassembly strategies.
    - Develop de-bondable coatings, adhesives and integration processes that enable re-pair, material repurposing, recycling and recovery instead of irreversible material dis-persion.

  - Extend product lifetime through reliability, modularity, spare parts availability, upgradeability and secure software or hardware updates.
  - Use low-power operation, context awareness, energy harvesting and hardware-software co-design to reduce energy use during operation and eliminate or reduce the need for battery replacement.

- Sustainable manufacturing of ECS:
  - Reduce resource use in wet, dry, additive and subtractive processes, including energy, materials, water and chemicals.
  - Use additive manufacturing and printing to enable circular, thin, flexible and single-use devices with defined end-of-life concepts.
  - Reduce cleanroom energy demand, greenhouse-gas emissions and the CO2 footprint through renewable energy, efficient tools and optimized process flows.
  - Increase water reuse and improve analytics for hazardous production remnants.
  - Integrate inline sensors and abatement systems to monitor and mitigate GHGs, PFAS and other hazardous substances.
  - Improve recycling and material recovery processes, especially for energy storage components.
  - Move toward CO_2-neutral and zero-waste ECS manufacturing.

- Sustainable products and business models:
  - Encourage sustainable supply chains and create incentives for eco-design, repairability, reuse, remanufacturing and recyclability.
  - Introduce product category rules, product indexes and environmental product declarations covering energy efficiency, resource efficiency, durability, repairability, recycled content, carbon footprint and expected waste generation.
  - Promote, test and establish Digital Product Passports to close data gaps and enable traceability at component, material and system level.
  - Establish repairability metrics, such as an EU-wide repair index, and support repair processes through diagnostics, manuals, schematics, spare parts, re-certification and trained repairers.
  - Use condition monitoring, authenticity validation and health or performance tracking to support predictive maintenance, safe second-life use and anomaly detection.
  - Improve recycling efficiency through robotics, sorting, material identification and automated disassembly.
  - Develop circular business models that connect component providers, product manufacturers, repair centres, recyclers and circularity service providers.
  - Identify regulatory and economic conditions that make repair, reuse, remanufacturing, repurposing and recycling profitable and scalable.

1.2.4 Timeline

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

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
Major Challenge 1: Functionality	**Topic 1.1: Sensing, imaging and actuation**	• Selective gas and chemical sensing • Disease monitoring and diagnostics platforms, including in-vitro and wearable systems • Lidar, radar, sonar and CMOS-integrated IR sensing • Functional materials for sensing and actuation, including piezoelectrics, ceramics, polymers and metamaterials • Novel CMOS-integrated sensing materials and devices, including spintronic and metallic-glass concepts • Hydrogen pressure and exhaust-detection sensors • Silicon-integrated mmWave and THz sensors • Quantum-sensor materials and concepts	• Selective detection of allergens, residues and hazardous substances • Integrated fluidics and drug-delivery functions • Affordable IR imagers, hyperspectral imaging, X-ray and magnetic-resonance sensing • Integrated quantum sensors • Hydrogen detection in ambient environments • Scalable THz sensor SoCs with edge AI and advanced packaging • Portable VR/MR sensing systems for precision agriculture and digital society • Spintronic sensor arrays with AI accelerators for real-time edge sensing	• Converged sensing platforms combining thermal, optical, lidar, radar and other modalities • Multifunctional healthcare support systems, including wearables and implants • Intelligent THz sensing systems for autonomous, health, space and consumer applications • Unified spintronic platforms for neuromorphic and quantum-related functions
	Topic 1.2: MEMS technology	• Novel piezoelectric materials and devices for MEMS/NEMS • Micro-optical MOEMS components • Inertial, tactile, navigation-grade and high-acceleration MEMS for robotics and autonomous systems • Compact audio MEMS • Lifetime stability via optimized design and process, self-monitoring and self-calibration for robust MEMS/NEMS devices	• Medical-grade MEMS for point-of-care devices • MEMS pumps for precise fluidic, gaseous and dosing functions • Low-power audio MEMS systems with active noise cancellation • Miniaturized MEMS for everyday biomarker monitoring • ASIL-D grade MEMS modules for autonomous systems and humanoid robotics • Environment sensors for robotics and autonomous operation in unstructured or harsh environments	• Microchip-based DNA sequencing enabled by highly integrated MEMS, fluidics and sensing functions • On-edge sensor fusion for individualized health analysis and context-aware feedback • Merging of photonics, quantum and MEMS sensors into multifunctional sensing platforms

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
	Topic 1.3: Integrated photonics	• Photonic devices beyond telecom wavelengths • Co-design and co-packaging of integrated photonics and high-speed electronics • Photonic health and medical sensors	• Tunable laser sources, detachable fiber-chip connectors and built-in self-test of photonic components • AI-driven device and circuit design for photonic ICs • Materials and devices for quantum PICs • Beam-shaping and manipulation optics, including curved waveguides, metasurfaces, tunable lenses, filters and holograms • Display and sensing technologies, including micro-LEDs, MEMS mirrors, phased arrays and eye-tracking sensors	• Growth or bonding of light-emitting structures on silicon photonic platforms • Analogue and neuromorphic photonic computing concepts
	Topic 1.4: Flexible electronics	• Flexible integration of thinned silicon devices and ICs • Non-fossil flexible and structural materials, including active components, transparent conductors and barriers	• Large-area flexible and stretchable sensors and actuators • Organic and biocompatible materials • Wearable smart systems combining biochemical and biophysical sensing	• Stretchable wearable systems combining biochemical and biophysical sensing • Metamaterial-based flexible sensors
	Topic 1.5: Communications	• Real-time, low-latency, low-power and fault-tolerant networks for edge and IoT devices • High-speed photonic communication modules for chip-scale and module-scale connectivity in data communication and controlled or harsh environments • EMI reduction for robust communication modules • Compact and efficient THz transceivers	• Quantum key distribution • Advanced interconnect photonics at component and system level • High-speed hybrid photonics modules beyond 1 Tb/s • Beyond-5G and 6G communication, including non-terrestrial networks • Secure high-rate THz communication and integrated sensing • Energy-constrained adaptive networks at node and network level • Accurate and stable clocks for 6G and quantum devices	• Quantum internet and quantum-safe cryptography • Beyond-6G communication concepts • Digital twins for energy-constrained wireless sensor networks • Integration of THz sensing with quantum technologies and 6G+ networks

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
	Topic 1.6: Energy and thermal management	• Lightweight energy harvesters and storage devices • Multi-source energy-harvesting PMICs operating below 10 mV and 10 µW • Low-power components and energy-autonomous systems • Energy storage for extreme-temperature and harsh environments • Thermal management across integration levels, including advanced and active cooling • Simulation models for energy harvesting, power consumption and overall balancing at device and system level	• Low- and zero-power components and systems • Thermal management for integrated photonics • Advanced encapsulation materials for energy harvesters • Chiplet concepts extended to non-IC components • Sensors and actuators for battery-cell optimization over lifetime	• CO_2-neutral and circular ECS energy systems • Energy-harvesting PMICs embedded in MEMS/NEMS wireless sensor nodes • Sensors embedded in energy sources for condition monitoring, provenance and anomaly detection • Laser-propulsion concepts where relevant to autonomous systems
	Topic 1.7: Information processing	• Security and privacy for edge and sensor systems • Edge AI and explainable AI for embedded systems • Hybrid physical and data-driven modelling • Federated edge-to-cloud data collection • Energy-aware adaptive networks for battery-powered edge devices • AI-assisted THz imaging and spectral analysis • Hardware-software and security co-design	• Information processing close to data acquisition • Hardware-based security and privacy • Neuromorphic and low-power edge computing • Quantum simulation and cloud-based quantum data analysis • Real-time AI-enhanced THz hyperspectral imaging • Self-diagnosis, self-monitoring and sensor-level security features	• Low-power AI for integrated systems • Neuromorphic edge computing for sensors and actuators • Quantum computing and simulation • Autonomous THz sensor networks with embedded AI • Self-learning and self-repairing systems using in-memory and bio-inspired spintronic computing

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
Major Challenge 2: Advanced & Heterogeneous Integration	**Topic 2.1: Advanced packaging and SiP technologies**	• Hybrid integration of heterogeneous components on IC carriers, PCBs, flexible substrates and SiP platforms • System health monitoring, self-diagnosis and integration of biological, molecular and fluidic functions • Embedded power sources and energy-harvesting functions in SiP and IC carriers • Heterogeneous SiP for audio MEMS, drivers, sensors and actuators • Packaging for thermal, EMI and environmental protection • Low-power, energy-harvesting-compatible wake-up radio technologies	• Integration for harsh environments and implantable electronics • System health monitoring, self-diagnosis, self-healing and adaptive materials • Sensor hubs and sensor fusion for multifunctional modules • Chiplet interfaces and reliability tests for autonomous-system applications using different technology nodes and integration routes • 3D heterogeneous integration for miniaturization and robustness • Chiplet substrates, embedded bridges and glass-core substrates for fine wiring and low-warpage packages • Organic IC substrates with increasingly fine line/space and via dimensions for selected chiplet and interposer applications • Package-level power delivery networks and embedded voltage regulators close to processors and accelerators • Resilient supply chains for programmable and critical system components	• Maximum functional integration in minimum volume and footprint • Advanced photonic and biological-electronic hybrid systems • Radiation-hardened and ultra-reliable THz packages for deep-space, space-infrastructure and harsh environments
	Topic 2.2: Integrated photonics and co-integration with electronics	• Photonic integration with RF electronics, sensors and electro-optic co-packaging • High-precision component placement, bonding and alignment processes • Low-loss fiber coupling to PICs	• Heterogeneous integration of active optical components, including III-V materials, on PICs at wafer scale • Combining electrical and optical interconnects into electro-optical IC carriers • Metamaterials and metasurfaces for beam shaping and compact optical functions	• Monolithically integrated quantum photonics, including III-V quantum-dot platforms

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
	Topic 2.3: **Flexible electronics**	• Integration processes for flexible, structural and 3D conformable electronics • Chip interconnection materials and methods, including ACA, ICA and flip-chip assembly • Roll-to-roll compatible interconnection processes and equipment for heterogeneous integration	• In-line inspection, yield monitoring and automated high-accuracy manufacturing for flexible, stretchable and structural electronics • Compostable and biodegradable substrate and housing materials • Roll-to-roll compatible chip assembly and interconnection on stretchable substrates	• Structural and conformable electronics in polymer, composite, textile and elastomeric components manufactured by printing, lamination, thermoforming, injection moulding, overmoulding or additive manufacturing • Stretchable electronics and system integration • Automated interconnection processes and equipment for heterogeneous integration
	Topic 2.4: **Quantum systems**	• Cryogenic materials and integration methods for quantum technologies • Low-loss components and materials for high quantum coherence • Cryo-CMOS and cryogenic electronics • Initial wafer-level bonding for ion-trap and other quantum chips	• Integration of superconducting, photonic and silicon-based quantum systems • Solid-state cooling and compact cryogenic integration • Cryogenic multiplexing ASICs for scalable control and readout	• Quantum SiP concepts operating at room temperature or with integrated cooling • Monolithic integration of trapped ions with integrated photonics • Scalable packaging approaches for quantum sensing, communication and computing
	Topic 2.5: **Manufacturing methodology, characterization and testing**	• Industry 4.0 methods for manufacturing optimization • Additive manufacturing and rapid prototyping technologies • Automation and customization for smaller lots • Material-property databases for simulation and reliability • Digital twins for manufacturing process optimization	• Zero-defect integration with automated inspection and process feedback • Automation and customization for smaller lots • Additive manufacturing and rapid prototyping technologies • Materials-by-design approaches for functional and structural components	• Lot-size-one integration and highly automated customization • Standardized and scalable manufacturing ecosystems for systems and packages • Fully digitalized manufacturing process descriptions and digital twins

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
Major Challenge 3: Sustainability	**Topic 3.1: Eco-design of ECS**	• Replacement of hazardous substances and critical raw materials, including RoHS- and REACH-relevant materials such as PFAS • Use of recyclable materials and lightweight, material-efficient designs • Life Cycle Assessment as a design tool, supported by certified data for LCA, PEF, PCR and EPD • Design strategies for recovery, reconfiguration, reuse, repairability and disassembly • Modular design, spare parts availability, upgradeability and security support for lifetime extension • Low-power, context-aware and energy-harvesting concepts for reduced operational energy use	• Cross-company reuse of stable chip and More-than-Moore designs • Hardware-software co-design methods for sustainable ECS • Biodegradable, compostable and non-fossil materials • System-level recycling concepts, including energy storage components • Energy-efficient manufacturing processes and integration methods • Shared, lean and reliable environmental-impact data for LCA and Safe-and-Sustainable-by-Design approaches • Traceability of reused components and design backup options to reduce obsolescence risk • Packaging co-design for reuse and disassembly	• Reusable circuit blocks and circular ECS architectures • Full recycling and material recovery concepts, including for energy storage components • Environmental-footprint-based recycling planning for final-stage material recovery • Established repair processes, including failure characterization, repair, re-characterization, manuals, schematics and spare parts • Durable devices with warranty and safety requirements addressed from design to end-of-life
	Topic 3.2: Sustainable manufacturing of ECS	• Condition monitoring and predictive maintenance for manufacturing tools and integrated systems • Improved energy and resource efficiency across components, modules and systems • Energy harvesting to reduce or eliminate battery replacement • Extended additive manufacturing methods for sustainable functional modules • Increased water reuse and improved analytics for hazardous production remnants	• Reduced energy consumption and CO_2 footprint of integration processes, tools and ECS systems • Inline sensors and abatement systems for GHGs, PFAS and other hazardous materials • Processes for reuse, second life, recycling and material recovery • Alternative integration strategies and replacement of critical process steps to comply with RoHS and REACH • Lead-free and material-efficient packaging approaches	• CO_2-neutral ECS manufacturing and value chains • Zero-waste additive manufacturing for functional modules • Recycling processes adapted to flexible, sustainable electronics with novel materials

Major Challenge	Topic	Short Term (2027–2031)	Mid-Term (2032–2036)	Long Term (2037 and beyond)
	Topic 3.3: Sustainable products and business models	• EU-wide repairability index and product-category rules for ECS • Product indexes covering durability, repairability, resource efficiency and environmental impact • Methodologies to quantify how technologies contribute to sustainability	• Condition monitoring and energy harvesting for long-term reliability and anomaly detection • Repair-as-a-business models, including bonus-malus systems and third-party repair centres • Digital Product Passports to close circularity and recycling data gaps and enable component-level traceability • Robotic sorting and disassembly to improve e-waste recyclability • Lifecycle traceability of condition, carbon footprint, authenticity and recyclability • Circular business-model synergies between component providers, product providers, repair centres and circularity centres • Regulatory conditions that make circular business models profitable	• Skilled repairers, re-certification processes and safe repair workflows • Material-level traceability enabled by Digital Product Passports • Wider rollout of fully circular business models • Use of Digital Product Passports to enable repair, reuse and recycling business models

1.3



Foundational Technology Layers

EMBEDDED SOFTWARE AND BEYOND

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 ("classical" or ML-based) 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. independently 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.

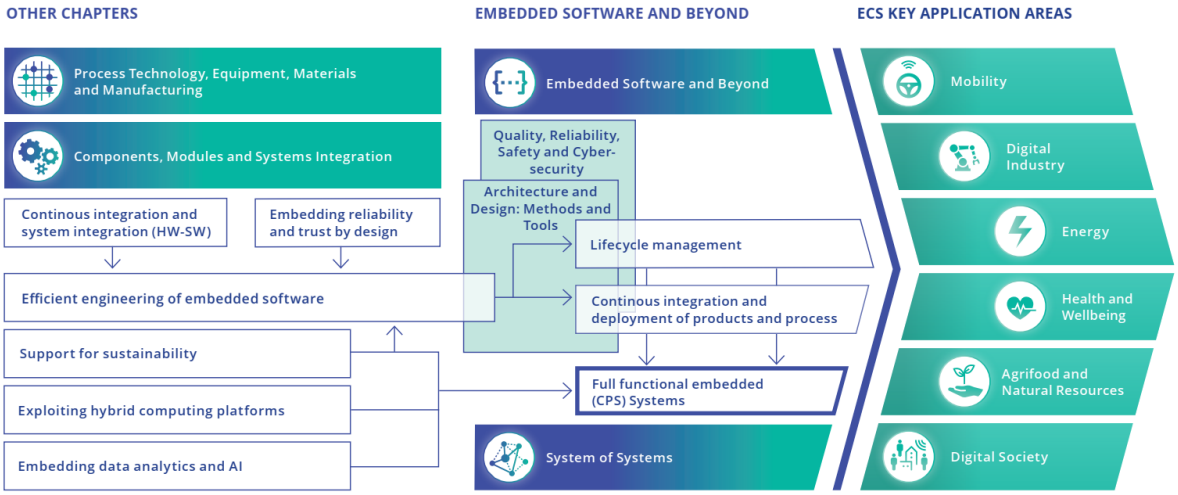

Figure 1.3.1 - Positioning of the Embedded Software and Beyond Chapter in the ECS-SRIA

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 Systems 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

[1] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Downloadable from: https://www.inside-association.eu/publications

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 such as security, privacy and autonomy). In these systems, most innovation nowadays comes from software. 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 drive towards digitalisation of our society.

At the same time, ECPS need to exhibit required quality properties such as sustainability and 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, ECPS must evolve their functionalities and hardware capabilities 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 lifetimes 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.
- Resilience and adaptability to the dynamic environment of ECPS.
- Maintenance, integration and rejuvenation of legacy software solutions.
- Incorporation of beyond-CMOS hardware, such as physics-based neuromorphic processors or unclonable function generators.
- Embedded agentic AI.

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 depend on new software engineering tools and processes (e.g. quality assurance, Verification and Validation (V&V) techniques and methods at 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 affects everyone, the effort required to make it reliable, maintainable and usable for longer periods is routinely underestimated. As a result, there are news articles every day about expensive software bugs and over-budget or failed software development projects. Also, major challenges remain concerning software correctness and quality, 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, 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 viable development of SoS with their 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.

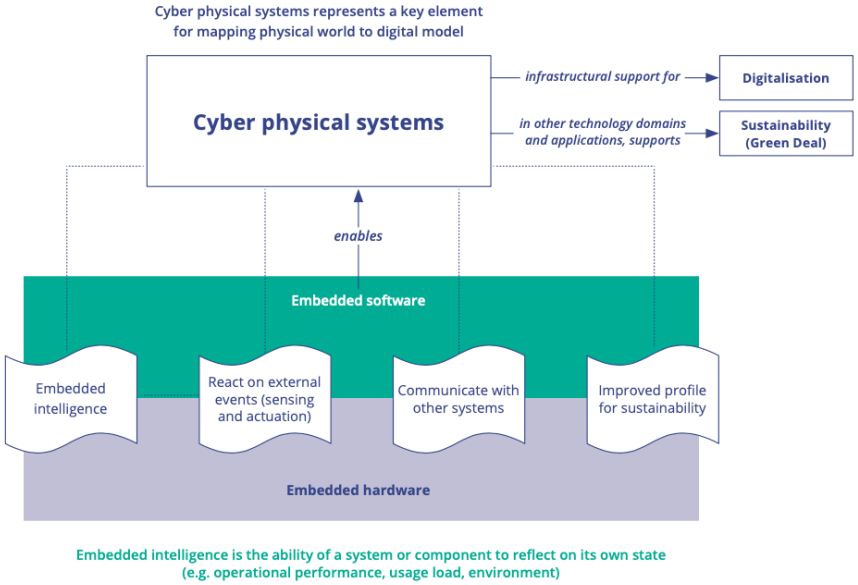

Figure 1.3.2 – Importance of Embedded Software for Cyber physical systems and its roles.

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 field. 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

[2] Preskill, J. (2018). Quantum Computing in the NISQ era and beyond. Quantum, 79.

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, still preventing wide-spread use at this moment[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 long been used in 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.

[3] Post-Quantum Cryptography - Setting the Future Security Standards. (n.d.). Retrieved from https://www.nxp.com/applications/enabling-technologies/security/post-quantum-cryptography:POST-QUANTUM-CRYPTOGRAPHY

[4] Singh, A., Dev, K., Siljak, H., Joshi, H., & Magarini, M. (2021). Quantum Internet—Applications, Functionalities, Enabling Technologies, Challenges, and Research Directions. IEEE Communications Surveys & Tutorials, 2218-2247. doi:10.1109/COMST.2021.3109944

[5] Kantsepolsky, B., Aviv, I., Weitzfeld, R., & Bordo, E. (2023). Exploring Quantum Sensing Potential for Systems Applications. IEEE Access, 31569-31582.

1.3.3 Application Breakthroughs

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 [6] (see Figure 1.3.3).

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.

[6] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Downloadable from: https://www.inside-association.eu/publications

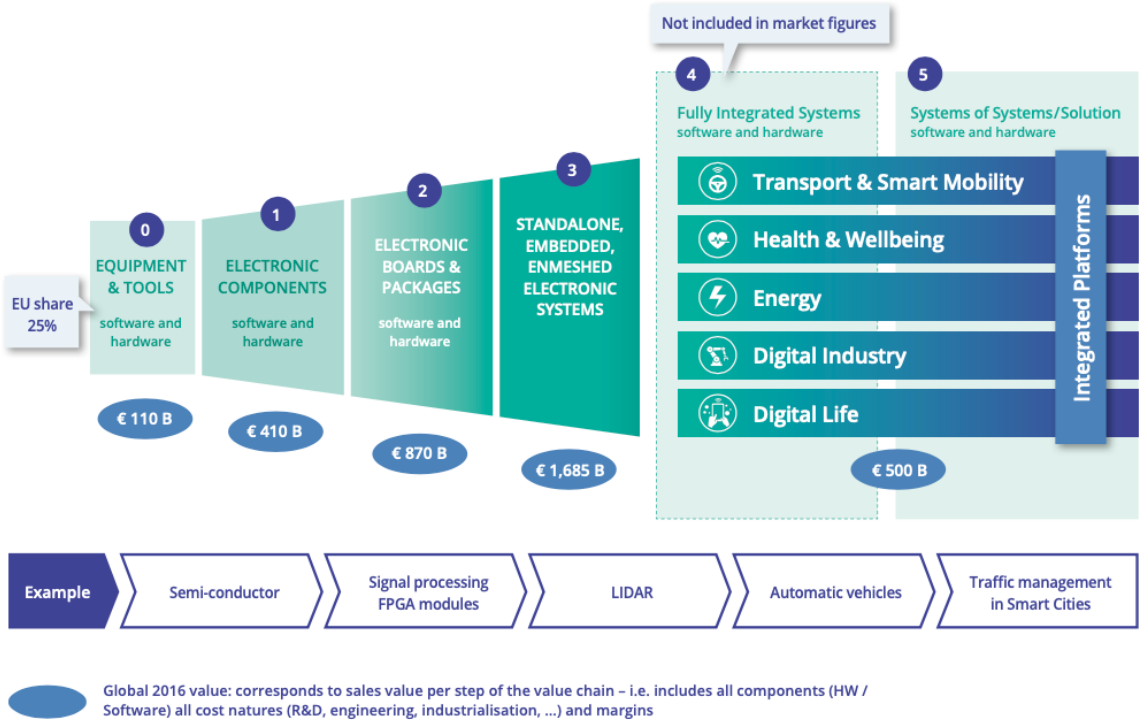

Figure 1.3.3 - Advancy (2019) [7]report: value creation

1.3.4 Major Challenges

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

- **Major Challenge 1**: Efficient engineering of embedded software.
- **Major Challenge 2**: Continuous integration and deployment.
- **Major Challenge 3**: Lifecycle management.
- **Major Challenge 4: Embedded Artificial Intelligence**.
- **Major Challenge 5**: Support for sustainability by embedded software.
- **Major Challenge 6**: Resilience, Dependability, Reliability and Trust.
- **Major Challenge 7:** Hardware virtualisation for efficient SW engineering.
- **Major Challenge 8:** AI in Embedded Systems Engineering and Operations

[7] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Downloadable from: https://www.inside-association.eu/publications

1.3.4.1 Major Challenge 1: Efficient engineering of embedded software

1.3.4.1.1 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 in embedded software engineering 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 prove to be challenging. If no solutions are introduced which automatically tailor software to specific accelerators[8, 9], 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; methods and tools to enable strongly linked, yet independent and heterogeneous development processes in new areas like software defined vehicles (SDV); empirical and automated software engineering; and safe, secure and dependable software platform ecosystems.

1.3.4.1.2 Vision and expected outcome

The demand for embedded software is greater than we can currently meet, 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 its 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.

[8] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Downloadable from: https://www.inside-association.eu/publications

[9] https://www.intel.com/content/www/us/en/developer/articles/technical/efficient-heterogenous-parallel-programming-openmp.html#gs.85zv3a

Instead of focusing only on the efficiency of embedded software engineering, we already see that the field is evolving towards cyber-physical systems engineering (cf. Chapter 2.3 **Architecture and Design: Methods and Tools**), and software is one element of engineering. Rather than silos and handovers at the boundaries between disciplines, 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. Chapter 2.3 **Architecture and Design: Methods and Tools**).

Furthermore, the lack of unified engineering approaches limits progress towards energy-efficient computing across the full technology stack, from advanced materials (e.g. spintronics, 2D materials, and polymers) to hardware architectures, embedded software, and applications. Such integration is essential for edge computing and future IoT nodes based on printed and flexible electronics, combining miniaturized sensors, circuits, antennas, and energy harvesters on lightweight, recyclable substrates. These autonomous, energy-constrained systems will increasingly also rely on adaptive, event-driven embedded software that efficiently exploits intermittent harvested energy while enabling neuromorphic computing and edge AI capabilities.

Software-defined systems enable the implementation of complex and customisable functionalities in CPS. The equivalent for the automotive industry is the software-defined vehicle (SDV), which often includes the concept of the connected vehicle and the associated cloud services. SDVs combine mechatronic - often safety-critical and real-time-capable - systems with edge, internet, app and cloud technologies. This requires the integration of embedded software (open and closed source), which in turn is often developed according to different paradigms, standards and business models. In the target vehicle system, these parts must not only function together, but also fulfill strict quality standards and, where applicable, legal regulations. SOA-based approaches are expected to contribute significantly towards these goals. Methods and tools are required that support individual but linked development cycles in the respective paradigms and at the same time enable the composition of the overall system, but also the decomposition of results from diagnostics, verification and validation back to the individual part.

Open source is increasingly used by the industry for Software-Defined Vehicles (SDV), specifically for non-differentiating components and frameworks, to accelerate innovation and reduce development costs. This approach can speed up the development process, share costs, and provide the flexibility to customize and adapt software to meet specific needs and long-term support. **Eclipse S-CORE** is a project that develops an open source core stack for SDVs, capable of being safety-certified (planned: ASIL-B), targeting embedded high-performance ECUs. Besides the stack itself, this project also defines the development process, methods and tool chain.

Artificial intelligence is a technology that has 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, expanding the range and scale of tasks that are humanly possible in software engineering.

(B) Software architectures for optimal edge computing

At the moment, edge computing lacks a clear 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 such as resource, device, and network management (between edge devices as well as 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 the diversity of edge devices and the 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 prioritise 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 (such as magnetics, spintronics, 2D materials, polymer, etc.), via software architecture to embedded/application software. Energy efficiency is vital for optimal edge computing. For the same reason, future (sensor) nodes for IoT and Embedded Systems might be implemented via printed and flexible electronics, integrating miniaturized sensors, circuits, antennas, and energy harvesters such as organic photovoltaics directly onto lightweight, recyclable substrates. This enables the creation of low-cost, autonomous nodes that operate without frequent battery replacement by harvesting ambient light. These designs will fully depend on maximally energy-efficient 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 urgently 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, on the one hand, virtual machine-like architectures, and on the other hand 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, among other things, 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 benefit 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 with 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 making 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 domain-specific language. 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 helps to bridge 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.

(E) 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 will increase 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 improve processes 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.

(F) AI in the Software Development Life Cycle

The software development life cycle (SDLC) comprises a wide set of actions and tasks, in which writing software code is just one small part of the whole picture. It includes actions such as understanding the problem domain, architecting solutions, implementation, testing, integration, deployment, etc. In addition, challenges include knowledge transfer between team members, maintenance of documentation, management of discussions between different stakeholders, making trade-offs, etc. Therefore, in this context, it is necessary to understand where agentic AI can help, considering its

limitations. For instance, we are aware that large codebases enable the training of AI models that produce results similar to those of humans, especially for well-scoped problems. However, when it comes to understanding the context of the problem and the evaluation of potential solutions that should guide the implementation, we see limitations of AI technologies. Therefore, we need to explore the role of humans in the age of AI in the SDLC. This implies understanding the value that humans bring to the tasks in the SDLC, where AI can assist, and what the general limitations of AI are, where humans work more efficiently or are simply irreplaceable. In particular, it is necessary to imagine methodologies and processes that facilitate co-working between humans and agentic AI.

Finally, as humans are utilising AI to perform tasks in the SDLC, the main questions are what the new skill set is that engineers—especially in embedded systems—need, and what should be the focus of their work as they potentially save time using agentic AI.

1.3.4.1.3 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 specialised design methods, such as contract-based design) to guarantee safe and secure updates (cf. Chapter 2.3, Architecture and Design: Methods and Tools).
  - 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, diagnosability, and adaptability).

- Constrained 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 and digital twins, also at run-time for maintainability 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 permissive open-source licences.
  - Methods and tools that support individual but linked development cycles in the respective paradigms (safety, real-time, edge/cloud, open/closed source) and velocities on the one hand, and integration, verification and validation in complex target systems like SDV on the other hand.

- AI in the SDLC:
  - Tasks in the SDLC that agentic AI can perform, producing results of the same or higher quality than those generated by humans. e.g., generating solutions for well-defined problems, such as generating code snippets.
  - Tasks in the SDLC where agentic AI struggles to achieve performance similar to that of humans. e.g., understanding the broader context of the problem/solution, such as defining the problem domain in terms of requirements and the solution domain in terms of architectural decisions.
  - Tasks in the SDLC connecting contextual understanding and well-defined tasks. e.g., translating architectural decisions into application architecture and decomposing it into code snippets, as well as merging code snippets.

1.3.4.2 Major Challenge 2: Continuous integration and deployment

1.3.4.2.1 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 number 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[10], 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, which 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)), and ISO/TS 5083, 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 have already been sold and are '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 and validation by physically accurate simulation are a mandatory asset for any system company to manage the complexity of ECPS and their quality properties. Systems engineering employing model-based design and digital twins must become a regular new engineering activity.

1.3.4.2.2 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 is often 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 the IoT. In addition, automated engineering processes such as CI/CD will be crucial to adopt. The primary DevOps methodology needs to be adjusted for the ECPS. For example, CI pipelines will enable toolchain selection configuration for cross-compiling or include real-time testing and validation, which can be more challenging to automate and verify. Integrating automated

[10] https://www.khronos.org/sycl/

tests for hardware interactions can be complex and require specialised 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 operation as 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 subsystems in the SoS or IoT. This should be followed by automated engineering processes that apply the patterns and address 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 remains fast-paced. While typical ECPS-needs such as Computer Vision have been dominated by AI for some time, recent progress in Large Language Models (LLMs) opened the door to serious AI-assisted engineering tools. Hence, AI is 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 datasets need to be provided.

In addition to these challenges, we are facing the rise of a new type of software products: AI agents. These agents are deployed not only for software engineering (see Major Challenge 1), but also as part of software systems going into production. This creates a need for seamless integration of embedded systems with agentic software throughout the development, validation, deployment, and operation lifecycle. Ensuring trustworthiness, safety, security, and compliance becomes particularly challenging, as autonomous, goal-directed agents enlarge the attack surface and may exhibit adaptive behaviours that are difficult to predict, validate, and certify. Research and innovation are therefore needed in: (i) architectures and engineering frameworks for the secure integration of agentic AI into embedded, IoT, and System-of-Systems environments; (ii) continuous monitoring, verification, and anomaly detection mechanisms for autonomous software agents operating in dynamic environments; and (iii) governance, traceability, and oversight mechanisms that maintain human accountability and system resilience against threats, including supply chain attacks targeting AI models, training data, and external services. These capabilities are essential to support continuous integration and deployment in systems that increasingly rely on autonomous and partially opaque software components.

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 fitness for purpose of 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 systems-on-chip, 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[11] 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[12] and

[11] R. Kazman, K. Schmid, C. B. Nielsen and J. Klein, "Understanding patterns for system of systems integration," 2013 8th International Conference on System of Systems Engineering, 2013, pp. 141-146, doi: 10.1109/SYSoSE.2013.6575257

[12] https://digital-strategy.ec.europa.eu/en/library/recommendations-and-roadmap-european-sovereignty-open-source-hardware-software-and-risc-v

the Eclipse Foundation[13] 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.

1.3.4.2.3 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.
  - Co-existence and collaboration between embedded software and AI models and agents.
  - 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 and validation (especially the focus on dependability), using model-based design technologies and digital twins; also when SoS and IoT are involved.
  - Secure deployment and lifecycle management of agentic AI components, including resilience against model and supply chain vulnerabilities.
  - Certification of safety-critical software in CPSs.

[13] https://www.openhwgroup.org/projects/

1.3.4.3 Major Challenge 3: Lifecycle management

1.3.4.3.1 State of the art

Complex systems such as airplanes, vehicles 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 are even required for the 'continuous development and integration' paradigm.

Embedded software also must be maintained and adapted over time, to fit new product variants or even new product generations and enable updateability of existing 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 can be cost-efficiently evolved and migrated to use new technologies, such as spintronics, photonics, quantum, flexible systems, etc. 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.

1.3.4.3.2 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. Over-The-Air solutions become key enablers to this regard, especially for distributed systems,

and they will have to cover the different paces at which HW and SW evolve, determining when updates become necessary. Edge-to-cloud continuum represents an opportunity to create software engineering approaches and engineering platforms that together enable deployment and execution of the same code anywhere on this computing continuum.

The ability to keep 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. In this regard, the onboarding process of the constituent systems becomes a crucial phase to maintain the desired levels of security and safety: SoS integration platforms should provide solid onboarding procedures that ensure that no compromised HW or SW becomes part of the SoS. The adoption of blockchain technologies, digital contracts and security certificates, etc. could prevent similar situations, which could impact not only the SoS during operation but also the entire supply chain associated to it. The onboarding phase should also be automated to increase security levels and ensure scalability.

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.

1.3.4.3.3 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-shelf/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: new functionalities enabling and facilitating secure and automated onboarding processes, OTA software maintenance (see also the SoS chapter), ….
  - Embedded software architectures to enable SoS.

1.3.4.4 Major Challenge 4: Embedded Artificial Intelligence

1.3.4.4.1 State of the art

For various reasons – including privacy, energy efficiency, latency and the increasing necessity of smart data analytics on site – processing and artificial intelligence are moving towards the edge (edge computing), forcing the software stacks of embedded systems to coherently evolve supporting these new computing paradigms. 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 the cloud to the 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 contains AI-based solutions, it is important to understand the challenges that such solutions introduce. Indeed, AI contributes to address challenges of embedded software, but it does not define them exclusively itself, as quality properties of embedded software depend on integration of AI-based components with other software components.

For efficiency, the **inference phase** (the use of a model after training), which often involves intensive computations such as those required by deep neural networks (DNNs), is increasingly handled by **accelerators embedded in system-on-chip (SoC) architectures**. Most mid-range and high-end smartphones have SoCs embedding one of several AI accelerators, as well as Apple M-series processor family for laptops, tablets and future wearables – 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.

To fully exploit hardware capabilities and accelerate inference, a neural network must be **tuned and optimised for its embedded target** by **pruning the network topology** or using **lower-precision operations** (ranging from floating point down to 1-bit coding) while maintaining accuracy. Until recently, this was not a major concern for traditional cloud AI development environments such as TensorFlow, PyTorch, JAX, or Tinygrad. As a result, specialised environments have emerged to

optimise neural networks for embedded architectures, facilitating the transition to edge deployment. A notable example is the **Eclipse Aidge platform**[14], which aims to facilitate the **design and optimisation** of neural networks—including quantization and compression—for **efficient deployment on heterogeneous embedded hardware** with constrained power and memory resources.

Most of the time, the learning of DNNs is done in the **cloud**, after which the trained model is **fixed for inference on edge devices**. Similarly, foundational models and compact language models (SLMs) are undergoing a similar shift toward edge inference. However, for some applications or domains, being able to **update the model live** is a desired feature, for example to adapt to new data or changing conditions.

There are two main ways to evolve models after deployment. One is **federated learning**, where multiple edge devices collaborate on a shared learning task without centralising all the data. The other is **local learning directly on the edge device**, adapting the model to its specific context. In the latter case in particular, **the need for computing power and storage at the edge continues to increase and relies on efficient software support**.

It is important to note that this **ability to adapt models at the edge** can introduce security risks, such as interception or tampering. Mitigating these risks will require advances in both **algorithmic techniques and software frameworks** to ensure that AI deployed on edge devices remains secure and reliable.

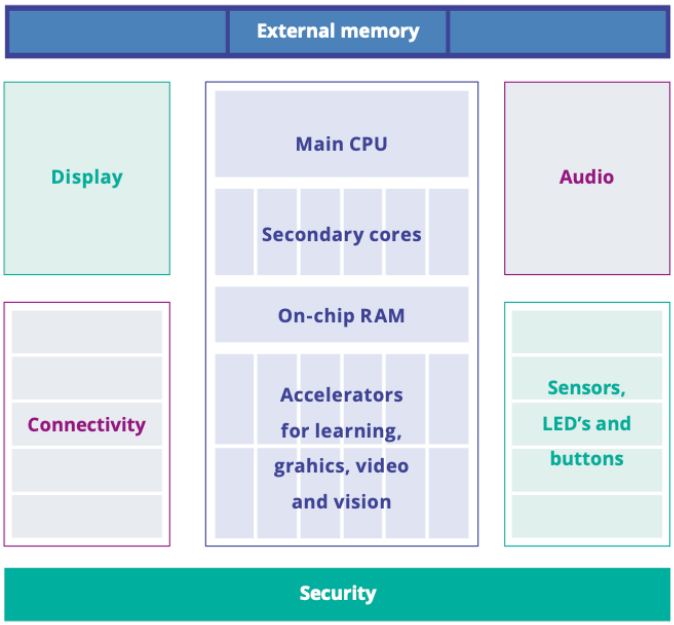

Figure 1.3.4 - Data analytics and Artificial Intelligence require dedicated embedded hardware architectures

[14] https://projects.eclipse.org/projects/technology.aidge

1.3.4.4.2 Vision and expected outcome

European semiconductor companies lead a consolidated market of microcontrollers and low-end microprocessors for embedded systems, but are increasing the performance of their hardware, mainly driven by the automotive market and the increasing demand for higher-performance AI for advanced driver-assistance systems (ADAS) and self-driving vehicles. With edge computing and embedded AI this trend has extended to other vertical domains that are key for Europe. European semiconductor companies are also moving towards greater heterogeneity by adding specialised accelerators. On top of this, Quality, Reliability, Safety and Security Chapter lists personalisation 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 programming environments, standards and libraries to support software developers. A good example here is the Open Neural Network Exchange (ONNX) format to represent machine learning models, which helps AI developers to move models between frameworks. Besides 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.

1.3.4.4.3 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 locally 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 system's own state.
  - Dynamic adaptation of systems when environment parameters and sensors like IoT devices are changing.

- Data streaming in constrained 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. pattern analysis, movement detection (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).

1.3.4.5 Major Challenge 5: Support for sustainability by embedded software

1.3.4.5.1 State of the art

The complete power demand in the whole ICT market currently accounts for 5% to 9% of the global power consumption[15]. 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. Partitioning hardware enables smart power-up/power-down strategies. Together with support through resource-aware algorithms, this could lead to significant energy savings. The same applies to software power and energy modelling and analysis: the first step towards reducing energy consumption 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-wide energy-conservation perspective 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 defective 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 the green computing movement, resource-aware computing and, more generally, 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 optimisation, the process scheduling optimisation or energy-efficient workload distribution, the management of HW and SW resources oriented to energy saving, the correct use of software abstraction, etc.

1.3.4.5.2 Vision and expected outcome

The concept of sustainability is based on three main pillars: ecological, economic and 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.

[15] https://www.enerdata.net/publications/executive-briefing/between-10-and-20-electricity-consumption-ict-sector-2030.html

To reach the sustainability goal, the embedded software design shall also focus on energy-efficient design methodologies and tools, energy efficient and sustainable techniques for embedded software and systems production and on the development of energy- and resource-aware applications and frameworks for embedded systems, edge computing, embedded intelligence and their applications.

It is evident that energy/power management has to be analysed with reference to the context, to the underlying hardware resources and the overall system functionalities. The coordinated and coordinated efforts of a system architect, hardware architect and software architect should help to 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 resources and their energy profile, 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 terms of their quality properties. Strategies must exist for HW/SW co-design and accelerators to enable such configurations, and the entire integrated development environment should facilitate a rational use of abstraction (abstraction simplifies software development but increases the energy consumption) and supports optimisation of HW and SW resource use from the energy perspective directly from the programming language and through the compiler, linker, assembler, etc. 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 also enable balancing mechanisms between local and remote computations to reduce communication and processing energy consumption.

Models (digital twins) should be aware of energy use, energy sources, HW and SW resources and their sustainability profile. An example of this in SoS is solar cells that give different amounts of energy depending on the time of day and weather conditions.

1.3.4.5.3 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 key embedded software application areas (e.g. IoT, Smart Industry, wearables, etc.).
- Management of computation power on embedded hardware:
    - Management of energy awareness of embedded hardware, embedded software with respect to, among other things, embedded high-performance computing (HPC).

- Composable efficient abstractions that drive sustainable solutions while optimising performance:
    - Enabling resource-aware computing.
    - 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 support the management of quality properties of software with the goal of reducing power consumption, as the major contributing factor to the Green Deal, enabling sustainability.

1.3.4.6 Major Challenge 6: Resilience, Dependability, Reliability and Trust

1.3.4.6.1 State of the art

Emerging challenges for resilience, dependability, reliability and trust in ECPS relate to (A) computing architectures, (B) hard-to-prove-correct algorithms, and (C) the dynamic environment in which ECPS exist. The first challenge is closely related to the end of Dennard scaling[16]: 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, industry has turned to stronger coupling between software and computing hardware, leading to heterogeneous architectures. The modern RISC-V ISA, for example, supports adding custom instructions for tighter HW/SW coupling. The motivations for this coupling are the effects of dark silicon[17] and better performance-to-power ratio of heterogeneous hardware with computing units specialised for specific tasks. Two 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[18]. In addition, new challenges related to verification and optimal usage of custom instructions and accelerators arise.

Challenge (ii) has become even more significant due to the rise of AI-generated code and ML-based functions that will run on ECPS. Advances in Generative-AI (cf. other major challenges) will lead to code generated and tested by AI with only a certain level of human inspection and understanding. While this will unlock smart, reliable systems that can adapt to changing environments in a short development time, proper functional and non-functional verification (e.g., towards achieved levels of resilience, security) is an open question.

Another 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

[16] John L. Hennessy and David A. Patterson. 2019. A new golden age for computer architecture. Commun. ACM 62, 2 (February 2019), 48–60. DOI: https://doi.org/10.1145/3282307

[17] Hadi Esmaeilzadeh, Emily Blem, Renee St. Amant, Karthikeyan Sankaralingam, and Doug Burger. 2011. Dark silicon and the end of multicore scaling. In Proceedings of the 38th annual international symposium on Computer architecture (ISCA '11). Association for Computing Machinery, New York, NY, USA, 365–376. DOI: https://doi.org/10.1145/2000064.2000108

[18] F. A. Bianchi, A. Margara and M. Pezzè, "A Survey of Recent Trends in Testing Concurrent Software Systems," in IEEE Transactions on Software Engineering, vol. 44, no. 8, pp. 747-783, 1 Aug. 2018, doi: 10.1109/TSE.2017.2707089.

time, and embedding resilience, 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 of 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[19] or reliance on third-party software modules; and (iii) hardware-related security issues[20]. 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[21], supported by appropriate engineering processes including verification (see Chapters 2.3 and 2.4). Once security is established, safety and resilience of systems can be aimed for.

1.3.4.6.2 Vision and expected outcome

European industry today relies on developed frameworks that facilitate production of highly complex embedded systems (the automotive domain, for example, has established AUTOSAR and is now transitioning towards open abstraction and middleware layers for SDV).

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 customisable computing architectures 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 dependability, providing means for developing of resilient, distributed systems, including verification and validation. 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 or hybrid computing platforms, which promise high performance with optimised power consumption. Recent developments in programming languages - such as Rust - look promising, as they aim to solve some of these inherent problems by default, based on available programming language constructs, however, the advent of Generative-AI might lead to a system development less tied to certain programming languages.

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 create models, 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 achieve this is the use of digital twins. Digital twins are particularly suitable for the

[19] V. D'Silva, M. Payer and D. Song, "The Correctness-Security Gap in Compiler Optimization," 2015 IEEE Security and Privacy Workshops, 2015, pp. 73-87, doi: 10.1109/SPW.2015.33.
[20] Moritz Lipp, Vedad Hadžić, Michael Schwarz, Arthur Perais, Clémentine Maurice, and Daniel Gruss. 2020. Take A Way: Exploring the Security Implications of AMD's Cache Way Predictors. In Proceedings of the 15th ACM Asia Conference on Computer and Communications Security (ASIA CCS '20). Association for Computing Machinery, New York, NY, USA, 813–825. DOI: https://doi.org/10.1145/3320269.3384746
[21] Dalia Sobhy, Leandro Minku, Rami Bahsoon, Tao Chen, Rick Kazman, Run-time evaluation of architectures: A case study of diversification in IoT, Journal of Systems and Software, Volume 159, 2020, 110428, ISSN 0164-1212, https://doi.org/10.1016/j.jss.2019.110428.

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 models, 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.

1.3.4.6.3 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 collaborative 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.

New concepts for programming languages, such as Rust, by their default design resolve some of the listed issues in developing computing architectures. For example, one of the main goals of Rust is handling concurrent and parallel programming in a safe and efficient way[22]. New concepts in the area of programming languages need to balance between several factors. On the one hand, new programming languages need to offer higher productivity to engineers. Programming languages need to enable more efficient collaboration between engineers by being more suitable to higher level architectural thinking that prioritise decoupled development of individual software components. Furthermore, traditional programming languages, such as C and C++, are challenging for static analysis due to undecidability of their statements[23] and in general have a huge test space making them susceptible to security issues. Finally, new languages need to solve by design complex problems in programming, such as concurrency and parallelism. On the other hand, it is necessary to minimise overhead of abstractions in new programming languages (performance[24] and energy[25] [26] overhead). Besides creating such languages or extending the existing ones with new features, it is still necessary to provide methodologies that will guide industry to migrate their codebases to new programming

[22] https://doc.rust-lang.org/book/ch16-00-concurrency.html

[23] Michael Hind. 2001. Pointer analysis: haven't we solved this problem yet? In Proceedings of the 2001 ACM SIGPLAN-SIGSOFT workshop on Program analysis for software tools and engineering (PASTE '01). Association for Computing Machinery, New York, NY, USA, 54–61. https://doi.org/10.1145/379605.379665

[24] There's plenty of room at the Top: What will drive computer performance after Moore's law? E. Leiserson et al., Science 05 Jun 2020: Vol. 368, Issue 6495, DOI: 10.1126/science.aam9744

[25] Rui Pereira, Marco Couto, Francisco Ribeiro, Rui Rua, Jácome Cunha, João Paulo Fernandes, and João Saraiva. 2017. Energy efficiency across programming languages: how do energy, time, and memory relate? In Proceedings of the 10th ACM SIGPLAN International Conference on Software Language Engineering (SLE 2017). Association for Computing Machinery, New York, NY, USA, 256–267. https://doi.org/10.1145/3136014.3136031

[26] Rui Pereira, Marco Couto, Francisco Ribeiro, Rui Rua, Jácome Cunha, João Paulo Fernandes, João Saraiva, Ranking programming languages by energy efficiency, Science of Computer Programming, Volume 205, 2021

constructs, or at least ensure co-existence and interaction between new and old code bases. The introduction of AI into software engineering opens the opportunity for programming languages that will facilitate a new AI-assisted[27] software development approach. That means programming languages that engineers can use to easily and as deterministically as possible express their intentions, while those languages are suitable for AI to enable code generation and automation of validation, verification, and testing activities. The ultimate goal for such programming languages would be to facilitate, with the assistance from AI, analysis of quality properties of whole software stacks (e.g., WCET analysis, safety analysis[28]).

The next focus area is testing resilience of systems, e.g., 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, including heterogeneous systems.
- Verification and validation of ML models as well as AI-generated code
- Resilience and 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.

1.3.4.7 Major Challenge 7: Hardware virtualisation for efficient SW engineering

1.3.4.7.1 State of the art

Hardware virtualisation provides abstraction from physical hardware, decoupling software engineering lifecycles from it. Implementations include hypervisors such as VMware and KVM, high-assurance separation kernels such as PikeOS, or containerisation with the host 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.

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[27] Russo, Daniel & Baltes, Sebastian & van Berkel, Niels & Avgeriou, Paris & Calefato, Fabio & Cabrero-Daniel, Beatriz & Catolino, Gemma & Cito, Jürgen & Ernst, Neil & Fritz, Thomas & Hata, Hideaki & Holmes, Reid & Izadi, Maliheh & Khomh, Foutse & Kjærgaard, Mikkel & Liebel, Grischa & Lafuente, Alberto & Lambiase, Stefano & Maalej, Walid & Vasilescu, Bogdan. (2024). Generative AI in Software Engineering Must Be Human-Centered: The Copenhagen Manifesto. Journal of Systems and Software. 216. 112115. 10.1016/j.jss.2024.112115.

[28] https://hightec-rt.com/rust

1.3.4.7.2 Vision and expected outcome

- **Standardised Abstraction Models** for hardware components to enable cross-platform compatibility, fostering ease of development and integration.
- **Timing Models**: Developing reliable 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.
- Use of certifiable high assurance separation kernels on traditional embedded systems as well as cloud/edge systems
- 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.

1.3.4.7.3 Key focus areas

To realise 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.

To cover these aspects, it is necessary to understand what they aim to achieve in software system engineering terms. To facilitate software development in virtual environments, the most common requirement in industry is to enable functional testing on virtual hardware. Such testing must provide fast execution feedback suitable for continuous engineering. Techniques already exist that try to achieve this[29]. What we also need is greater integration of such virtual platforms in common engineering development methodologies (e.g., Agile). To achieve other goals from the list above (e.g., performance and temporal properties evaluation), it is necessary to have more complex, detailed models of virtual hardware. Examples of such models currently exist[30], but can be extremely slow to execute. Besides integration of virtual platforms into existing methodologies and making execution of these models faster, it is necessary to observe the challenge around this effort in a wider scope. Development of virtual prototypes is not easy and often requires significant effort and investment. Moreover, management of platforms on which these prototypes execute is also a complex task (e.g. using BlueChi[31]). Finally, management of models, their variations, and integration activities with software repositories and test suites is challenging and time consuming. Therefore, we need approaches that facilitate faster development of virtual platforms, infrastructure around using them in software engineering, and management of both the models and the infrastructure. With these

[29] https://newsroom.arm.com/blog/isa-parity
[30] https://www.gem5.org/
[31] https://projects.eclipse.org/projects/automotive.bluechi

efforts, we hope to migrate a larger part of the development of embedded software systems to the cloud, facilitating collaboration and enabling higher engineering efficiency.

1.3.4.8 Major Challenge 8: AI in Embedded Systems Engineering and Operations

1.3.4.8.1 State of the art

There are several ways in which AI, and especially GenAI, can complement software engineering and help engineers handle challenges across software development life cycle (SDLC)[32]. However, engineering software is only part of the problem in embedded systems. Managing software execution and ensuring that it meets quality requirements is a system-level problem. This is especially true for challenges related to concurrency and scheduling. For example, it has been demonstrated that "the worst-case-execution-time of even the simplest single-path program running alone on a CPU does not stay the same when other programs run on other CPUs"[33]. This challenge only gets worse as the number of programs executing concurrently increases. For example, "Cache sharing can cause unacceptably high interference; the task's execution time is increased by 103 times due to co-runners on different cores"[34]. Furthermore, it has been proven that no optimal online scheduler can exist for a set of jobs with two or more distinct deadlines on any multiprocessor system[35]. Finally, the performance of embedded software is heavily influenced by system decisions, such as memory management and partitioning of software into parts that execute concurrently (e.g., when only 1% of the time is serial, the speedup for a 64-processor configuration is about 35)[36].

Therefore, from the system point of view, it is necessary to understand:

- How will the adoption of AI in software engineering influence the quality of the software developed?
- Can AI help to solve challenges in managing runtime execution of software in embedded systems (e.g., concurrency, scheduling, memory management)?
- How can we ensure scalable and engineering-friendly training, retraining and deployment of AI models?

1.3.4.8.2 Vision and expected outcome

The view that embedded systems have limited resources is slowly fading. However, when it comes to computing AI workloads, existing computing power is still not sufficient. Besides the lack of hardware support for AI agents, we need to address requirements around communication between agentic AIs, such as throughput and bandwidth. Therefore, it is necessary to answer questions around what

[32] U. K. Durrani, M. Akpinar, M. Fatih Adak, A. Talha Kabakus, M. Maruf Öztürk and M. Saleh, "A Decade of Progress: A Systematic Literature Review on the Integration of AI in Software Engineering Phases and Activities (2013-2023)," in IEEE Access, vol. 12, pp. 171185-171204, 2024, doi: 10.1109/ACCESS.2024.3488904.
[33] A glimpse of real-time systems theory and practice in the wake of multicore processors and mixed-criticality, Tullio Vardanega, University of Padua, Italy, ACACES 2020, HiPEAC
[34] Yun, Heechul. "Evaluating the Isolation Effect of Cache Partitioning on COTS Multicore Platforms." (2015).
[35] Kwang S. Hong and Joseph Y.-T. Leung. 1992. On-Line Scheduling of Real-Time Tasks. IEEE Trans. Comput. 41, 10 (October 1992), 1326–1331. https://doi.org/10.1109/12.166609
[36] Effect of Amdahl's law on speedup as a fraction of clock cycle time in serial mode, John L. Hennessy and David A. Patterson. 2019. A new golden age for computer architecture. Commun. ACM 62, 2 (February 2019), 48–60. DOI:https://doi.org/10.1145/3282307

hardware (and software) requirements are needed for embedded devices to run AI agents efficiently and effectively.

We have solved complex problems in embedded systems, such as scheduling, through algorithms that are designed to be generally applicable while focusing on ensuring that the average case works well. Other problems we have no choice but to solve by accepting overhead (e.g., meeting real-time requirements). One reason for such solutions is that we struggle to describe complex problems with many variables using classical algorithms.

With AI, we are able to generate non-linear functions that are able to optimise solutions taking many parameters into account. As such, AI can generate solutions that go beyond what classical algorithms or humans can manage in terms of complexity. We can divide these decisions into two levels:

- OS level and lower abstraction levels closer to hardware
- Above application level, moving in the direction of business goals

When it comes to decisions on the lower level, such as scheduling and deployment, AI can create complex solutions that take into account multiple dependencies, including the context in which the software runs. However, these decisions must be made with low latency so as not to contribute to existing real-time deadlines. Furthermore, the overhead and computation resources needed for AI to make such decisions must not outweigh the benefits gained from such approaches.

With agentic AI, we have a technology that can observe a large number of parameters and the system holistically to decide how to optimise communication, privacy, autonomy and interdependencies to achieve overall business goals on a dedicated platform. For example, agentic AI can understand when it has all the resources to autonomously make a decision about system management to achieve system, user, or business goals, or when it requires cooperation with other entities (connectivity, bandwidth, privacy, security). This was not previously possible with non-AI approaches.

Management and execution of AI models remain a challenge. There are still significant challenges around gathering data (especially for legacy embedded systems). Furthermore, we need more efficient and scalable techniques and tools for optimisation of AI models. Finally, it is necessary to enable seamless deployment on a variety of hardware platforms. Solving these challenges requires updates to development methodologies and toolchains, with concepts that enable optimal use of the underlying hardware. Some of these challenges are addressed by project "Independent deep learning platform for embedded AI" (Eclipse Aidge).

1.3.4.8.3 Key focus areas

To facilitate the adoption of AI in embedded systems and their SDLC, researchers need to focus on:

- Identification of actions and challenges in SDLC that are suitable for assistance with AI.
- Changes that AI will introduce in software methodologies for embedded systems in the presence of AI.
- Integration of AI agents to support a wide range of software-related activities, such as compliance.
- Empirical evidence of short-term (e.g., programming productivity) and long-term (e.g., influence on software architecture) benefits and challenges of adopting AI in the SDLC.

- Development and deployment of AI algorithms for scheduling and managing the execution of embedded software.
- Tools and methodologies for gathering data necessary for AI approaches, especially in legacy embedded systems.
- Management of AI models, aligned with the principles of CI/CD and continuous engineering.
- Efficient and effective deployment of AI-enabled functionalities to the variety of hardware platforms.

To cover these topics, it is necessary to provide not only concepts and tools but also empirical data on the long-term and short-term benefits of AI in the SDLC and in the management of software in embedded software. Unfortunately, there is a lot of unfounded hype suggesting the use of AI will solve all problems. The reality is that AI-enabled tools and approaches can be incredibly efficient when used in the proper context and by people with adequate skills. Therefore, it is paramount to collect empirical data about the influence of AI on software engineering. Some of the benefits and challenges can be observed immediately (e.g., faster coding, time to process queries). However, other potential challenges can only be understood over time. For example, it will be very important to understand how the adoption of AI influences system understanding, knowledge transfer between engineers, and even team organisation. Embedded systems are critical to the functioning of our digital society. Disruptions to the functioning of these systems can have far-reaching consequences. Hence, before making any radical decisions, it is necessary for companies to have proper data about potential consequences.

AI is a highly disruptive technology, and its adoption changes both the scope of challenges that engineers have to deal with and the focus of those challenges. Therefore, in this context, it is necessary to understand how development methodologies will change and what new trade-offs architects have to consider when adopting AI into their systems (e.g., freedom from interference vs. optimal AI-based scheduling).

Finally, it is important to understand that AI is fully dependent on the quality of the supplied data. Therefore, it is necessary to ensure that we prevent bias in our AI systems. Furthermore, since embedded systems can be safety-critical, it is absolutely necessary to create approaches that provide reassurance and guardrails for the deployment and inference of AI models in critical environments.

1.3.5 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 (2027-2031)	MEDIUM TERM (2032-2036)	LONG TERM (2037 and beyond)
Major Challenge 1: 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: Constrained environments	Resource planning and scheduling 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 Technology for safe and dependable software ecosystems	Interface management enabling systems to become part of SoS	Develop new software architectures for edge computing
	Topic 1.5: Software engineering tools	Co-simulation platforms	Middleware controlling dynamically embedded (mobile) hardware solutions Compilers and link to new hardware	Programming languages for developing large-scale applications for embedded SoS
Major Challenge 2: Continuous integration and deployment	Topic 2.1: Continuous integration	DevOps modelling Virtualisation	Simulation on a virtual platform	Digital twin 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: Life-cycle management of embedded software	Topic 3.1: Rejuvenation of existing systems	Software legacy and software rejuvenation Design for rejuvenating systems in a later phase	End-of-life and evolving off-the-shelf/open- source solutions	The cloud-for-edge continuum - “Write once, run anywhere” on this computing continuum Composability, properties contracts and orchestration systems 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 tracking	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 Autonomous processes (IoT & edge embedded HW/SW co-design)
Major Challenge 4: Embedded Artificial Intelligence	Topic 4.1: Federated learning	Create federated learning at the edge in heterogeneous distributed systems Embedded intelligence	Federated intelligence at the edge	Safe, trustworthy & explainable AI

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027-2031)	MEDIUM TERM (2032-2036)	LONG TERM (2037 and beyond)
	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 (Edge-AI, ...)	Support dynamic adaption of systems
	Topic 4.3: Data streaming in constrained 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 speed up analysis and learning	Actual usage- based learning applied for accelerators and hardware/software co-design	Use of AI in autonomous systems
Major Challenge 5: 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 scalable 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: Resilience, Dependability, Reliability and Trust	Topic 6.1: Reliability of software and new hardware	Code coverage of reliability tooling and porting Simulation- and mock-up- based approaches for handling concurrency	Embed reliability on software architecture level	Use of quantum computing IoT digital twin simulation Validation and verification through simulation- and mock-up-based approaches for handling concurrency
	Topic 6.2: Robustness (trustworthy, secure, safe, privacy- aware, resilient)	Trustworthy, secure, safe, privacy-aware Testing self-adapting systems using simulation	Define a maturity model for robustness of embedded software and beyond	Resilience and dependability guarantees for AI-based (even agentic) systems
	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	Security guarantees for agentic AI systems
Major Challenge 7: Hardware virtualisation 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.)

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027-2031)	MEDIUM TERM (2032-2036)	LONG TERM (2037 and beyond)
	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 & analysable 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)
Major Challenge 8: AI in Embedded Systems Engineering and Operations	Topic 8.1: Use agentic AI to assist with engineering embedded systems	AI-assisted engineering tasks to improve software quality and reduce costs: including code generation and refactoring, system modelling and simulation, smart debugging and anomaly detection and data driven requirements engineering,	• Generative hardware–software co-design • Collaborative design agents • Autonomous verification and validation • AI-assisted standards compliance and certification • Semantic design assistants with domain knowledge	• Self-verifying systems • Closed-loop self-optimizing design environments
	Topic 8.2: Use AI to optimise runtime of embedded systems	• Edge-level orchestration of AI tasks • On-device reasoning and decision loops	• Federated agent collaboration frameworks • Adaptive runtime environments for agents	• Emergent collective intelligence • Self-healing and ethical governance mechanisms • Convergence of symbolic reasoning and foundation models

1.4



Foundational Technology Layers

SYSTEM OF SYSTEMS

1.4 SYSTEM OF SYSTEMS

1.4.1 Scope

The System of Systems (SoS) technology layer represents the upper layer of the 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 in a System of Systems (SoS) is an embedded hardware–software unit built to perform a specific function. 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 of 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 hardware-software technologies, as well as the rising demand from 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 behavior; and (v) evolutionary development processes. The introduction of hardware chiplets creates the possibility that one or more systems can reside within a chiplet, which makes geographical distribution less generally applicable today.

The operational and managerial independence result in SoS difficulties regarding composability and the integration of systems that were not designed together. SoS engineering aims to develop architectures, methods and tools that can address such difficulties. Model-based techniques for the design of an SoS can be used in a similar way to those for regular systems; however, the systems being integrated rely on different models and paradigms. Further methodologies and tools are needed to address this systematically.

New systems must be designed such that they are prepared for SoS integration and composability. Here, model-based techniques can be useful in applying AI techniques to learn how systems should work together to increase the semantic level of interoperability. Research should address the development of methodologies, tools, data models and APIs for SoS that complement current methodologies for system design. Focus should be on SoS-specific aspects such as the mentioned managerial and operational independence and the new development of chiplet technologies. Research should also provide support for SoS dynamics, evolution and life cycle. Advanced development and life cycle use will also include SoS business models and suitable technology for machine execution of such models.

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. An 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 operationally and managerially autonomous and/or independent,

[1] Architecting Principles for Systems-of-Systems, Mark W. Maier, Systems Engineering journal, John Wiley &Sons 1998

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 increasing dynamism and variability along its 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.

Like a nervous system – i.e., partially centralized, distributed and peripheral – a software integration infrastructure is a key element of a SoS. The nervous system has an architecture, and so should any SoS. The most common architectural approach in SoS is based on SOA (Service-Oriented Architecture) and microservices from edge to cloud. Splitting such an architecture into three parts - Infrastructure, Integration Platform and Solution Implementation - provides a logical base for what can be shared and what will be company-specific among the involved stakeholders, as shown in Figure 1.4.1.

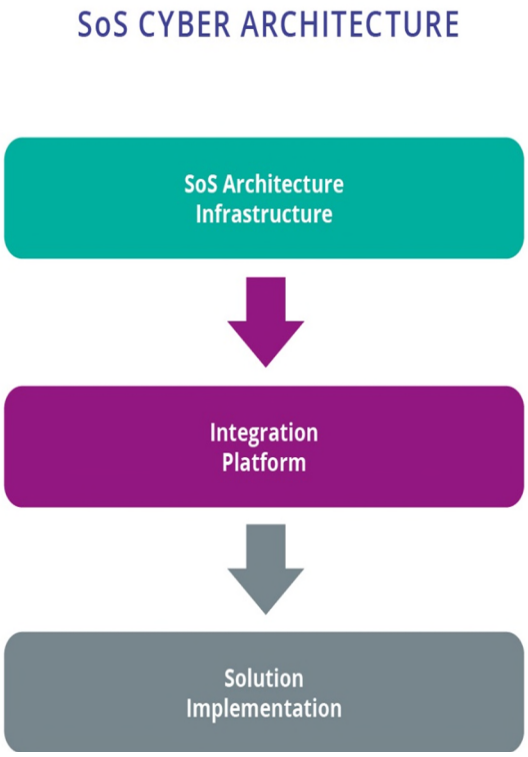

Figure 1.4.1. An SoS cyber architecture based on SOA provides an infrastructure supporting fundamental service-oriented properties such as look-up, late binding and loose coupling plus a number of support functionalities to build working solutions.

The SOA architecture infrastructure will provide, for example:

- Fundamental SOA property support: Look-up, Late binding and Loose coupling
- Service orchestration
- Security and safety support
- Interoperability support
- System of Systems integration support
- Basic engineering and operations support
- Model-based engineering support

Chiplet development calls for new approaches to SOA integration with chiplet-system hardware. An emerging view is that chiplet integration can also be viewed as a SoS.

Using the SoS infrastructure, SoS platforms are created by vendors and larger companies. SoS platforms will be used for solution-specific implementations, engineering, deployment and operation.

To create added value, an SoS needs 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 against its misuse. Moreover, it is not enough to ensure that each of the constituent systems is secure, safe and stable in the pre-deployment phase, but also that the evolved/composed/integrated SoS, whose exact composition may not be known in advance, is secure, safe and stable. Dynamic adaptation to, e.g., security, safety and stability requirements, as well as risk 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 methodologies and tools for risk and vulnerability assessment and threat modeling are needed. Artificial intelligence, machine learning and ontology- and semantics-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. Ontologies/semantics and knowledge graphs provide information enabling human- or machine-supported reasoning for various sorts of functional optimization and adaptations. Clearly, non-functional properties can be addressed similarly.

SoS will be deployed across computing infrastructure from the cloud to the very deep edge, enabling E2CCC. This calls for engineering and management capabilities supporting the edge-to-cloud compute continuum paradigm throughout evolution and the lifecycle. This will require additional SOA architecture infrastructure capabilities:

- Compute orchestration
- Deployment orchestration
- Network orchestration

It is unrealistic to imagine that a single SoS infrastructure 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-sectoral requirements such as security, safety, evolution, maintenance and trustworthiness. For example, security and safety certification issues at the component, system and SoS levels should be properly addressed with the aim of effectively mitigating risks/threats in competitive scenarios, while also considering the EU Cybersecurity Certification framework.

Recent advancements in interoperability, particularly information interoperability based on semantic integration, translators and AI approaches, open up advanced AI usage in complex SoS solutions such as complex products, production, and distributed infrastructures.

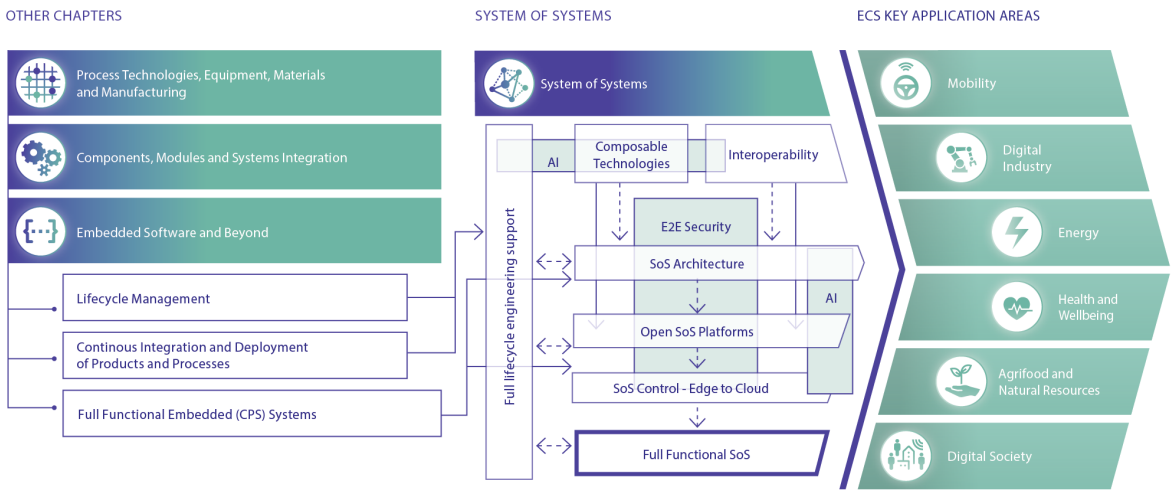

Figure 1.4.2 - Structure: System of Systems

1.4.2 Application breakthroughs

Improvements in SoS technology will have an impact on all ECS application areas. They will enable or support faster translation of ideas into economically viable solutions and might open new markets by further upscaling.

Examples of health and well-being application breakthroughs supported by SoS are:

- Interoperability of health information.
- 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.
- Information security technology for interoperability between secure hardware and software components.
- Improved integration and analysis of multimodal data.
- Integration platforms for embedded ultrasound, low-power edge computing, AI and digital health.

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

- Software-defined vehicle product engineering and life cycle evolution
- Increased road safety through V2V information sharing
- Improving the competitiveness of the European industrial mobility digitalization 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:

- Management of multi-domain coupling (electricity, heating / cooling, mobility) for the future all-electric society.
- Supporting grid stabilisation through intermediate storage of renewable energy, peak control or viability management to increase energy flexibility.
- Energy supply infrastructure for e-mobility, digital life, 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).
- 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.).
- Addressing 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 recycling capabilities.
- Aligning with standardization of different 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.
- The 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.
- Semantically annotated data models enabling the use of advanced AI/ML technology for, e.g., intelligent decision-making, energy efficiency and product quality.
- Remotely piloted autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, to improve efficiency.
- Smart systems based on portable real-time pest and disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced).
- IoT devices specialising in pest 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.
- IoT configuration and orchestration management that allows for the (semi)autonomous deployment and operation of a very large number of devices.

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.
- By introducing 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.
- Remote engineering and operations, tele-presence: operating or assisting in operations of industrial systems from remote sites.
- Local and global services: organizing services locally close to customers and centrally at vendors' sites.
- Edge/cloud solutions: implementing distributed service applications on effective edge-cloud systems.
- Moving from SoS generations to evolvable SoS, extending solution life cycles.

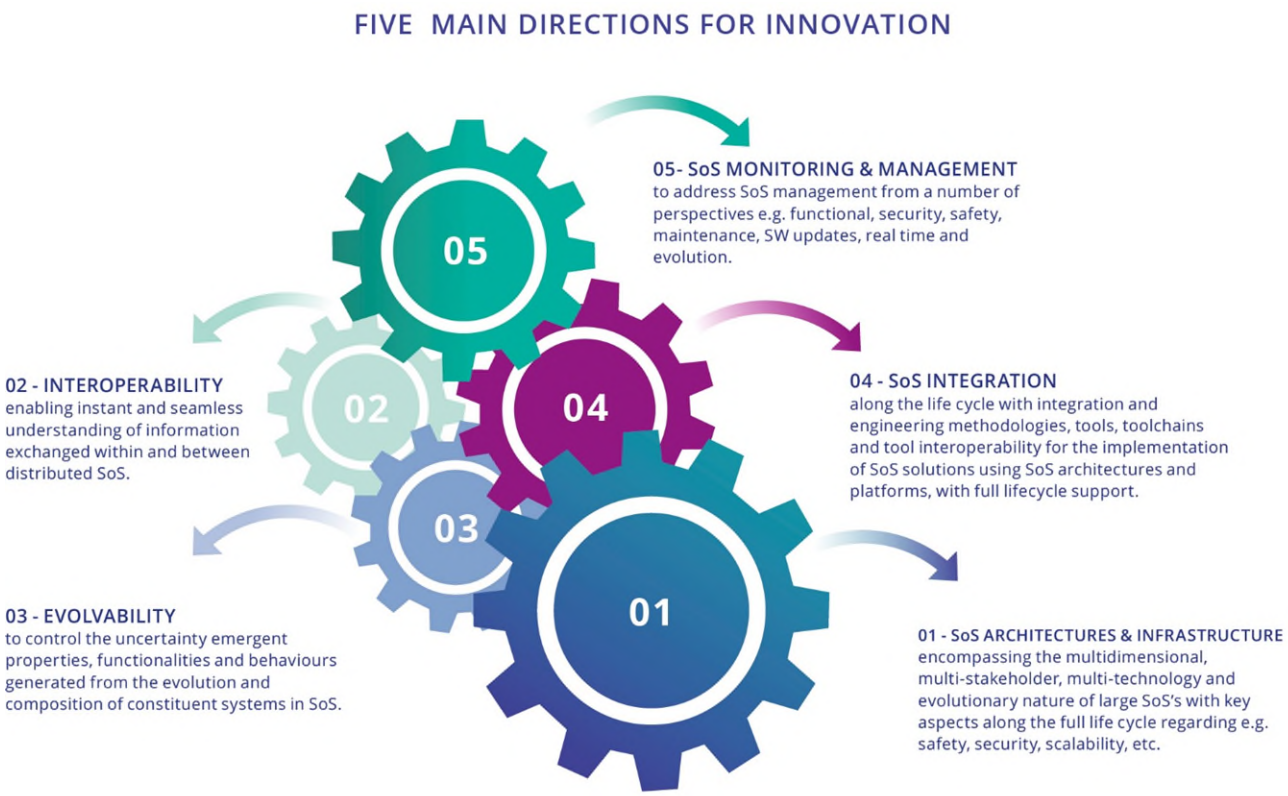

Figure 1.4.3 - Five Main Directions of Innovation (source: Eurotech).

1.4.3 Major Challenges

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

- **Major Challenge 1**: Open SoS architecture and infrastructure.
- **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**: SoS monitoring and management.

1.4.3.1 Major Challenge 1: Open SoS architecture and infrastructure

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

1.4.3.1.1. State of the art

SoS requires an architecture and available infrastructure that encompass 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 subsystems, stakeholders, technologies and evolutionary nature.

The current industrial state of the art consists of a couple of major commercial and proprietary information/communications/control/technology platforms offering industrial solutions for complex systems from companies such as Schneider Electric[2], Siemens[3], Bosch[4], Emerson[5], ABB[6], Advantech[7], 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. It is also clear that the fundamental computer science basis for these products is quite old.

The current industrial state-of-the-art SoSs 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 with cloud-based solutions. For emerging SoS application areas such as autonomous driving, smart energy grid, smart agriculture and smart cities, the SoS technology is still in an emerging phase.

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[2] https://ecostruxure.schneider-electric.com/
[3] https://www.plm.automation.siemens.com/ global/en/webinar/iiot-the-next-big-digital- disruption/31921
[4] https://blog.bosch-si.com/bosch-iot-suite/
[5] https://www.emerson.com/de-de/ automation/operations-business- management/plantweb-digital-ecosystem
[6] https://ability.abb.com/
[7] https://www.advantech.com/resources/ news/advantech-launches-30-iiot-solutions- through-the-co-creation-model-and-the- wise-paas-platform-and-announces-a- large-scale-showcase-in-november

To take the next step, Europe and other regions have invested in a number of open SoS integration frameworks and platforms. The approach is moving from classical Operational Technology (OT) towards extensive use of IT technology from cloud to edge. Europe has been building from the current edge towards the cloud while competing regions have taken the cloud and IT technology as the starting point for distributed automation. [8]A summary of such platforms and frameworks is shown in Figure 1.4.4.

In general, the spectrum of systems making up an SoS includes both systems in the cloud, where security can be closely monitored as, e.g., in 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).

Most platform initiatives are based on Service-Oriented Architectures (SoA) and microservices, which points to 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 the IMC-AESOP approach[9], Eclipse Arrowhead[10], Eclipse Basyx[11], FiWare[12], PERFoRM30[13] provide 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 include, e.g., DIN Specification 91345[14] "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. To further support E2CCC, compute, deployment and network orchestration are important. Here open architectures and[15] reference implementations such as ColonyOS and OpenSlice[16] are important emerging technologies beyond, e.g., Kubernetes[17].

Europe has strongly invested in large projects that have delivered open platforms for the implementation of solutions based on SoS platforms[18]. 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.

[8] Industrial Frameworks for Internet of Things: A Survey, IEEE System journal 2020
[9] https://link.springer.com/ book/10.1007/978-3-319-05624-1
[10] https://www.taylorfrancis.com/ books/e/9781315367897
[11] https://www.eclipse.org/basyx/
[12] https://www.fiware.org/
[13] https://www.taylorfrancis.com/ books/e/9780429263316
[14] https://www.en-standard.eu/din-spec-91345-reference-architecture-model-industrie-4-0-rami4-0/
[15] ColonyOS https://colonyos.io
[16] OpenSlice https://osl.etsi.org
[17] Kubernetes https://kubernetes.io
[18] From Internet of Things to System of Systems – Market analysis, achievements, positioning and future vision of the ECS community on IoT and SoS, P Azzoni, Artemis 2020.

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 (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[19]

For cross-domain requirements on, e.g., security, safety and 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 that are not part of the SoS, but also to 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 an SoS is determined by the system with the lowest security level, and by the link with the lowest security level between systems

[19] Industrial Frameworks for Internet of Things: A Survey, C. Paniagua and J. Delsing, in IEEE Systems Journal, vol. 15, no. 1, pp. 1149-1159, March 2021, doi: 10.1109/JSYST.2020.2993323.,

("weakest link in the chain"). Thus, requirements such as 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 an 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. Segmentation of an SoS is thus of great importance both for architecture and for actual implementation, maintenance and lifecycle updates.

A growing concern is the inherent stability of SoS from a local to a global perspective. A key question is: how to engineer for SoS stability along the life cycle? Systems must not only defend against and monitor possible attacks, but also provide measures to ensure that SoS evolution will preserve local or global SoS stability.

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

1.4.3.1.2 Vision and expected outcome

This Major Challenge is expected to lead to a set of EU-strategic open SoS architectures and infrastructures. From such infrastructures, vendor and large-company platforms can be devised, capable of supporting a wide range of solutions in diverse application fields covering the ECS supply chain and supporting efficient life cycle management.

This requires new and improved infrastructure technologies comprising:

- Robust design- and run-time infrastructure enabling integration and orchestration of functionalities from edge to cloud, E2CCC.
- Infrastructure support for multi-level security, security management, safety, safety management, scalability, engineering efficiency, real-time performance, closed-loop and digital control, QoS, distributed intelligence that is energy-aware and event-driven, enabling scalable deployment of energy-autonomous sensing nodes and neuromorphic processing across large-scale infrastructures**.**
- Autonomous information and connectivity interoperability addressing both OT and IT technologies.
- Support for autonomous operation, resilience, failover and mitigation management.
- Enabling SoS flexibility.
- Engineering support through model-based engineering and associated domain-specific languages (cf. 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 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 that 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 often interlinked extra-functional requirements that play 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 numerous 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,
- Autonomous interoperability -- seamless integration of data models enabling scalable exchange and machine understanding of information
- Edge to Cloud Compute Continuum, E2CCC
- Engineering tools and procedures,
- Energy consumption,
- Unified environmental data model,
- Environmental footprint optimisation,
- Resilience.

1.4.3.1.3 Key focus areas

The key focus is how SoS architectures and their open infrastructure 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:

- Robust SoS infrastructure capable of supporting a wide range of solutions in diverse application fields from edge to cloud,
- SoS infrastructure and associated engineering tools and toolchains that support the complete engineering processes in both design- and run-time, including SoS critical aspects such as information interoperability, security, safety and risk mitigation,
- Suitable and adaptable engineering processes, with associated training material for solution engineering.
- Methods for the handling of (often wide-spread) legacy elements, e.g. as black box models.

1.4.3.2 Major Challenge 2: SoS interoperability

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

1.4.3.2.1 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 widespread industrial solution to this problem. Academia and industry are experimenting with approaches based on, for example, ontologies[20], machine learning[21], model-based engineering and open semantic frameworks[22]. Even if no clear winning approach can be identified based on current research results, growing interest can be noted in, e.g., ontology, data and model-driven approaches. Automating considerable parts of interoperability engineering (design-time and run-time) will improve SoS operational quality and will be very cost-efficient. Recent developments in semantically based data model integration show very promising results and growing industrial interest. It is clear that semantically annotated data will help AI models to produce more accurate results, which will enhance the value of AI usage.

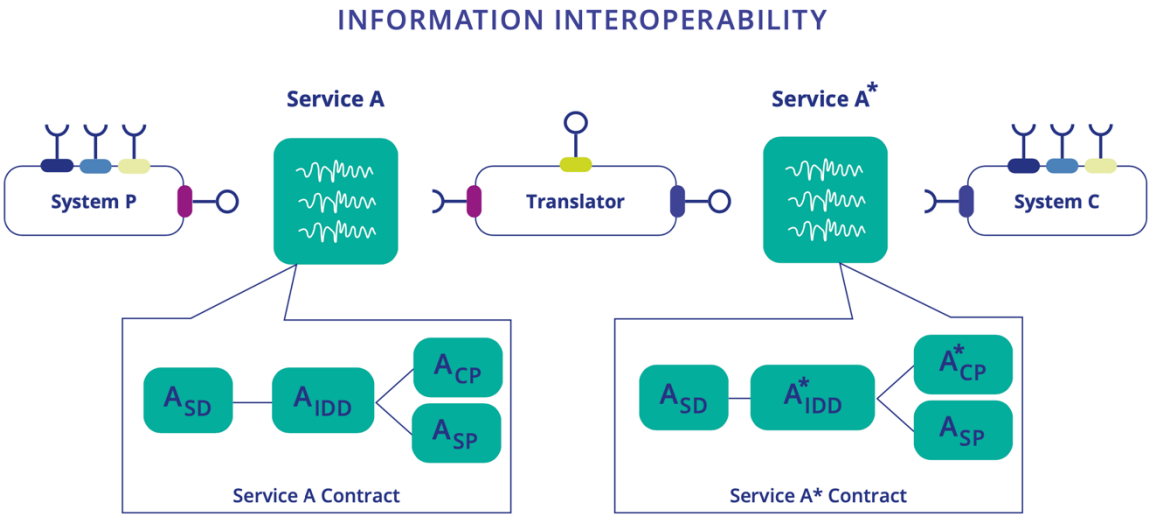

Figure 1.4.5 - Information interoperability between two service providers can be addressed by means of translators. The design of such translators for the payload information is currently necessary for every situation where interoperability is requested.

[20] Extended semantic annotations for generating translators in the arrowhead framework, F Moutinho, L Paiva, J Köpke, P Maló - IEEE Transactions on Industrial Informatics, 2017

[21] Interoperability and machine-to-machine translation model with mappings to machine learning tasks, Jacob Nilsson, Fredrik Sandin and Jerker Delsing, IEEE INDIN 2019

[22] An open semantic framework for the industrial Internet of Things, S Mayer, J Hodges, D Yu, M Kritzler, F Michahelles - IEEE Intelligent Systems, 2017

1.4.3.2.2 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[23]). To enable the cost- and time-efficient engineering of solution integration and extension, updates and upgrades over the lifecycle are crucial. Therefore, SoS integration platforms have to provide mechanisms for dynamic and instant information translation across the ontologies and semantics used by the individual constituent systems of the SoS.

1.4.3.2.3 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 and integration between standardised data models (e.g. ISO 10303[24], ISO 15926[25], BIM[26]).
- Translation and integration between different implementations of standardised data models.
- Automated data model translation and integration.
- Autonomous data model translation and integration.
- 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 and integration engineering, e.g., AI-driven, model-based code generation.

1.4.3.3 Major Challenge 3: Evolvability of SoS composed of embedded and cyber-physical systems

The intrinsic nature of SoS 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). An 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 governed, with monitoring and management are key ingredients. Because the results of the composition/evolution could be uncertain and unstable, SoS architectures and platforms, both 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, stability, functionalities and behaviours.

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[23] H. Derhamy, J. Eliasson and J. Delsing, "IoT Interoperability—On-Demand and Low Latency Transparent Multiprotocol Translator," in *IEEE Internet of Things Journal*, vol. 4, no. 5, pp. 1754-1763, Oct. 2017, doi: 10.1109/JIOT.2017.2697718.

[24] https://www.iso.org/standard/66654.html

[25] https://15926.org/home/

[26] https://en.wikipedia.org/wiki/Building_information_modeling

1.4.3.3.1 State of the art

Evolvability and composability are multi-dimensional aspects of SoS evolution that affect SoS 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 an SoS (see Maier, 1998[27]). Vertical (hierarchical) composability provides the most common way to build an 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[28], for an extensive report on trustworthy composable architectures).

In the hierarchical structure of an 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[29]).

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 operation of the SoS, to address the dynamic nature of SoS over time (run-time composability associated with evolutionary development and potential emergent properties, behaviours, and functionalities).

A rising question for evolving large and complex SoS is stability, locally and globally. Technology to provide SoS stability will be increasingly important as our SoSs grow in size.

1.4.3.3.2 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, stability, etc.), and the functionalities and behaviors 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 hindering the market uptake and diffusion of SoS.

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[27] Architecting Principles for Systems-of-Systems, Mark W. Maier, Systems Engineering journal, John Wiley & Sons 1998

[28] Peter G. Neumann, “Principled Assuredly Trustworthy Composable Architectures”, DARPA, Computer Science Laboratory SRI International EL-243, 333 Ravenswood Ave, Menlo Park, California 94025-3493, USA.

[29] Wagner, M.; Koopman, P. A Philosophy for Developing Trust in Self-driving cars. In Road Vehicle Automation 2; Meyer, G., Beiker, S., Eds.; Lecture Notes in Mobility; Springer: Cham, Switzerland, 2015; pp. 163–171, doi:10.1007/978-3-319-19078-5_14.

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 component lifetimes 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 on the SoS, guaranteeing the survival and sustainable evolution of the SoS. Composability also has to consider cross-sectoral requirements such as security, safety, stability, 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 characterizes a constituent system with a certain attribute, it is not guaranteed that the same property will characterize it when the constituent system becomes part of an 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, behaviors, etc.

As a consequence, one major effect of the composition, integration and evolution of the constituent systems is the evolution of the SoS, with emergent properties, functionalities and behaviors that 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 human interaction along the SoS lifecycle. The protection of human life should be ensured during SoS evolution. Uncontrolled and unmonitored composition could lead to deviations from expected behaviors or generate unknown emergent behaviors 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 behaviors require that SoS development, when applying composability, is evolutionary and adaptive over the continuously evolving SoS lifecycle, which may potentially 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.

1.4.3.3.3 Key focus areas

Since the technology base and the organizational 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 the owners of the SoS gain 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 (cf. 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 of 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.
- SoS evolution stability.
- Governance of SoS evolution.
- 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.
- Autonomous machine evolution through self-engineering, verification and validation.

1.4.3.4 Major Challenge 4: SoS integration engineering along the life cycle

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

1.4.3.4.1 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 engineering 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. Engineering practice and associated standards provide design-time solutions based on, for example, IEC 61512 (ISA 88)[30], IEC 62264 (ISA95)[31], IEC 81346[32], ISO 10303, ISO 15924, IEC 62890[33]. The proposed Industry 4.0 architectures, formally provided by the DIN specification 91345 RAMI 4.0, have not yet made it into industrialized engineering procedures, or associated tools and toolchains. Many

[30] https://www.isa.org/standards-and-publications/isa-standards/isa-standards-committees/isa88
[31] https://www.isa.org/standards-and-publications/isa-standards/isa-standards-committees/isa95
[32] https://en.wikipedia.org/wiki/IEC_81346
[33] https://webstore.iec.ch/preview/info_iec62890%7Bed1.0%7Den.pdf

of these standards are investigating updates of their data models to be based on, e.g., ontologies and the semantic web.

The current state of the art in SoS engineering 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.

1.4.3.4.2 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 tool chains. Please also refer to Chapter 2.3 and Chapter 1.3.

This is expected to lead to engineering processes, tools and tool chains covering the whole life cycle that can, to a significant extent, be automated or even become autonomous, while supporting integration between multiple stakeholders, multiple brands and multiple technologies. To support such integration and engineering efficiency[34], solution quality and sustainability, concrete advancements such as those in Figure 1.4.6 will become necessary. These advancements may include integration and engineering process capabilities such as:

- Flexible integration and engineering procedures.
- Model-based engineering procedures and tools,
- Supported by interoperable and flexible toolchains.
- Integration of multi-stakeholder engineering processes.
- Automation of substantial parts of the integration and engineering process.
- Autonomous machine self-engineering, verification and validation

[34] Urgese, G.; Azzoni, P.; van Deventer, J.; Delsing, J.; Macii, A.; Macii, E. A SOA-Based Engineering Process Model for the Life Cycle Management of System-of-Systems in Industry 4.0. *Appl. Sci.* 2022, *12*, 7730. https://doi.org/10.3390/app12157730

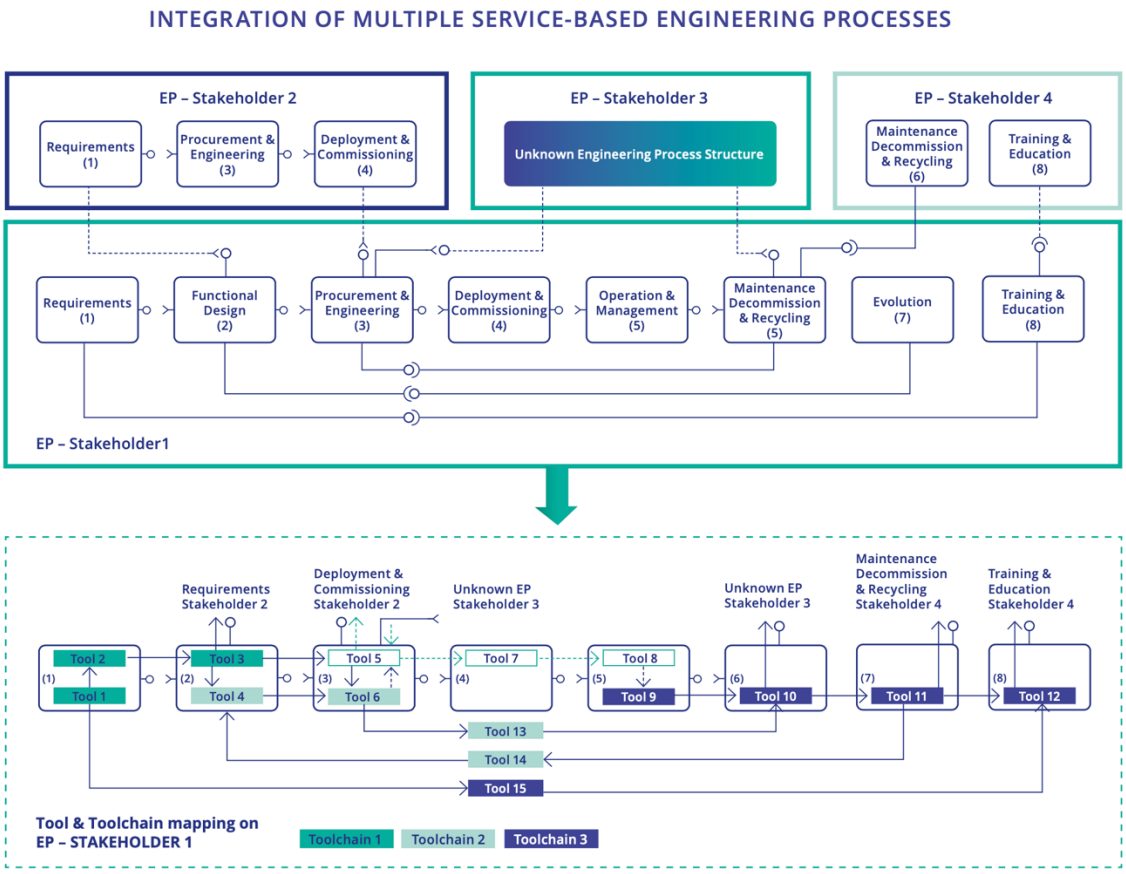

Figure 1.4.6 - Example of conceptual service-oriented view on the integration of multiple service-based engineering processes (EP) from different stakeholders, including the engineering process mapping with integrated toolchains and tools.

1.4.3.4.3 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 architectural infrastructures and their associated tools, tool chains 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, flexible and automated 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, low-code 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.
- Autonomous machine self-engineering, verification and validation

In particular, SoS TV&V introduces significant challenges, mainly due to complexity, the effects of composition (not always known in advance), and the dynamic evolution of SoS 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 SoS TV&V as features and capabilities evolve. For this reason, a structured framework, methodology and tools are necessary to demonstrate an appropriate level of confidence that the feature under test is present in the SoS, and that no undesirable behaviours are present. This implies a need for end-to-end system capability 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 when addressing changes in the constituent systems and receiving feedback on anomalous behaviours.

1.4.3.5 Major Challenge 5: 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 and evolution. It is clear that a high degree of automation and autonomy needs to be introduced to keep quality up and cost down. Management and monitoring of SoS play a particularly crucial role when application faults result in personal injuries or property and environmental damage: e.g., critical infrastructures (electric grid, rail network), connected (semi)-autonomous automotive systems, medical monitoring, industrial plant control systems, robotics and autopilot avionics.

1.4.3.5.1 State of the art

Current industrial state of the art for monitoring and management of SoS reflects practices used in the monitoring and management of production automation, energy grid automation and similar systems. 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 range of realms to be monitored and managed, ranging from modern production processes, smart grids, smart cities, automotive traffic networks, to name only some of them. Furthermore, the operation of each of these realms requires different competences and groups within an organization, and 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
- Detection of deviations from expected system behaviors

These aspects have more or less known and understood relationships/dependencies that will also change at run time. This provides a monitoring and management landscape that is very heterogeneous and dynamic. As a result, management methodologies need to be supported by automated and autonomous control technology. In this context and in view of limiting data traffic in an SoS,

synchronization of systems becomes a major goal as it is directly linked to the stability of the management system.

In addition, management of complex cyber-physical SoSs must address scalability (i.e. to deal with a variable number and interconnections of systems and automated 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.

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 correlate with current major industrial standards such as ISA95, BIM, ISO 15926 and ISO 10303.

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

1.4.3.5.2 Vision and expected outcome

The increasingly close 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. Enabling this will require closer cooperation and integration between several levels of the ECS domain stack and societal policies and governance. An example thereof is the integration and functional interoperability between open and proprietary SoS architecture and implementation platforms that reside under different jurisdictions. Here, solution requirements for lifecycle and evolution also need to be considered.

Emerging outcomes are systems or SoS that exhibit plasticity behaviors like those of biological neural systems.

1.4.3.5.3 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 across SoS dimensions and societal borders.
- Engineering support, tools and methods for monitoring and management strategy and policy implementation
- 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.
- Autonomous system testing, validation and verification (TV&V) in design and run-time.

1.4.4 Timeline

The following tables illustrate the roadmaps for System of Systems.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 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 application fields	Open SoS platforms validated in multi-vendor industrial deployments, with secure orchestration and measurable integration effort.	Bounded autonomous operations, including M2M transactions, qualified with explicit policies and recovery.	Self-reconfiguration validated across independent operators with assured safety and rollback.
	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	Lifecycle toolchains demonstrated for traceable safety, security, energy and environmental requirements.	Cross-vendor lifecycle management qualified across deployment, maintenance and component replacement.	Bounded autonomous trade-off management validated against explicit functional and extra-functional constraints.
	Topic 1.3: suitable and adaptable engineering processes with training material for solution engineering	Model-based and AI-assisted engineering workflows validated in representative projects, with reproducible training and competence assessment.	Engineering automation qualified across interoperable modelling, simulation and deployment tools.	Automated engineering qualified for selected multi-domain SoS classes with independent verification.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 2: SoS interoperability	**Topic 2.1**: Translation between standardised data models e.g. ISO 10303, ISO 15926, BIM, …	Selected standardised-model mappings demonstrated in operational pilots with semantic consistency and provenance checks.	Cross-standard mappings qualified within defined domains, with automated validation and exception handling.	Bounded standard/legacy translation qualified with explicit information-loss and trust controls.
	Topic 2.2: Translation between different implementations of standardised data models	Conformance-tested translation between implementations of standardised models, including version and unit consistency.	Cross-domain exchange qualified for selected standards and profiles.	Legacy and proprietary model adapters qualified through governed semantic mappings.
	Topic 2.3: automated data model translation	AI-assisted generation of model translations validated against curated mappings and test cases.	Automated translation pipelines qualified with regression tests and review of ambiguous mappings.	Continuous translation maintenance validated under evolving schemas and provenance requirements.
	Topic 2.4: autonomous data model translation	Runtime translation demonstrated for bounded vocabularies, with confidence thresholds and safe rejection.	Autonomous translation qualified for selected standardised models under monitored policies.	Cross-domain runtime mediation qualified with semantic validation and controlled fallback.
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	Engineering methods validated for preserving constituent independence and specified composition constraints during updates.	Contract-based composition analysis qualified for selected functional and extra-functional properties.	Runtime composition assurance validated for bounded reconfiguration; no claim of universal predictability.
	Topic 3.2: evolutionary architectures in systems of embedded and cyber-physical systems	Modular architectures validated through replacement and upgrade of heterogeneous constituent systems.	Evolvability-by-design qualified using interface contracts and lifecycle impact analysis.	Automated composition analysis qualified at design time and for controlled runtime adaptation.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
	Topic 3.3: evolvable solutions for trust, availability, scalability, and interoperability.	Modular trust and interoperability frameworks demonstrated with attestation, fault containment and versioned interfaces.	Open integration platforms qualified for availability and scalable trust management across vendors.	Federated platforms validated for cross-domain evolution with explicit ownership and assurance responsibilities.
	Topic 3.4: evolvable solutions capable of managing resulting uncertainty, emergent properties, functionalities and behaviours, including resilience to failures	Adaptive control frameworks demonstrated with uncertainty estimates, failure containment and safe fallback.	SoS-level resilience validated against representative interacting faults and communication degradation.	Bounded uncertainty management qualified for evolving compositions and cascading failures.
	Topic 3.5: evolvability in SoS supported by virtual engineering (e.g. digital twins)	Operational digital twins demonstrated for SoS integration and update assessment on open edge-to-cloud platforms.	Automated twin deployment and synchronisation qualified across selected vendor platforms.	Runtime optimisation qualified using federated twins with validated fidelity and uncertainty bounds.
	Topic 3.6: methods and tools to manage emergencies in embedded and composable SoS.	Emergency-adaptation frameworks demonstrated with operator authority, safe states and incident scenarios.	Coordinated emergency adaptation qualified across independently managed constituent systems.	Bounded autonomous emergency responses validated with human override and recovery procedures.
	Topic 3.7: service-based vertical and horizontal evolvability to enable high-level, and potentially cross-domain, evolvability of SoS	Versioned open services validated for cross-domain data and technology migration.	Service-based integration platforms qualified for controlled vertical and horizontal evolution.	Automated service migration qualified with compatibility checks and verified continuity.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 4: SoS integration along the life cycle.	**Topic 4.1**: efficient and flexible engineering processes	Service-oriented engineering workflows validated with traceable interfaces and reproducible integration tests.	Engineering tools qualified to analyse emergent behaviour in representative SoS configurations.	Scalable analysis validated for very large SoS with explicitly bounded models and coverage.
	Topic 4.2: model-based engineering	Model-based and AI-assisted SoS software generation validated with traceability and independent testing.	Automated generation qualified for defined software classes, with verified interfaces and operator review.	Model-driven engineering qualified across complex multi-domain SoS; assurance remains independent.
	Topic 4.3: engineering tools supporting the complete engineering process along the system's lifecycle	Runtime engineering tools demonstrated with controlled deployment, versioning and rollback.	Multi-stakeholder engineering workflows qualified across selected domains and toolchains.	Highly automated cross-domain engineering validated with shared traceability and change governance.
	Topic 4.4: support for key automation requirements	Engineering tools demonstrated for combined real-time, safety and security constraints in selected use cases.	Integrated assurance qualified for specified operating envelopes and controlled updates.	Cross-domain automation qualified with compositional real-time, safety and security evidence maintained through controlled runtime change.
	Topic 4.5: automated engineering	Automated requirements-to-deployment workflows demonstrated with independent verification gates.	Design-time control analysis qualified for interacting SoS models and uncertainty.	Bounded runtime control analysis qualified for safe reconfiguration and rollback.
	Topic 4.6: automated testing, validation and verification (TV&V)	Automated and runtime SoS TV&V demonstrated for selected lifecycle stages and defined coverage.	Continuous TV&V qualified across lifecycle changes using traceable evidence and monitored assumptions.	Adaptive runtime TV&V validated for changing compositions within specified assurance bounds.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 5: SoS monitoring and management	**Topic 5.1**: Monitoring and management strategies and architectural concepts in OT-IT environments	OT-IT monitoring architectures demonstrated with synchronised telemetry, access controls and diagnosed data quality.	Monitoring qualified across large-scale SoS with measured overhead, latency and fault coverage.	Federated monitoring validated across operators, evolving interfaces and governance boundaries.
	Topic 5.2: Methodologies and technologies for monitoring and management of multiple and interrelated SoS dimensions	Joint monitoring demonstrated for functional, safety and security dependencies, including correlated incidents.	Multi-dimensional monitoring qualified with consistent models and actionable diagnostics.	Coordinated SoS management validated using monitored interdependencies and bounded corrective actions.
	Topic 5.3: Processes and technology for life cycle monitoring and management over SoS dimensions	Lifecycle monitoring demonstrated across updates and replacement, preserving identity and health histories.	Monitoring architectures qualified across vendor and technology transitions.	Evolving monitoring platforms qualified with transferable evidence and verified continuity over successive upgrades.

2

Strategic Research and Innovation Agenda

CROSS-SECTIONAL TECHNOLOGIES

2.1



Cross-Sectional Technologies

EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

2.1 EDGE COMPUTING AND EMBEDDED ARTIFICIAL ITELLIGENCE

2.1.1 Summary

Edge computing and embedded AI advance digital technologies while addressing energy efficiency, system complexity and sustainability. By processing sensitive data close to its source, edge computing and embedded AI, as part of the edge–cloud computing continuum, improve performance, latency, bandwidth, privacy, safety and security while reducing data transfers and overall power.

Embedded and agentic AI are already used in several application domains, including productivity, environmental protection and security, transport, autonomous and other vehicles, with open-source initiatives supporting innovation, lower costs and security. Initially optimized for energy-efficient perception—vision, audio and signal processing—embedded AI now includes generative AI running locally on smartphones and PCs (Copilot+ PC, Apple Intelligence), a first step towards wider adoption. Local processing will extend to robotics, interfaces and high-level environmental perception, creating new computing and memory-efficiency constraints.

The four major challenges, common for edge computing and embedded AI, are:

1. **Energy efficiency**: innovative hardware and less data movement are essential as AI shifts computing from a compute-centric to a data-centric paradigm. Edge devices need efficient memory and computing, near-zero standby energy and consumption proportional to load.

2. **System complexity**: modern embedded systems need safety, security, interoperability, modularity and dynamic resource allocation. As they become increasingly connected, web technologies—including containers, WebAssembly (WASM) and protocols—extend to the edge, while federations of smaller models (Mixtures of Agents or agentic AI) can reduce dependence on cloud resources and improve modularity, privacy and lower communication costs.

3. **Device lifespan**: hardware must support software upgrades, interoperability, second-life uses, unforeseen functions and new operating modes, larger memory capacities and future communication stacks. Aggregating older devices into a larger, more powerful, virtual device can keep them useful for longer.

4. **Sustainability**: Europe must turn ethical embedded-AI innovation into commercial success through open standards (such as RISC-V and innovative technologies such as neuromorphic computing). It should master the full value chain for collaborative AI agents, advanced AI hardware and systems directly integrated into the physical world, with traceability (Life Cycle Assessment) and lower ecological impacts.

2.1.2 Scope

This chapter covers computing components for embedded architectures, edge devices and systems using AI at the edge. These depend on process technology, embedded software, system-of-systems composition, design methods and tools, under quality, reliability, safety and security constraints.

The elements foreseen to be used to compose AI or edge systems are:

- Processors (CPUs) with high energy efficiency,
- Accelerators (for AI and for other tasks, such as security):
  - GPUs (including their general-purpose use),
  - NPUs (neural processing units)

  - DPUs (data processing units, e.g., controlling data communications and logging and collecting information for automotive and other systems) and processing data early or on the fly (decreasing the load on processors/accelerators),
  - Other accelerators (xPUs) (FPU, IPU, TPU, XPU, …)
- Memories and associated controllers, specialized for low power and/or for processing data locally (e.g., using non-volatile memories such as PCRAM, ReRAM, MRAM, FeRAM for synaptic functions, and In/Near Memory Computing), etc.
- Power management.
- …[1]

A key development and recommendation for edge computing is a shift from isolated SoCs to distributed, low-power architectures across the cloud–edge computing continuum, with AI placed where appropriate to create distributed intelligence and added value (like the computing infrastructure of SDx, such as Software-Defined Vehicles).

2.1.3 Introduction

2.1.3.1 Positioning edge and cloud solutions

The emerging "continuum of computing" combines edge and cloud resources so that each task runs where latency, bandwidth, cost, processing power and energy are best balanced (see Figure 2.1.2). Tasks and services may migrate dynamically (in a later step), while interconnected devices can form virtual meta-devices that divide a global task and extend the useful life of less powerful nodes[2]. This requires sophisticated orchestration, decomposition into subtasks, secure protocols and strong authentication.

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[1] 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 acceptance of LLMs / Generative AI calls for security measures, e.g., proof of origin/authenticity etc. will have an impact on the hardware that should efficiently support them. Tasks also run efficiently, in a protected environment (silo) without consuming too many resources.
- Field connectivity IPs (see connectivity chapter, but the focus here is on field connectivity) (all kinds, wired, wireless, optical), ensuring interoperability.
- Integration using chiplets and interposer interfacing units are detailed in the chapters 1.1 and 1.2.
- 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.).

[2] Some OS are designed for this kind of distribution, like HarmonyOS (https://developer.huawei.com/consumer/en/doc/harmonyos-guides-V3/harmonyos-overview-0000000000011903-V3) : « *The devices running HarmonyOS are aggregated at the system layer to form a super device, allowing flexible scaling of device hardware capabilities.*
With the support of HarmonyOS, users can integrate capabilities of their various smart devices, implementing ultra-fast connection, capability collaboration, and resource sharing among them. This way, services can be seamlessly transferred to the most suitable device, delivering smooth all-scenario experience. ». Some concepts are also developed in the open source Oniro project (https://oniroproject.org/)), also based on OpenHarmony (https://gitee.com/openharmony).

An illustration of the edge to cloud continuum can be observed in the local processing of AI tasks in Apple devices: voice recognition, routine summarization and text organization run locally on the device's NPU when resources permit, providing fast responses, lower network energy and greater privacy. More demanding tasks are offloaded to Apple's trusted cloud, and the largest language-model workloads can use external cloud AI services such as ChatGPT. This layered approach matches resources to task complexity without overloading the device (see Figure 2.1.1).

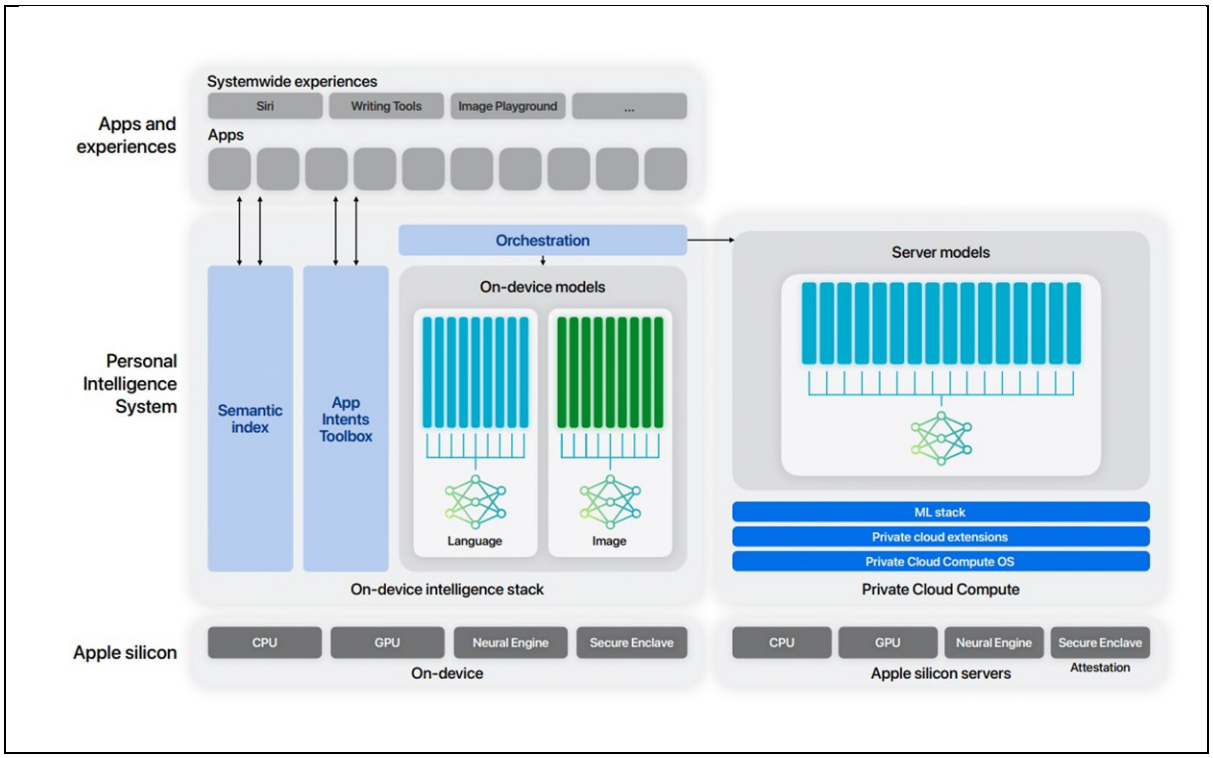

Figure 2.1.1: Structure edge to cloud of Apple intelligence, from https://arxiv.org/abs/2407.21075

Edge architectures must therefore support web and cloud protocols, communications, security, encryption and containerized execution of external code in secure sandboxes. Modern microcontrollers already integrate wired and wireless stacks (IP, Wi-Fi, Bluetooth, Thread), security IP and multiple operating systems, such as an RTOS and Linux on separate cores.

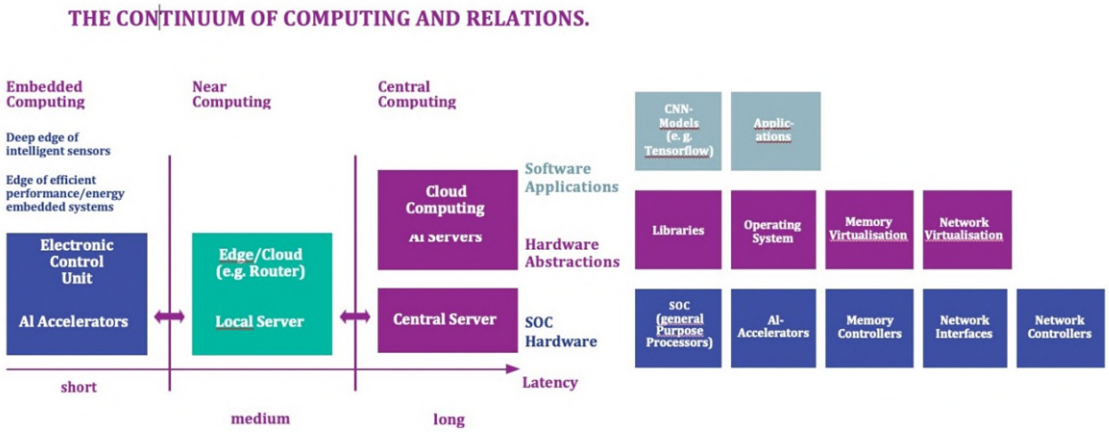

Figure 2.1.2: The continuum of computing and relations between the elements constituting an embedded AI system (figure from Gerd Teepe)

Inside the “continuum of computing”, edge computing involves processing data locally, close to where it is generated, for example by sensors. This has the benefit of reducing communication cost (as local processing generally generates higher-level data that are more compact to transmit) and latency, while decreasing the load of the other levels of processing. For intelligent embedded systems, the edge computing concept is reflected in the development of edge computing levels (micro, deep, meta) that cover the computing and intelligence continuum from 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 comprises intelligent sensors, machine vision and IoT devices close to the data source. Small neural networks on low-cost, low-power microcontrollers such as Arm Cortex-M4 and RISC-V process raw data with minimal latency, generate insights or actions, and may perform local inference and self-training. Embedded AI adds new functions and can replace complex exact algorithms with more embeddable approximations, improving performance, latency, power and usefulness—especially when networked devices collaborate, with a minimum loss of quality.

The deep-edge includes intelligent PLC and SCADA controllers, connected machine vision, network equipment, gateways and computing units that aggregate sensor and actuator data. Processors and microcontrollers such as Intel i-series or Atom and Arm M7+, together with CPUs, GPUs, TPUs and ASICs, enable controllers to acquire, aggregate, interpret, exchange and react to 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.

These levels mainly reflect distance from the data source and therefore communication latency. The following table (Figure 2.1.3) gives indicative ranges from sub-millisecond micro-edge processing to cloud or data-centre processing beyond 1,000 km and 50–100ms.

	LATENCY	DISTANCE
Micro-edge	Below 1ms	From 0 cm to 15 m
Deep-edge	Below 2-5ms	Below 1 km
Meta-edge	Below 10ms	Below 50 km
Fog	10-20ms	Up to 50 km
Multi-access edge computing (MEC) + near-edge	10-2ms	100 km
Far-edge	20-50 ms	200 km
Cloud/data centres/HPC	More than 50-100ms	1000 km and beyond

Figure 2.1.3: A tentative classification of the edge-to-cloud levels

In general, the edge (at the periphery of a global network such 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 virtualization and abstraction of the resources,

including standard APIs to support interoperability. The edge can scale to several nodes, distributed in distinct locations and the location and identity of the access links are essential. Ultimately, 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.

Flexible edge deployments can combine specific accelerators (like neuromorphic), efficient microcontrollers and AI units to meet local needs while reducing traffic, storage, energy and carbon footprint. It is important to consider that optimization should start from what data is collected and why, then co-optimize hardware and software and measure the energy used to achieve the target on the whole chain, rather than making only local optimizations.

2.1.3.2 Positioning Embedded Artificial Intelligence

Although many applications will not use AI, embedded systems increasingly need AI-ready architectures. The hardware landscape spans Cloud AI, high-performance Embedded AI and low-power Deep Embedded AI (for near sensor processing). Across this continuum, computation should be placed according to latency, energy, privacy, bandwidth and total-cost KPIs.

Embedded artificial intelligence devices can be classified into 3 clusters.

1. Cloud AI (~1 to 20 TOPS/W):

Cloud AI offers the greatest processing power: GPUs above 2,000 TOPS and LLMs with more than eight billion parameters support training and inference in data centres and servers. Leading systems exceed 5 TFLOPS/W in FP32 and reach above 20 TOPS/W in FP4 tensor-core operation.

2. Embedded AI (1 to ~50 TOPS/W):

Embedded AI brings NPUs of roughly 40 TOPS, several GB of RAM and models from about one million to eight billion parameters closer to data sources. It serves PCs, smartphones, vehicles, robotics and factories. The rapid emergence of sub-billion-parameter models shows that specialized small models can compete with much larger ones.

In the near future, we can expect that high end embedded AI hardware will be able to serve larger models, in the sub 30G range (for example Qwen 3.8 27B has the performances of frontier model of few months before its release – in the range of Claude 4.5 Opus). LLM based on mixture of experts can benefit from tricks allowing to reduce the RAM memory footprint by reading data from flash (for example, the project TurboFieldfare[3] allows to run Gemma 4 26B-A4B inference in about 2 GB of RAM).

As illustration of this category, for automotive ADAS, Embedded AI hardware provides the necessary computational power to process sensor data in real-time, enabling advanced features like object detection, lane keeping, and adaptive cruise control.

3. Deep Embedded AI (>10 TOPS/W):

Deep Embedded AI targets lower compute with very high efficiency through specialized ASICs, Compute-Near-Memory or Compute-In-Memory and compact models such as CNNs and Bayesian approaches rather than transformers. Typical platforms deliver 1–100 TOPS with kilobytes to a few

[3] https://github.com/drumih/turbo-fieldfare

megabytes of RAM for microcontrollers, IoT nodes and embedded control. This tier also hosts most perceptive AI, typically using CNN-related methods for sensor, image, video, audio and signal data.

Another dimension can also be used to characterize AI devices: their memory capacity and hence the size of the model they can perform:

- below 1GB RAM: microcontrollers, CNN accelerators, local AI near sensors, etc.
- 1 to 8 GB RAM: able to execute small LLM, VLA or VLM[4], on device (e.g., phone, laptops, specialized accelerators in M.2 format, ...)
- up to 128 GB: near consumer/on-premises local servers, with unified memory between CPU and GPU/NPU. "Consumer" systems with these characteristics are now available (but not cheap!), but they can run AI model that are now of similar capabilities than frontier models of few months before.
- up to 1 TB: local servers on-premises, able to run larger (open-weights) LLMs for companies with privacy in mind.

Systems above 1 TB are outside the scope of this chapter; these belong to servers and HPC computers. Other characteristics, such as latency, energy, generality and accuracy, can also be used, but are harder to assess across models and applications. Additional R&D could identify more representative end-to-end benchmarks

2.1.4 State of the Art

The key issues for the digital world are the availability of affordable computing resources and transfer of data to the computing node with an acceptable power budget. Each computing device should be as efficient as possible and reduce the amount of energy used.

Low-power neural network accelerators 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. Edge computing and embedded AI shall further advance toward highly energy-efficient and event-driven architectures, enabling intelligent processing under constrained and harvested energy conditions, including neuromorphic approaches for continuous operation at ultra-low power. Intelligent power and energy management policies remain essential for extending operational lifetime and enabling scalable energy-autonomous embedded systems.

AI also changes the way people interact with machines, by adding new modalities besides switches, keys and screens such as voice interaction, gesture recognition, etc.

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 and encrypted.

[4] A VLM (Vision-Language Model) understands and reasons about visual and textual information, while a VLA (Vision-Language-Action model) extends this capability to generate actions that allow an embodied system, such as a robot, to interact with the physical world.

Online-learning intelligent sensors require more than semiconductor advances. Neuroscience and information theory could provide new ways to turn sensory data into knowledge, model cortical coding and guide efficient neural-network structures and learning rules.

Compared to the previous SRIA, we can observe new trends:

- The recent explosion of AI, and more precisely of generative AI, has driven the development of new solutions for embedded systems (for now mainly PCs and smartphones), with potentially very large market growth.
- Parallel to the development of data centres for AI (training and mainly inference), their demand for semiconductors, especially in RAM and Flash, makes these resources scarce for other markets, like embedded systems, smartphones and other consumer devices. Therefore, there is a need to find solutions to decrease the size of RAM (and Flash) in systems to keep an affordable price.
- RISC-V is coming to various ranges of products, and especially from ICs from China that support many features for connectivity (security), IOs and accelerators.
- AI accelerator chips for the embedded market have traditionally been designed to support convolutional neural networks (CNNs), which are particularly effective for image, audio, and signal analyses. But now there is an evolution towards higher processing (cognitive) functions.

Generative AI at the edge (mainly for Embedded AI): the rise of federations of smaller models

Transformers—the basis of LLMs—use attention to map one sequence to another and support self-supervised learning without labelled examples. Beyond text generation, translation, summarization, question answering and code, they now address video and robotic reasoning. Although the largest models remain cloud-based, 1–13B-parameter models already run on Jetson Orin Nano, Raspberry Pi and smartphones. Quantization, including 4-bit models and GPU FP8/FP4 support, reduces memory, but efficient low-power edge execution remains a major challenge.

Generative AI can bring real-time analysis and decisions to micro- and deep-edge sensors, reducing latency, cloud traffic and bandwidth while improving privacy and sustainability in healthcare, mobility, robotics and industry. Its compute intensity nevertheless demands advances in hardware, memory and power management, plus interoperable orchestration of many devices. Security, privacy and local fine-tuning must be designed in, consistent with European ethical and sustainability goals.

Large LLMs are costly to train and update, whereas smaller models can be incrementally improved or replaced without disrupting the system. Multiple agents also provide fault tolerance: one failure need not disable the whole. Distributed edge deployment therefore requires integrated, secure connectivity between specialized models and devices.

Federations of specialized generative models—Mixtures of Agents or Agentic AI—can match or surpass a monolithic LLM with a suitable harness[5]. Each agent is trained for a domain, and tasks are routed dynamically to the best agent, improving accuracy while reducing training, inference and energy overhead. This modular approach also improves scalability and maintainability and suits one or more edge devices. Agentic AI harness coordinates smaller specialized models (and allows them to

[5] For example, in cybersecurity, Microsoft MDASH using 100+ specialized agents per bug type has better success rate than Claude Mythos preview; from https://www.microsoft.com/en-us/security/blog/2026/05/12/defense-at-ai-speed-microsofts-new-multi-model-agentic-security-system-tops-leading-industry-benchmark/

have access to tools), often tuned from open-weight foundations. Open-weight models are becoming competitive with closed ones[6].

Mid-2026 announcements (from Nvidia/Microsoft, Apple, …), (see section 2.1.4.4) reinforced interest in edge-scale models that could run on (high end) consumer devices. In any case, the field seems very active in small models operating on the periphery[7], and it is reasonable to assume that an optimized, very low-power NPU capable of running models with a few billion parameters are likely to find a market for specialized functions in edge devices.

Training large foundation models still requires cloud-scale data and compute, but they can be adapted locally through fine-tuning or a large context. Parameter-efficient methods such as LoRA and adapters update only a small share of weights on domain data (see Figure 2.1.4). PCs with sufficient storage, RAM and compute could perform this work locally while idle, for example overnight, allowing models to be adapted models to a particular use or set of data.

Model Size	Full Fine-tuning	LoRA	Q-LoRA
8B	60 GB	16 GB	6 GB
70B	300 GB	160 GB	48 GB
405B	3.25 TB	950 GB	250 GB

Note: These are estimated values and may vary based on specific implementation details and optimizations.

Figure 2.1.4: This table outlines the approximate memory requirements for training Llama 3.1 models using different techniques[8]

Another trend is to increase the token context. Leveraging a large context window refers to the model's ability to process and understand long sequences (of text for example). This extended context allows the model to capture more nuanced dependencies and relationships within the data, improving its comprehension and relevance to specific local contexts. Enlarging the context mainly implies more memory, as shown in Figure 2.1.5.

[6] See for example https://huggingface.co/Qwen/Qwen3.8-27B
[7] See for example, a list at https://www.intuz.com/blog/best-small-language-models/
[8] https://huggingface.co/blog/llama31

Model Size	1k tokens	16k tokens	128k tokens
8B	0.125 GB	1.95 GB	15.62 GB
70B	0.313 GB	4.88 GB	39.06 GB
405B	0.984 GB	15.38	123.05 GB

Figure 2.1.5: Requirements for the KV cache memory of Llama 3.1 models (FP16), from https://huggingface.co/blog/llama31

However, there are a lot of recent algorithmic innovations in this field, for example the Multi-Head Attention, followed by Multi-Head Latent Attention and Compressed Sparse Attention (from DeepSeek), and so on... Google proposed in 2026 the TurboQuant approach. If we combine all these techniques, the size of the KV cache (hence the RAM requirement) can be reduced by several orders of magnitude (see Figure 2.1.6).



Figure 2.1.6: Illustrative comparison of KV-cache memory reductions, compiled from DeepSeek technical reports and Google Research TurboQuant (2026). (from https://www.youtube.com/watch?v=3mX_dc9ZNRA)

Energy efficiency of AI training:

AI training can be energy-intensive: a 2019 estimate compared the carbon emitted by training an NLP model with the lifetime emissions of five cars. Algorithmic and hardware progress is rapid, however; a comparable model emitted 21 times less CO_2 in 2022 (see Figure 2.1.7).

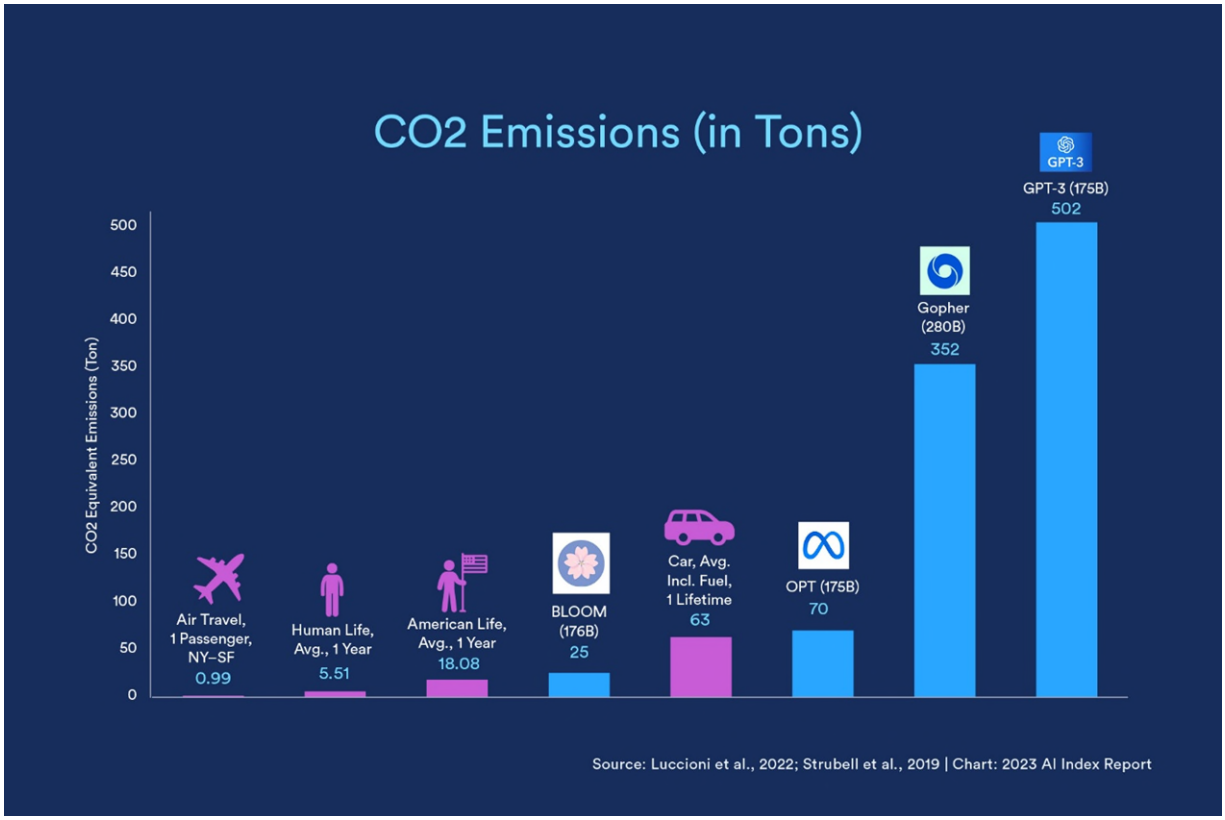

Figure 2.1.7: Decrease of CO2 emission over time for a similar size LLM, from "2023 State of AI in 14 Charts" available at https://hai.stanford.edu/news/2023-state-ai-14-charts

At billions of executions, inference can outweigh training emissions. Meanwhile, compute used by the largest training runs has grown exponentially, historically doubling about every 3.5 months rather than every two years as under Moore's law (see Figure 2.1.8). Both training and inference therefore need greener, more efficient computing, beyond what Moore's law alone can offer. This is achieved by global optimization, co-design, more efficient algorithms and smaller size data type (going from float 16 bits to 4 bits computations, and sometimes less). Neural-network progress is driven by operations per watt of accelerators. GPT-4 became economically trainable in 2022 because GPU performance had increased by roughly three orders of magnitude in eight years through new architectures, smaller process nodes and reduced data types from FP16 to FP4; energy per operation fell about 350-fold (see Figure 2.1.9).

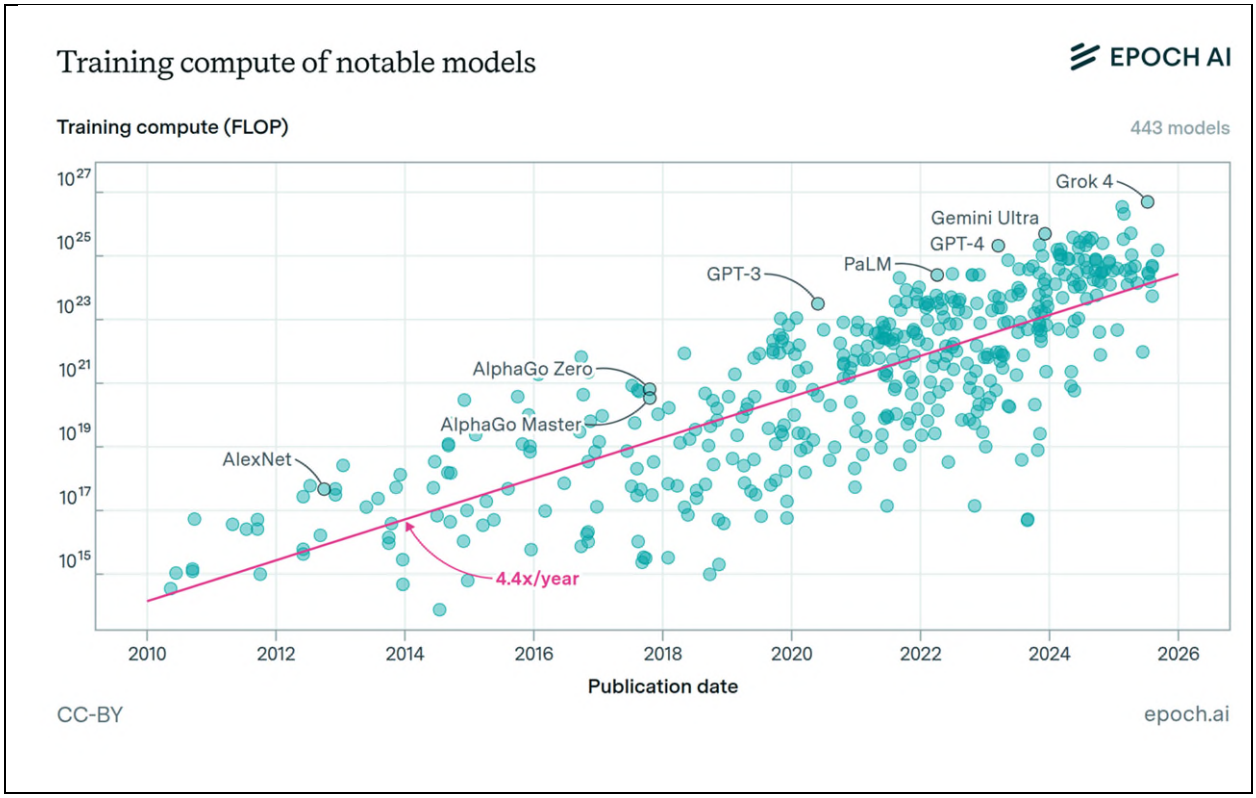

Figure 2.1.8: "Since 2010, the training compute used to create AI models has been growing at a rate of 4.4x per year" from https://epoch.ai/data/ai-models#data-insights

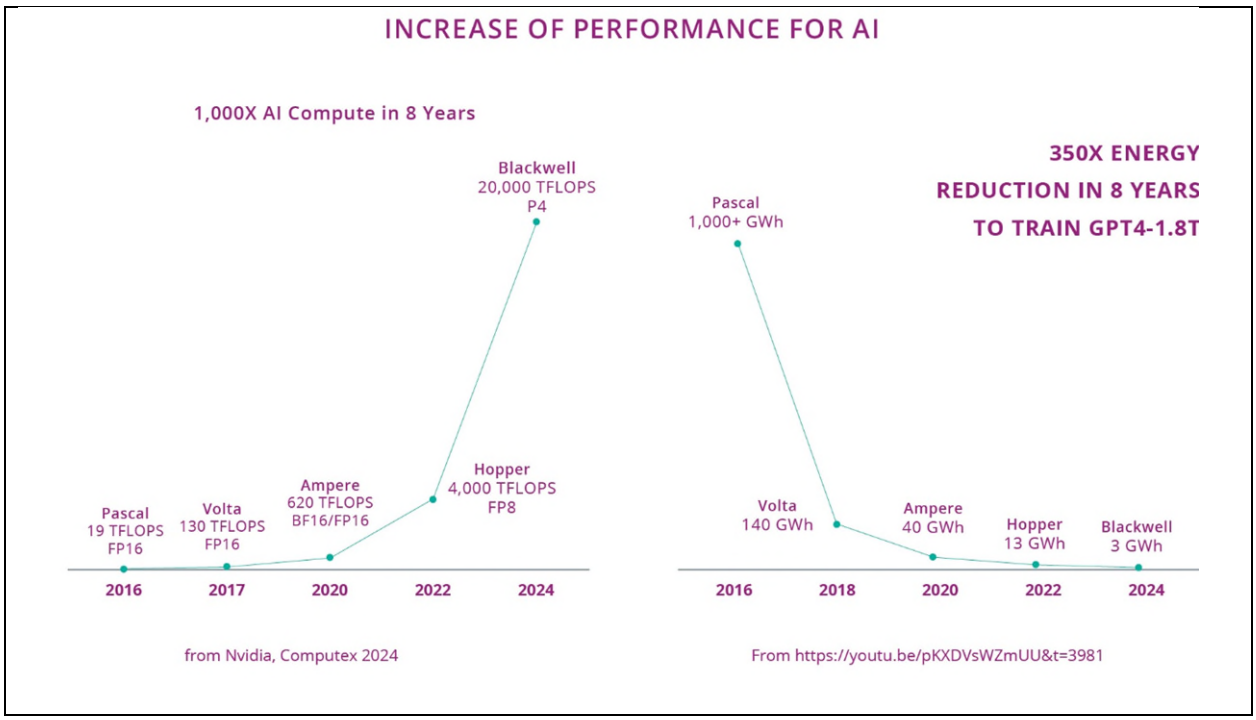

Figure 2.1.9: Increase of performance for AI accelerators

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 together with cost implications related to the hardware (processing power in terms of CPU and accelerator, RAM, etc.).

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 on particular applications (local post-training using specialized – often private – data) but also as an attempt to decrease the energy cost of the global learning scheme. Open weight models are often a base for post-training (by companies or even individuals), allowing to increase efficiency on particular use cases.

Non-trivial deep-learning inference often exceeds the 0.5–1 MB of SRAM typical of microcontrollers, so special tricks or other approaches are used for these very low power systems[9]. Quantizing weights and biases and pruning layers reduce model size and inference power (see Figure 2.1.11), but are not a complete long-term solution, so mid-range microcontrollers are teaming up with special accelerators in embedded context, such as the NXP Ara240[10]or Axelera Metis[11] allowing them to run efficiently billion-parameter models locally within a power envelope of a few watts.

The role of hardware-software co-design for improving sustainability of edge AI devices and algorithms should be highlighted, for example to reduce the memory footprint of LLM during their execution, and reducing the computing load (the Mixture of Expert approach is an example). Due to the cost of RAM, solutions are developed to dynamically stream experts (for the Mixture-of-Experts LLM) from storage (SSD) to RAM, allowing them to run models far larger than the RAM footprint would allow. Now the limiting factor is the bandwidth between the RAM and the SSD and the architecture of the system (unified memory between CPU and GPU is essential for those approaches). The speed is still very slow but usable for some applications[12]. Algorithmic improvements also reduce the RAM required for the KV cache by orders of magnitude (see Figure 2.1.6).

There is a large development of activities to design computing systems explicitly supporting novel AI-oriented use cases, spanning different implementations, from chips to modules and systems, usable from far edge to data centres (Figure 2.1.10).

[9] For example, the Cactus Needle 2 which is an open 14MB model for tool calling, device use, and structured extraction that can run even on a microcontroller like an ESP32S3 (https://cactuscompute.com/needle)
[10] https://www.nxp.com/design/design-center/development-boards-and-designs/ARA2-M2-16G-GT
[11] https://store.axelera.ai/products/axelera-embedded-110m
[12] For example, TurboFieldFare allows to run Gemma 4 26B-A4B (a 26B Mixture of exExpert model) inference in about 2 GB of RAM (https://github.com/drumih/turbo-fieldfare)

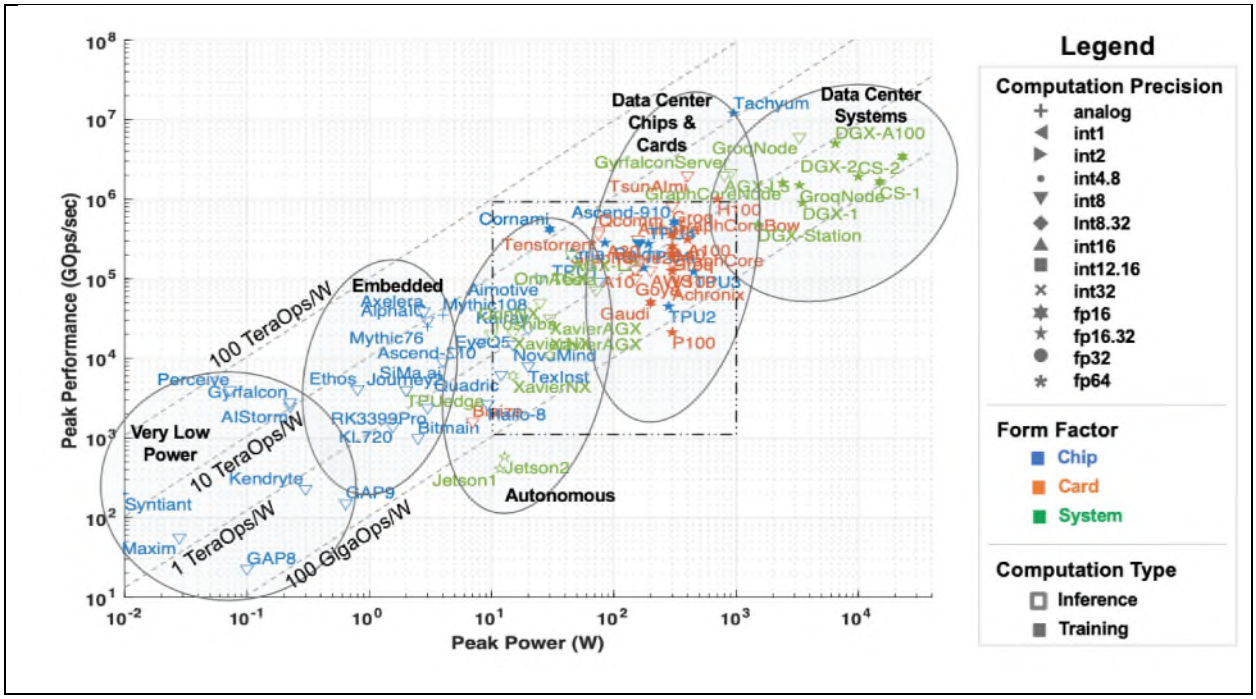

Figure 2.1.10: Landscape of AI chips according to their peak power consumption and peak performance (From https://arxiv.org/abs/2210.04055)

Complex neural networks can fit embedded devices through topology pruning, lower-precision weights and activations, or analog hardware that processes sensor signals without prior A/D conversion. Compression may occur during or after training; pruning removes low-contribution nodes, while quantization moves from BF16 toward FP16/FP8/FP4 or integers. Eight-bit inference usually has little accuracy loss and four-bit LLMs remain effective. Tools such as TensorFlow Lite and Aidge[13] already support post-training quantization, but further tools and algorithms are essential.

New server and edge accelerators must support variable precision, including bfloat formats, rather than defaulting to 32/64/128-bit floating point. Neural networks also require close coupling of various compute units and storage (hence the drive for unified memory architectures), adapted access patterns and memory hierarchies across local and cloud storage. Efficient edge LLMs will depend on 2–4-bit quantization, new memories, novel architectures and possibly beyond-CMOS hardware. Vendors are proposing their own data representation, efficiently supported in their hardware, but less suitable for portability (for example, Nvidia NVFP4 (see Figure 2.1.18), MXFP4) and with different middleware (CUDA for Nvidia, ROCm for AMD, MLX for Apple, …), creating challenges for applications that must run on hardware provided by various vendors. But there is a trend towards portability of AI models between hardware platforms (with tools such as Aidge[14]), helped by intermediate portable representations such as ONNX.

Edge AI accelerators must deliver real-time inference at low power. Deep learning uses simple multiply-accumulate operations over very large datasets, making data access and reuse—especially for CNNs and shared weights—the main challenge. Compute and storage are therefore intertwined, and accelerators must integrate efficiently with conventional systems. Fixing and optimizing some parts of the processing (e.g., feature extraction for CNNs) leads to specialized architectures with very high-performance, as exemplified in the ANDANTE[14] project. Many European and national projects

[13] https://eclipse.dev/aidge/
[14] https://www.andante-ai.eu/

produced isolated edge-AI accelerators without a complete software stack, limiting micro-edge adoption. Aidge—an Eclipse open-source initiative also supported by NeuroKit2E—provides a European development and mapping environment spanning microcontrollers, GPUs, NPUs and FPGAs.



Figure 2.1.11: Results of various quantization methods versus Top-1 ImageNet accuracy

2.1.4.1 Emerging technologies for AI accelerators

To improve AI-hardware efficiency further, non-silicon technologies are also being explored:

- Photonic: photonics hardware for AI acceleration[15]
- Neuromorphic: One innovative approach to reducing energy consumption in computing involves leveraging physical phenomena to perform computations (such as leveraging frequency multiplexing methods in spin-based or photonics components), effectively using the inherent properties of physical systems to solve complex problems.

The term "neuromorphic computing" covers various kinds of implementations, for example using sparse information coding method of "spikes" (impulses in which information is encoded in the timing), using RRAMs (resistive RAMs), memristive devices[16] or spintronic devices (that include MRAM and Nano-Oscillators) to perform the weighted summation which is the basis of artificial neural network-based AI, including LLMs. Scalability to large networks, variability in properties and interfacing with other systems still need improvement.

[15] https://www.eetimes.com/production-of-q-ant-photonic-ai-accelerators-begins-in-stuttgart/
[16] https://www.tdk.com/en/news_center/press/20241010_01.html

2.1.4.2 Impact of AI and embedded intelligence in sustainable development

Recently, the attention paid to the identification of sustainable computing solutions in modern digitalisation processes has significantly increased. Climate change and initiatives such as the European Green Deal 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. This is especially the case in the US where AI is associated with gigantic data centres using non-clean energy sources such as gas turbines[17], leading to a majority of young US adults saying they're more concerned than excited about AI.

Another direction could be taken in Europe, focusing on local AI. Local AI could become an important part of a more sustainable computing continuum. Open-weight models such as Qwen3.8-27B show how capabilities that recently required access to large cloud systems are gradually becoming available on personal computers, smartphones and other devices that people already own. For many everyday uses, including writing, translation, information retrieval, document processing and personal assistance, these local resources may provide sufficient computing power. Instead of systematically sending every request to a remote data centre, AI workloads could be executed close to the user whenever the local device can meet their requirements, while larger systems would remain available for tasks that genuinely need them. Such an approach makes better use of an enormous installed base of computing hardware and reduces data movement, network traffic and demand for additional data-center capacity. In the longer term, distributing AI across existing devices, edge systems and large computing facilities according to the needs of each task could help limit the energy use, water consumption and material footprint associated with the rapid expansion of AI infrastructure.

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 organizations in which we work, etc. AI is already impacting several heterogeneous and disparate sectors, such as companies' productivity, environmental areas like natural resources and biodiversity preservation, society in terms of gender discrimination and inclusion, smarter transportation systems, etc. just to mention a few examples.

From a technological perspective AI sustainability depends, at first instance, on the availability of efficient hardware and software technologies. Computing near, or in-memory, can lead to parallel and highly 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 report on "Recommendations and roadmap for European sovereignty on open-source hardware, software and RISC-V Technologies"[18] discusses these aspects in more detail.

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. 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) and their Chinese counterparts have large in-house databases required for the training and

[17] https://www.cnbc.com/2026/08/29/tech-backlash-ai-data-centers-elections.html
[18] https://digital-strategy.ec.europa.eu/en/library/recommendations-and-roadmap-european-sovereignty-open-source-hardware-software-and-risc-v

the computing facilities. Sustainability through open technologies extends also to open data, rules engines and libraries. Already, Aidge and the Edge AI Foundation are bringing Deep Learning to microcontrollers with limited resources and at ultra-low energy budget, and this should be extended to cover the complete spectrum of computing resources.

From the application perspective, impact of AI and embedded intelligence on sustainable development could be important. For example, AI-powered systems could be used to optimize energy consumption and improving the efficiency of renewable energy sources. Predictive analytics enable better forecasting of energy production and consumption patterns, reducing waste and enhancing the reliability of renewable energy.

Finally, embedded intelligence in consumer products promotes sustainability by enabling smarter usage and longer lifespans, mainly if various devices can be virtually combined to share their hardware resources to create a more powerful virtual computing device. This idea is already present in operating systems like Harmony OS and its European open-source counterpart Oniro[19].

2.1.4.3 Market perspectives

Several market studies, although they don't give the same values, show the substantial market opportunities for AI use in the coming years. 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.

According to a study (Figure 2.1.12), the global AI chip market is expected to grow to USD 253.30 billion by 2030, with a CAGR of 35.0% from 2020-2030.

[19] https://projects.eclipse.org/projects/oniro.oniro4openharmony

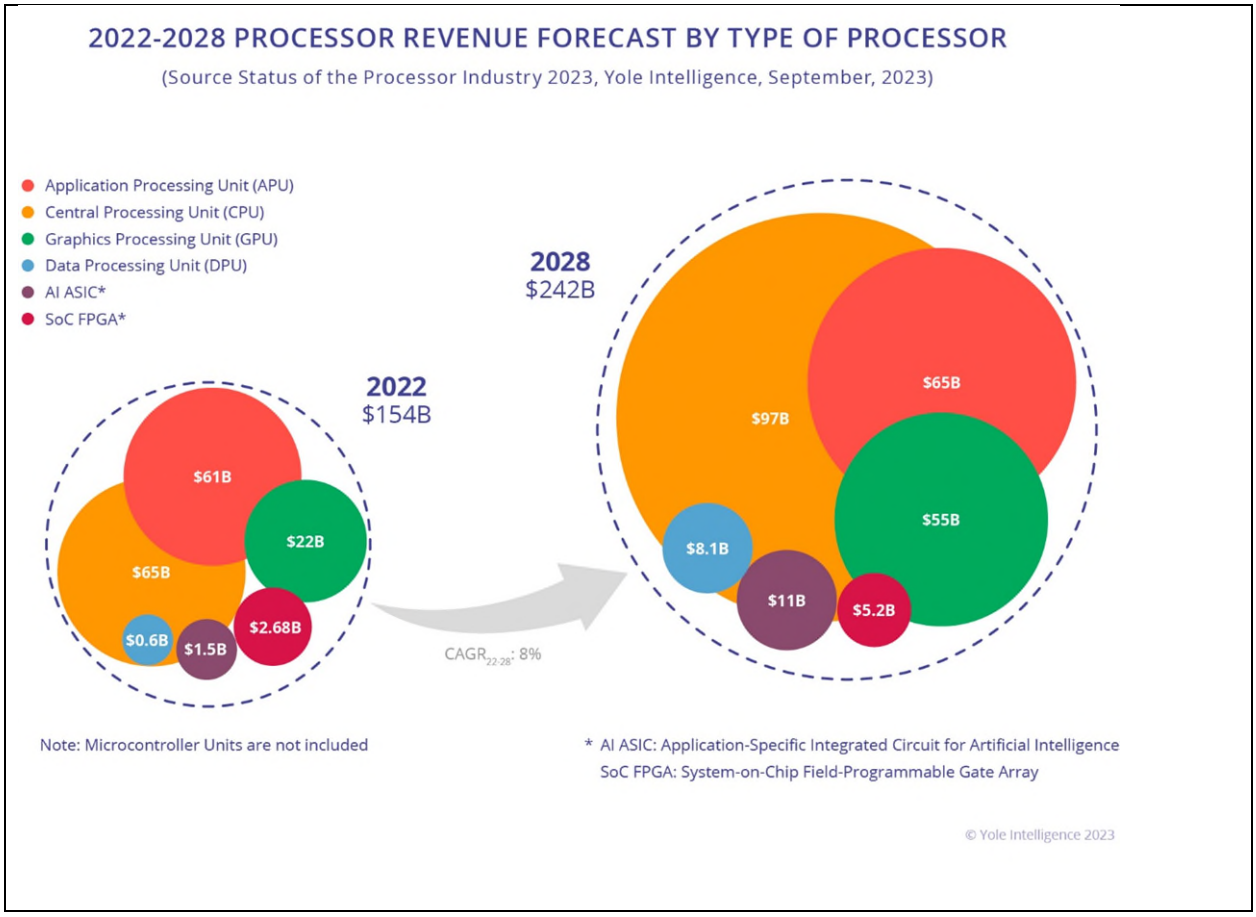

Figure 2.1.12: Market of high-end chips from https://www.yolegroup.com/product/report/status-of-the-processor-industry-2023/

The market value is increasing strongly in the field of AI chips (Figure 2.1.13) mainly for servers/data centres, but the market for Edge AI is also forecasted to have a large increase in the coming years.

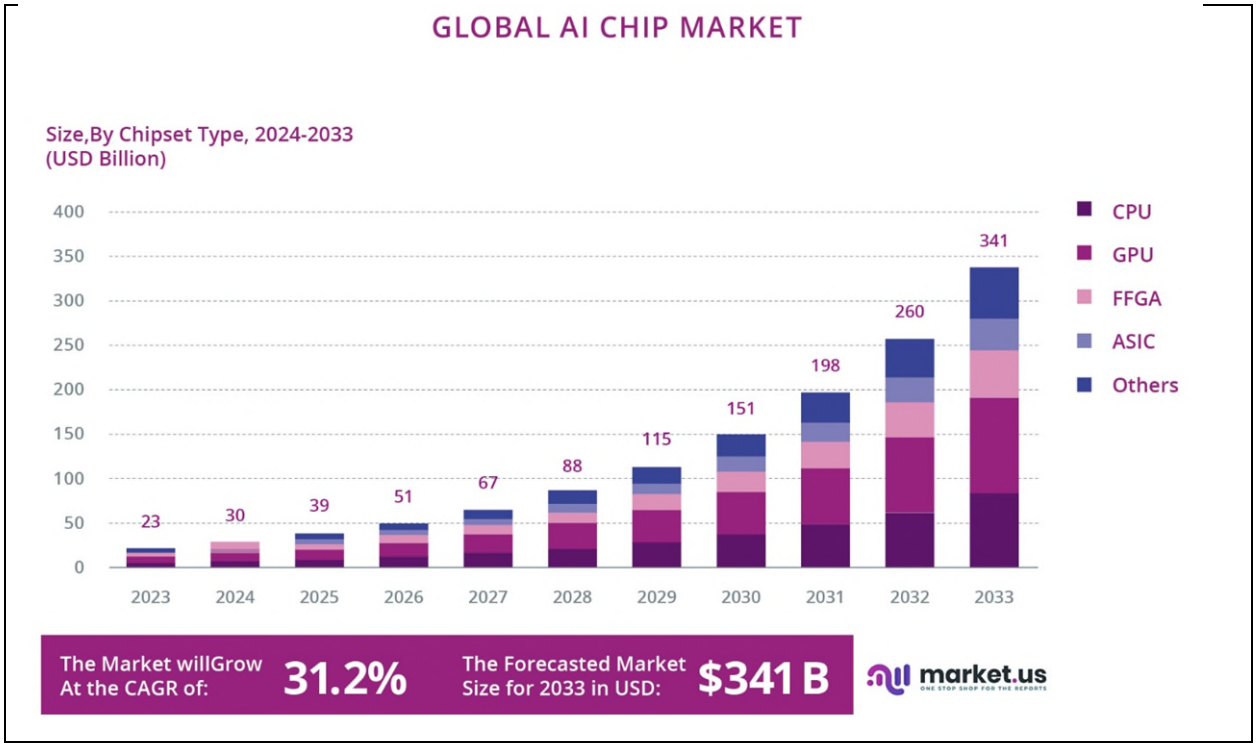

Figure 2.1.13: Market forecast of AI chips, from https://market.us/report/ai-chip-market/

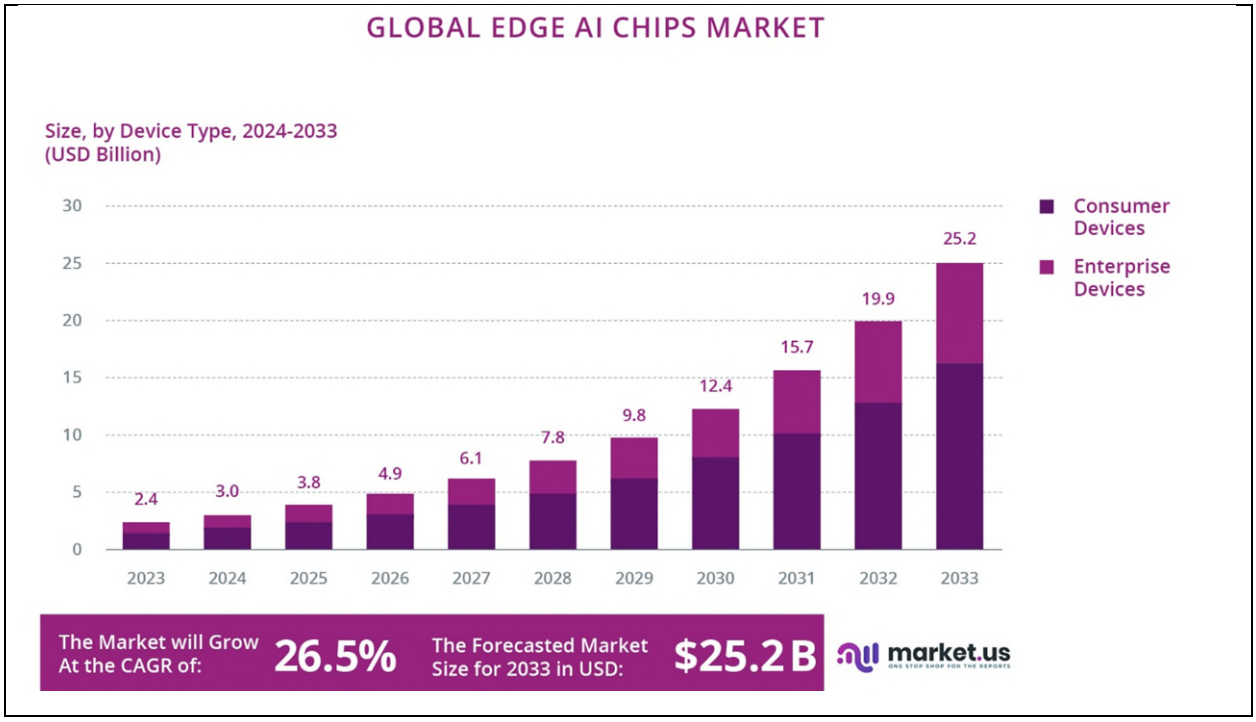

Figure 2.1.14: Edge AI market growth 2023-2033, from https://market.us/report/edge-ai-chips-market/

However, there is now an increasing trend towards AI chips that can execute generative AI models at the edge, and this trend is clearly increasing in 2025 mainly for smartphones (Figure 2.1.14). These models can generate new content, predict complex sequences, and enhance decision-making processes in more sophisticated ways.

European semiconductor companies are not in this market of chipsets for smartphones or PCs, but it is expected that, with the progress in the size reduction and specialization of large Foundation Models, generative AI at the edge will be used in the near future in more and more domains, including the ones primarily targeted by European chip manufacturers.

Another recent trend is that the RISC-V instruction-set-based chips are also developing rapidly, especially in China or Taiwan. Various Chinese companies are announcing high-performance RISC-V chips for servers, for example Alibaba with its C930. US companies are also present in this market (SiFive, Esperanto, Meta – MTIA chip, etc.). European companies are also involved in developing or using RISC-V cores (Codasip, Bosch, Infineon, NXP, Nordic semiconductors, …).

2.1.4.4 AI components vendors

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

Qualcomm has launched a generation of Snapdragon processors, with NPU, allowing them to run models more than 10 billion parameters in smartphones (such as Samsung Galaxy S26) or in PCs (Copilot+PCs), MediaTek also has chips allowing them to run generative AI on smartphones and Google, with its Tensor G6 (for the Pixel 11) also introduces chips able to run small models in consumer grade (embedded) devices.

In the field of (advanced) PCs, there is also a trend towards more efficient support for local AI. One key element is to have unified memory for the processor and the GPU, and high memory bandwidth. This was originally implemented by Apple in its ARM based architecture, and then in the NVIDIA DGX-

Spark, targeting developers and having a 128 GB of unified memory between the processor and the GPU. This trend was also followed by AMD with its Strix halo and the NVIDIA Microsoft joint announcement[20] of PC based on the RTX Spark, a derivative of the GB10 used in the DGX Spark. They are still very expensive (mainly due to the cost of the RAM) but they are powerful enough to run local models that have benchmark performance equivalent to that of frontier models of few months ago. These boxes are small enough to be embedded in various edge devices that can afford a 200 W power consumption.

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.

Arm is also developing several processors and accelerators for machine learning applications (Figure 2.1.15).

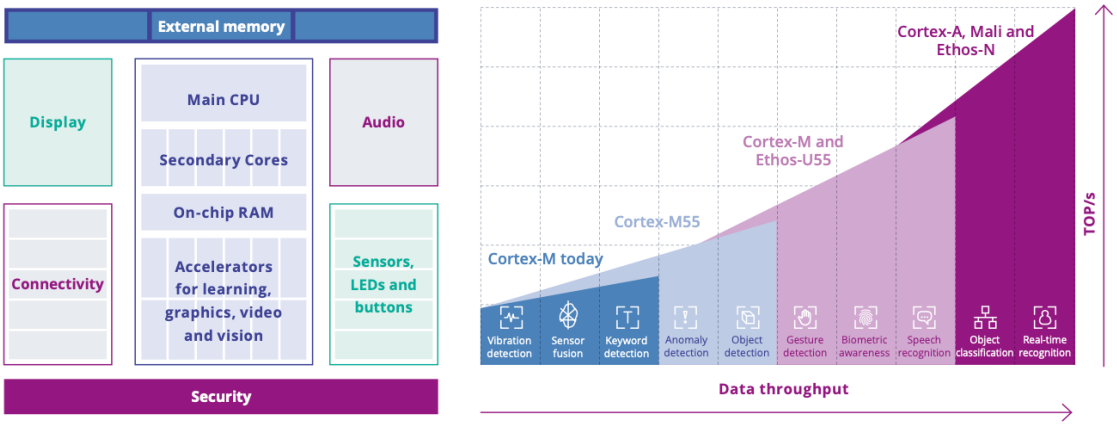

Figure 2.1.15: Example of architecture of a modern SoC (from Paolo Azzoni, see also Chapter 1.3) / Arm's Cortex-M55 and Ethos-U55 (now replaced by M85 and Ethos-U85) tandem, providing processing power for gesture recognition, biometrics, and speech recognition applications (Source: Arm).

Companies like Google, Gyrfalcon, Mythic, Axelera, NXP, STMicroelectronics and Syntiant are developing custom silicon for the edge.

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.

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

The major European semiconductor companies are already active and competitive in the domain of AI at the edge:

Infineon:

"Infineon enables reliable and efficient AI at the edge. As a global semiconductor manufacturer, our products, software, tools, and services enable the creation of the AI-based applications of today and tomorrow, by providing the right solution for every AI project in automotive, industrial and the IoT:

[20] https://nvidianews.nvidia.com/news/nvidia-microsoft-windows-pcs-agents-rtx-spark

Ranging from data, ML pipeline and chips to high-performance, low-power AI-enabled MCUs, e.g., Infineon's AURIX™, TRAVEO™, and PSOC™, to modern sensors and easy-to-integrate AI solutions.

Infineon's AURIX™ TC4x integrates AI with microcontrollers, enabling real-time applications like autonomous driving and eMobility. Its architecture combines a TriCore CPU cluster and a SIMD-based PPU for efficient AI tasks like linear algebra and signal processing. Together with Fraunhofer IKS, Infineon developed SAFE AI processes compliant with ISO 26262, 8800, and 21448.

Infineon's PSOC™ Automotive microcontrollers (MCUs) integrate artificial intelligence (AI) to enhance human-machine interfaces, smart sensing, and general-purpose applications in vehicles. PSOC™ Automotive 4 integrates capacitive sensing technology for Human Machine Interface (HMI) applications enhancing user experience by facilitating gestures over non-uniform surfaces or compensating for surface gradients.

TRAVEO™ T2G offers high performance, advanced human-machine interfaces, and robust security for automotive applications, among them: AI applications, including predictive maintenance, intrusion detection, and thermal management, enhancing vehicle performance and security, besides supporting the ARM ecosystem for AI training, development, and deployment via ModusToolbox™.

PSOC™ Edge series of Arm® Cortex®-M microcontrollers feature high-performance, low-power, secured MCUs with hardware-assisted machine learning (ML) acceleration for next generation applications. The PSOC Edge devices are based on high-performance Cortex-M55, including Helium DSP support paired with Arm Ethos-U55 as well as a low-power Cortex-M33 paired with Infineon's ultra-low power NNLite hardware accelerator intended to accelerate neural networks in Machine Learning and AI applications.

Infineon's **ModusToolbox** – a development ecosystem supporting a wide range of Infineon microcontroller devices, **DEEPCRAFT™ Studio** – a development platform for Edge AI / ML and **DEEPCRAFT™ Ready Models** – complete ML solutions guaranteed to be robust, high-performing, and production-ready for edge devices – complement Infineon's portfolio."

NXP:

NXP, a semiconductor manufacturer with strong European roots, has begun adding AI hardware accelerators and supporting software to several of their microprocessors and microcontrollers targeting the automotive, consumer, health, and industrial market, for example the NXP's i.MX 95 and eIQ Neutron. The Ara240 Discrete Neural Processing Unit (DNPU) enables real-time generative AI, large language models (LLMs) and vision language models (VLMs) execution on AI-enabled compute and embedded systems, delivering low latency, lower operational costs and enhanced data privacy. 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 flexible SW tooling to support engineers implementing their system solution.

STMicroelectronics:

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 aims to overcome the challenge of AI: opening technology access to all and for a broad range of applications. STMicroelectronics delivers a stack of Hardware and Software specifically designed to enable Neural Networks and Machine Learning inference in an extremely low-energy environment. Most recently, STMicroelectronics has started to bring MCUs and MPUs with Neural accelerators to market, able to handle workloads that were not conceivable in an edge device a few years ago. These devices rely on NPUs (Neural Processing Units) that execute Neural Network tasks up to 100 times faster than in traditional high-end MCUs. The STM32MP2 MPU has been made available in the second quarter of 2024, it will be followed by a full family of STM32 MCUs leveraging STMicroelectronics home-grown NPU technology, Neural Art. The first MCU leveraging this technology is already in the hands of tens of clients for workloads such as visual event recognition, people and object recognition, all executed at the edge in the device. On the software side, to adapt algorithms to small CPU and memory footprints, STMicroelectronics has delivered the ST Edge AI Suite, a toolset specifically designed to address all the needs of embedded developers from ideation with a rich model zoo, to datalogging to optimization for the embedded world of pre-created Neural Networks to creation of predictive maintenance algorithms. Two tools are particularly interesting: 1) STM32Cube.ai, an optimizer tool which enables a drastic reduction of the power consumption while maintaining the accuracy of the prediction. 2) NanoEdge AI studio, an Auto-ML software for edge-AI, that automatically finds and configures the best AI library for STM32 microcontroller or smart MEMS that contain ST's embedded Intelligent Sensor Processing Unit (ISPU). NanoEdge AI algorithms are widely used in projects such as arc-fault or technical equipment failure detection and extends the lifetime of industrial machines.

2.1.5 Applications breakthroughs

2.1.5.1 Example of AI application ranging from deep-edge to cloud

One example of an application that can leverage all three categories of AI hardware simultaneously in a practical example of "continuum of computing" is an advanced autonomous driving system in smart cities.

In the cloud, massive amounts of data from numerous autonomous vehicles, traffic cameras, and other city infrastructure are aggregated and used to train large-scale AI models. These models analyze patterns, improve decision-making algorithms, and enhance predictive capabilities.

In the vehicles themselves, high-performance NPUs handle real-time inferencing tasks based on smaller models. These processors power the Advanced Driver Assistance Systems (ADAS) within each vehicle, enabling real-time perception, decision-making, and control.

Within the vehicle, low-power AI hardware is used for continuous monitoring and processing of data from various sensors. This also ensures that continuous monitoring and safety features remain active without interruption.

The integration of these three AI hardware categories creates a robust autonomous driving ecosystem, leading to high-performance Embedded AI within the vehicle that handles immediate, critical decision-making and control functions, allowing the car to operate safely and effectively in real

time. It seems clear that advanced AI capabilities can enhance autonomous driving systems, in-car entertainment, and real-time vehicle diagnostics.

2.1.5.2 Other application domains

What we observe in the automotive domain can also be applied to other domains of edge computing and embedded Artificial Intelligence, such as systems for factories, systems for homes, monitoring of distributed infrastructures like the energy grid, etc. As we have seen, there is more and more convergence between edge computing and embedded (generative) AI.

An evolution of artificial intelligence is “embodied AI”, where, like for self-driving cars, drones and robots, AI directly interacts with the physical world by processing in real-time data coming from sensors and controlling actuators. “World models”, i.e., AI specialized for this kind of interaction with the world, are still in the research phase in 2026, but the domain is evolving rapidly. The rise of **Physical AI or embodied AI**, enabled by multimodal Vision-Language-Action (VLA) models and robot foundation models, is bringing increasingly capable perception, reasoning, and action directly into robots and autonomous systems. Running critical parts of these models **locally on-device** is essential to achieve the low and predictable latency required for real-time interaction, while improving autonomy and safety by avoiding dependence on remote infrastructure. Local inference also allows physical systems to continue operating reliably when connectivity is limited, intermittent, or unavailable.

Training these models is no longer done solely by feeding them with texts and books, but by having them interact with digital twins, that are modelling the world with the laws of physics, and allowing a faster training than through direct interaction with the real world. Omniverse from NVIDIA is an example of such digital twin system used to train AI; like alpamayo[21], an open-source AI for self-driving cars.

Industrial automation and robotics also stand to benefit from this technology. By embedding AI chips with generative capabilities, industries can improve productivity, reduce downtime, and enhance operational flexibility.

Internet of Things (IoT), smart home devices, wearable technology, and even agriculture technology can leverage generative AI for a variety of innovative applications, such as detection of diseases, automatic harvesting of fruits, crop analysis etc. While AI-accelerated chips have traditionally focused on supporting CNNs for image, audio, and signal analysis, the rise of generative AI capabilities is driving a new wave of AI chips designed for edge computing.

Another significant market is the healthcare sector. 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 and for personalized medicine, such as prediction of tumor neoantigens for personalized mRNA cancer vaccines[22].

[21] https://www.nvidia.com/fr-fr/solutions/autonomous-vehicles/alpamayo/

[22] This is now under experiment on humans. The technology is described, for example in https://febs.onlinelibrary.wiley.com/hub/journal/18780261/honourable-mention-2023-molecular-oncology-writing-competition-aviles-huerta

2.1.6 Major challenges

The convergence between edge computing and embedded generative AI is becoming increasingly evident, but many edge applications currently operate without AI integration. This trend includes areas primarily targeted by European chip manufacturers, signaling a shift towards broader AI integration in various applications.

Europe must maintain its status as a key player in the embedded MCU (Microcontroller Unit) and MPU (Microprocessor Unit) markets by preparing to introduce generative AI accelerators in their products, even in more affordable devices. Europe could leverage AI algorithms and models that are open source or open weights, enabling an early adoption of systems using these models. These systems should also be ready for software upgradability, and connectivity allowing modularity and collaborative performances.

Embedded systems are heavily hit by the increase of price of memories such as DRAM (and flash), caused by the large demand of memories for (US) data centres. Innovative approaches using less RAM could be rapidly developed until the RAM market becomes stable again (see Figure 2.1.16).

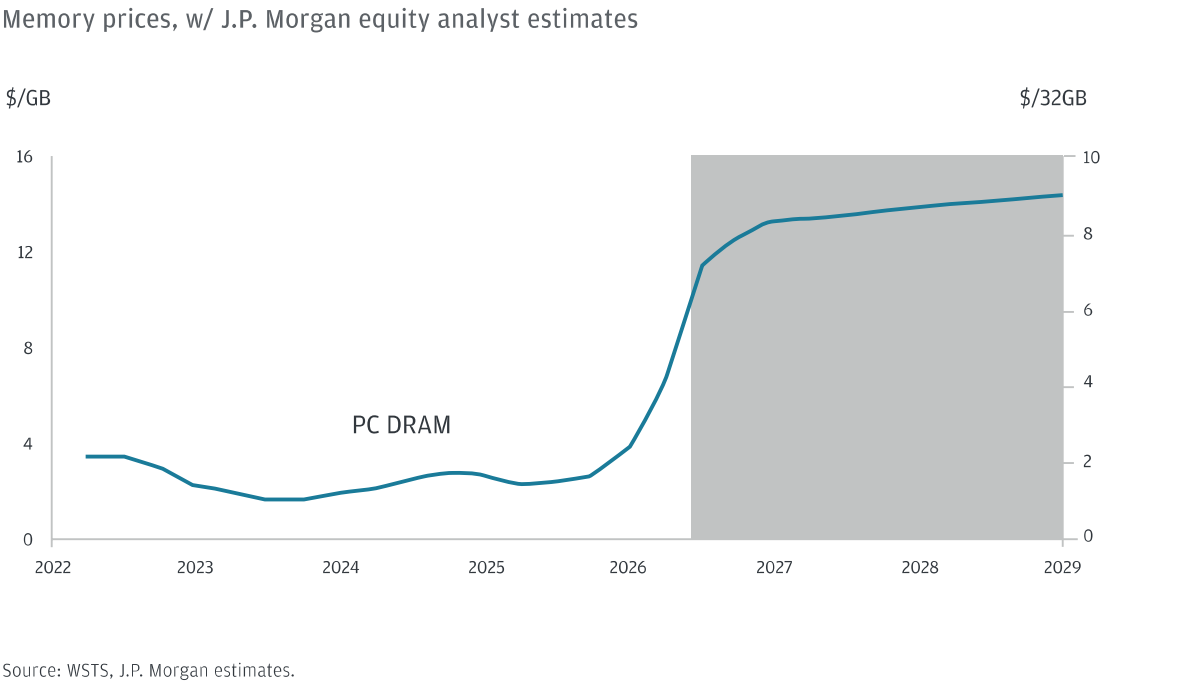

Figure 2.1.16: DRAM prices increased by around 400% between 2024 and 2026 (from https://www.jpmorgan.com/insights/global-research/artificial-intelligence/dram-memory-shortage-from-ai)

Europe should also be ready for the smooth integration of the devices into the computing continuum, which is forecasted to be an important trend.

The previous list only highlights some aspects that need to be further developed in Europe, and four Major Challenges have been identified to help Europe remain an important player in the further development of computing systems, especially in the field of embedded AI architectures and edge computing:

1. **Increasing Energy Efficiency**
2. **Managing the Increasing Complexity of Systems**
3. **Supporting the Increasing Lifespan of Devices and Systems**
4. **Ensuring European Sustainability**

2.1.6.1 Major Challenge 1: Increasing the energy efficiency of computing systems and embedded intelligence

2.1.6.1.1 State of the art

Increasing energy efficiency is the result of progress at multiple levels:

Technology level:

At the technology level (FinFet, FDSOI, silicon nanowires or nanosheets), technologies are pushing the limits of CMOS technology to be ultra-low power. However, the scaling is near its limits, and technology will have a limited impact on the improvement of efficiency in the coming years.

Device level:

Greater gains can now be expected at the architectural level, and various types of architectures are currently being developed worldwide.

- 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. Some applications also require further development due to their need for more flexibility and precision in numerical representation (32- or 16-bit floating point compared to the requirements of AI which codes information in a lower number of bits), 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 energy required to access off-chip memory is currently 10–100 times higher than access to on-chip memory. While IMC in particular is extremely promising, careful optimization at the system level must really take advantage of the theoretical peak efficiency potential. Figure 2.1.17 shows that moving data requires more energy than processing it (an operation on 64-bit data requires about 20pJ in 28nm technology, while getting the same 64-bit data from external DRAM takes 16nJ – without the energy of the external DRAM).

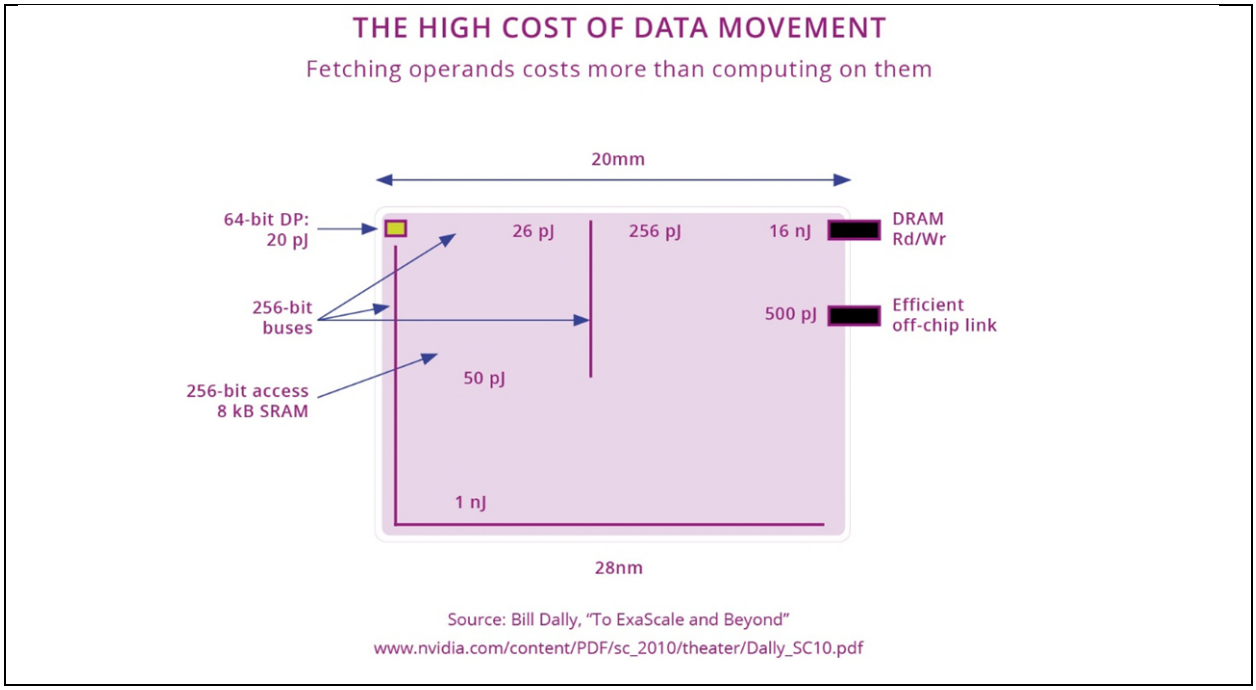

Figure 2.1.17: Energy for compute and data movement. This explains the order of magnitude of the problem of data movement, and this problem is still relevant in all technology nodes.15

Table 1 shows that in a modern system, large parts of the energy are dissipated in moving data from one place to another. Not only the memories themselves, 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 ~15ns	Core oxide device ~1ns	No HV devices ~5ns	No HV devices ~5ns	No HV devices ~5ns	Write after read (Destr. Read)
	Erasing granularity	FN mechanism Full page erasing	bit-2-bit erasing Fine granularity	bit-2-bit erasing Fine granularity	bit-2-bit erasing Fine granularity	bit-2-bit? Depend on archi	bit-2-bit erasing
Reliability	**Endurance**	Mature technology	High capability 10^15?	500Kcy	10^5 trade Off with BER	10^5 Gate stress sensibility	10^11 #10^6 with write after read

	Retention	Mature technology	Main weakness	150°C auto compliant	Demonstrated Trade Off with power	About 10 years (with the aim of replacing NAND flash by increasing the bias voltage)	To be proven
	Soldering reflow	Mature technology	High risk 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

Table 1: eNVM technologies, strengths and challenges (Andante CPS & IoT Summer School, Budva, Montenegro, 6–10 June 2023)

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 10mW (milliwatt) to 100mW with an estimated energy efficiency in the order of hundreds of GOPS/W up to a few TOPs/Watts in the next 5 years. On top, the device itself can go in standby or in sleep mode when not used, and connectivity need not be permanent. Devices currently deployed on the edge rarely process data 24/7 like data centres: to minimize 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 1mW in fully state-retentive sleep, and less than 1-10 µW in deep sleep. The possibility to orchestrate and manage edge devices becomes fundamental from this perspective and should be supported by design.
- Unified (or shared) memory, which allows CPUs and GPUs (or NPUs) to share a common memory pool, is gaining traction initially for high-end systems such as Mx series of systems from Apple, followed by architectures from Nvidia (GB10 and RTX Spark) and AMD (Strix). This is particularly advantageous for handling the diverse and dynamic workloads typical of AI applications and reduce the amount of energy required to move data between different parts of the system. In "classical" PC architecture, the weights of the Neural networks are first copied to the main memory (CPU) and then copied again to the VRAM of the accelerator, losing time and energy compared to a system with unified memory.
- Maximum utilization and energy proportionality: Energy efficiency in cloud servers relies on the principle that silicon is utilized at its maximum efficiency, ideally operating at 100% load. Unlike centralized cloud servers, edge devices often face fluctuations and unpredictable workloads. These devices must be capable of maintaining high efficiency across many utilization levels, not just at peak performance. To accomplish this, edge hardware needs to be designed with adaptive power management features that allow it to scale power usage dynamically in response to varying workloads. This means the hardware should be as efficient

at low workloads as it is at 100% utilization, ensuring that energy is not wasted during idle or low-demand periods. Energy proportionality aims to scale computing power according to the computational demand at any given moment. This concept is crucial for modern computing environments, which must handle a diverse range of workloads, from the intensive processing needs of self-driving vehicles to the minimal computational requirements of IoT devices. The ability to dynamically adapt power usage ensures efficiency and effectiveness across this spectrum of applications. In high-demand scenarios, such as those faced by self-driving cars, the computational power must scale up to handle complex algorithms for navigation, sensor fusion, and real-time decision-making. Conversely, IoT devices often require minimal computational power, as they are designed to perform specific, limited functions with a few lines of code. To minimize the power consumption at the edge, IoT sensors with integrated AI must evolve to "wake-up-and-process" paradigms where the processing only takes place under relevant contexts which might be triggered by relevant events (like a sensor readout moving above or below a certain threshold). This wide range of computational needs presents a significant challenge because the requirements and hardware for each application are vastly different.

Data level:

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 rates and hence, the energy necessary to access each memory in the hierarchy and avoiding to duplicate data.

The right data type should be also supported to perform correct (or as correct as acceptable) computation with the minimum number of bits and, if possible, using integers (the floating-point representation as specified in IEEE 754 is very costly to implement, especially with the particular cases). This seems to be particularly true for hardware that supports AI operations in close proximity to sensors (where the number of “synapses” can be limited). Current consensus is that 4-bit representation for the weights didn’t degrade too much inference performances, and quantization to fewer bits (down to a trinary coding +1,0,-1) is possible for particular cases.

Tools level:

At tools level, HW/SW co-design of systems and their associated algorithms are mandatory to minimize the data movement and optimally exploit hardware resources, particularly if accelerators are available, and thus optimize the power consumption. For LLM, we observe that concepts similar to those for system design can be reused (like replacement policies for the KV cache similar to the ones used for ordinary caches, mapping RAM in file system (SSD) to decrease the RAM requirement for MoE LLMs, etc.).

Additionally, new paradigms of computation based on beyond CMOS technologies (such as spintronics, photonics and memristors) require the development of specialized tools to implement the training and learning of the network.

2.1.6.1.2 Key focus areas

Therefore, there are several key axes to further develop to increase energy efficiency of computing and AI systems:

Processing Data Locally and reducing data movements:

Increasing the energy efficiency of computing systems in general is a multifaceted challenge that requires innovations across various domains, including hardware, software, and data management. Local-first software is designed to ensure that users maintain control over their data by storing it primarily on their local devices, thus enabling full functionality even without an active internet connection. In the local-first paradigm, the software architecture is designed to prioritize local operations, using Conflict-free Replicated Data Types (CRDTs) and other synchronization mechanisms to manage concurrent data updates and ensure consistency across distributed systems. As shown in the beginning of this chapter, this concept is involved in Apple Intelligence and in HarmonyOS.

Co-Design of Algorithms, Hardware, Software:

The co-design of algorithms, hardware and software represents a holistic approach to optimizing system performance and energy usage. This integrated design process can help to identify and eliminate bottlenecks, streamline operations, and reduce overall energy consumption. NVIDIA claims that the improvement of performance of their GPUs is mainly due to “global co-design” and not anymore to the technology improvement (Figure 2.1.18).

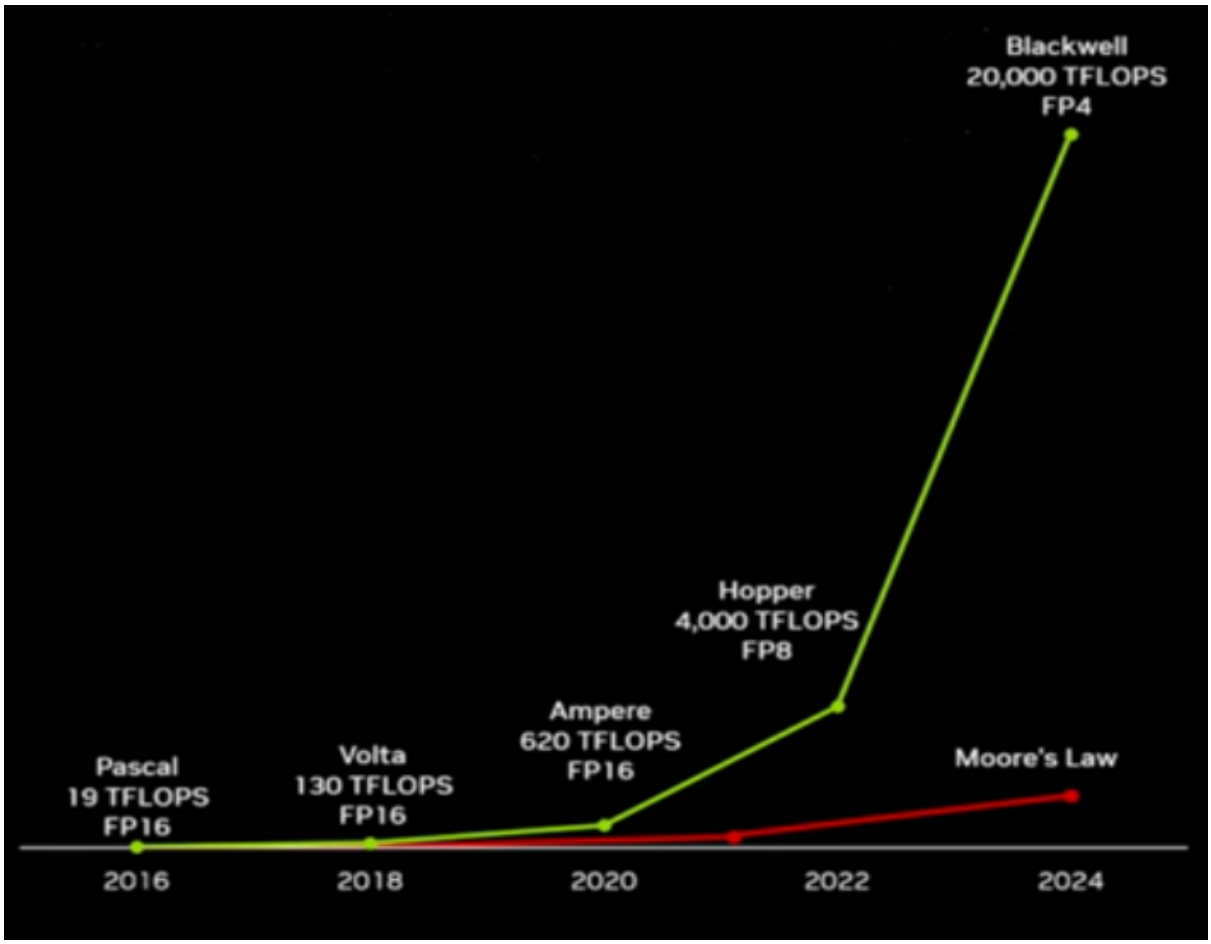

Figure 2.1.18: Performance improvement due to “global co-design”, reducing the compute precision (from FP16 to FP4) compared to the improvement of the technology “Moore’s law” (From Nvidia, Jensen Huang’s keynote, Computex 2024)

The **co-design of sensing systems and artificial intelligence**, particularly at the edge is very important direction and should be further considered and enforced. Currently, sensing is largely treated as a data source for AI, while future ECS systems will increasingly rely on tightly integrated sensor–AI solutions. This includes hardware–algorithm co-design, physics-informed machine learning, adaptive sensing strategies, and intelligent signal processing directly at the sensor or node level. Such approaches are essential to reduce data transmission, improve robustness under real-world conditions, and enable energy-efficient operation in distributed IoT and System-of-Systems environments. Strengthening this link between sensing technologies and embedded AI would better reflect emerging trends in edge intelligence and enhance the impact of ECS solutions across application domains.

Efficient Management of storage resources:

In the landscape of edge AI, the efficient management of memory resources is becoming increasingly critical to guarantee both a sustainable energy consumption profile and the required performances. Local execution of smaller language models (SLMs) often encounters bottlenecks primarily at the memory level.

Moreover, the cost of memory remains a crucial factor for deploying generative AI at the edge, mainly in this period of RAM shortage. This involves strategic allocation (between Flash, DRAM or other kind of memories) and utilization of memory to ensure that AI tasks are handled efficiently without unnecessary data copy (which consumes energy and requires more resources). Algorithmic innovations in compressing weights, pruning neural networks, or reducing the RAM requirement of long context are also important to reduce the usage of storage.[23]

Concept of Unified Memory:

The concept of unified memory, where a common memory pool is shared between the CPU and GPU/NPU, offers significant advantages for energy efficiency (see above).

Innovations in Memory Technology:

Advances in memory technology are essential for increasing energy efficiency (see Table 1).

Energy Proportionality:

Energy proportionality is a critical principle for hardware design, ensuring that devices are as efficient at low workloads as they are at 100% utilization.

Ultra-Low Standby Current:

Maintaining an ultra-low standby current is vital for devices that spend significant amounts of time in idle or low-power states, waiting to perform tasks triggered by specific events or intervals.

Leveraging Physical Phenomena for Computation:

One innovative approach to reducing energy consumption in computing involves leveraging physical phenomena to perform computations, effectively using the inherent properties of physical systems to solve complex problems (using Ohm's law for making products and Kirchoff law or summation of charges for addition). This is the case for neuromorphic computing. For example, the value of RRAM can be also locally modified, allowing to implement some training algorithms very efficiently. Scalability to large networks, variability in properties and interfacing with other systems still need

[23] see for example the state-of-the-art section of this chapter related to the improvement of the size of the KV cache.

improvement for industrial use. Neuromorphic technologies such as spiking neural networks and compute-in-memory architectures are compelling choices to efficiently process and fuse streaming sensory data. Event-based sensors, such as retinomorphic cameras, are becoming extremely important, especially in the case of edge computing where energy could be a very limited resource. Edge computing and embedded AI shall further advance toward highly energy-efficient and event-driven architectures, enabling intelligent processing under constrained and harvested energy conditions, including neuromorphic approaches for continuous operation at ultra-low power. Intelligent power and energy management policies remain essential for extending operational lifetime and enabling scalable energy-autonomous embedded systems.

2.1.6.2 Major Challenge 2: Managing the increasing complexity of systems and embedded intelligence

2.1.6.2.1 State of the art

The growing complexity of embedded systems and devices for embedded intelligence is becoming increasingly difficult to manage. Modern SoCs combine general-purpose processors, AI and domain-specific accelerators, memories, communication interfaces and many other functions, while requirements for performance, energy efficiency, safety and real-time operation continue to increase. Moving from large monolithic SoCs towards chiplet-based architectures can help address some of these difficulties, but it also moves part of the complexity from the chip to the system and package level. Interoperable interfaces, interposers, advanced packaging, system-level design methods and common ways of describing and combining chiplets will therefore be needed. Automotive computing is already driving work in this direction, with initiatives such as ASRA[24] in Japan and imec's chiplet program[25] in Europe. Shared architecture specifications and international agreement on interfaces and system architectures are important to reduce global costs and ensure reusability of IPs. Europe should build on these efforts and develop an end-to-end approach covering architecture, hardware, packaging, software, design tools and validation. Without such capabilities, increasing system complexity may become an obstacle to innovation and weaken the competitiveness of the European electronic components and systems industry.

A holistic end-to-end approach is necessary to manage the increasing complexity of systems, to remain competitive and to continuously innovate the European electronic components and systems ecosystem.

- Tools and techniques leveraging AI to help in the management of complexity, both for embedded systems and for embedded AI systems, e.g., tools to adapt LLMs to edge / embedded targets are required. The solutions for edge AI 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. They should also ensure hyperparameter tuning for automated machine learning scenarios, etc. Furthermore, and more generally, environments for modeling how the various parts interact together should be considered since this topic is still a challenge; having

[24] https://asra.jp/

[25] https://www.imec-int.com/en/expertise/cmos-advanced-and-beyond/compute/automotive-chiplet-program

accurate digital twins of complex systems with the right level of abstraction for the various uses (conception, runtime optimization, etc.) is still an unsolved challenge.

- New design and architecture concepts including HW-SW co-design with corresponding HW/SW platforms for AI-born embedded systems should be promoted to facilitate trust by providing 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.
- Enabling factors to manage the complexity of the continuum of computing are the use and development of standardized APIs for hardware and software toolchains, methods and interoperability across different system layers like sensors, gateways, on-premises servers and edge processing units. Additionally, interoperability concepts for AI edge-based platforms for data tagging, training, deployment, and analysis should be supported, allowing the development of distributed edge computing architecture with AI models running on distributed devices, servers, or gateways away from data centres or cloud servers. Protocols such as MCP[26] or A2A[27] are steps in the direction of agents communicating with each other (in a distributed manner).
- Deterministic behaviors, low latency and reliable communications are also important for other vertical applications, such as connected cars.
- The increasing complexity of systems will make them more prone to attacks so managing cybersecurity from the start is a mandatory action. Privacy-preserving, on-device AI compute is well-aligned with both regulatory direction and the operational realities of consumer device deployments. It should be further extended to explicitly include **on-device security tooling** as a parallel R&I priority — specifically, AI-powered threat detection capable of operating locally without dependence on cloud-side processing.

  Two converging pressures make this a strategically important research direction. First, EU privacy regulation is constraining the data flows that cloud-dependent security architectures rely on, requiring security inference to move closer to the device. Second, the rapid proliferation of edge AI devices is expanding the consumer attack surface at a pace that centralized security models cannot match. R&I into energy-efficient, on-device security inference — capable of detecting novel and evolving threats without continuous cloud connectivity — would strengthen European digital resilience while creating a meaningful competitive differentiator for European cybersecurity vendors. This aligns directly with the chapter's existing focus on energy-proportional, privacy-preserving compute and merits explicit treatment alongside it.

Five Key Focus Areas have been identified to tackle this complexity challenge:

- Complexity Management Utilizing AI
- Decomposition of Complex SoCs into Chiplets and Interposers
- Ensuring Programmability and Interoperability
- Combining Processing Devices to Work Together
- Modeling Interactions Among System Components

[26] https://en.wikipedia.org/wiki/Model_Context_Protocol
[27] https://en.wikipedia.org/wiki/Agent2Agent

2.1.6.2.2 Key focus areas

Complexity management utilizing AI

In the domain of edge AI, the concept of a Mixture of Agents (MoA) or Agentic AI, where a set of smaller Large Language Models (LLMs) called agents work collaboratively, presents an approach to managing complexity more effectively than relying on very large "universal" foundation models. In 2026, these agents are managed by a harness such as Codex (OpenAI), Claude Code (Anthropic) or open-source harnesses like OpenCode, Hermès, PI, DeepSeek etc. The harness manages the agents, their memory and the tools they can access. Consequently, the MoA paradigm not only simplifies the management of AI complexity but also optimizes performance and resource utilization in edge computing environments, paving the way for more responsive and efficient AI applications. It was observed that a harness can improve the performances of a "raw" LLM on complex and long tasks. Some harnesses, like DeepSeek harness, keep track of all the actions and messages, allowing to trace what was done. By end of 2026, AI is also starting to be used to improve the harness itself[28], in a RSI (Recursive Self Improvement) loop.

Decomposition of Complex SoCs into Chiplets and Interposers

The decomposition of complex SoCs into chiplets and interposers is an emerging strategy to manage system complexity. This approach involves breaking down a monolithic SoC into smaller, modular components (chiplets) that are interconnected using interposers. However, 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. Europe, with its large set of SMEs, is an ideal setting for creating this ecosystem of multiple providers of (interoperable) chiplets.

Chiplet integration can be realised using different packaging concepts, such as silicon interposers (2.5D), polymer-based RDL substrates, organic interposers (2.3D), or direct chiplet integration on organic substrates without an interposer (2.1D). These packaging concepts are not just implementation details; they directly determine die-to-die connectivity, bandwidth, latency, signal integrity, and power distribution. Organic substrates play a central role in chiplet-based systems, as they enable the practical partitioning of SoCs into chiplets, define the achievable interconnect density, and provide scalable and robust power delivery, while at the same time meeting requirements for industrial-scale manufacturability and system reliability.

Ensuring Programmability and Interoperability

To handle the increasing complexity of systems, it is essential to ensure programmability and interoperability for example through techniques and adherence to standards that originate from the web and cloud computing (but not necessarily involving the cloud). Technologies such as containers, orchestration, and WebAssembly (WASM) maintain high flexibility and adaptability and enable seamless integration and operation across different platforms managing the diversity and dynamic range of modern computing environments. These tools allow developers to manage and update systems more efficiently, ensuring that various components can communicate and function together effectively while developers' productivity can also be helped by generative AI.

Combining Processing Devices to Work Together

The combination of various processing devices working together is another key focus area for managing system complexity. By combining CPUs, GPUs, NPUs, and other specialized processors

[28] For example, in HarnessX, https://arxiv.org/abs/2606.14249

systems can distribute tasks according to the strengths of each device. Coordinating these devices requires sophisticated management and scheduling techniques, but it leads to more robust and scalable systems. Together with interoperability, the ability of devices to work together is the foundation of the computing continuum approach.

Modeling Interactions Among System Components

Modeling the interactions among various parts of a system remains a significant challenge in managing complexity. Advanced modeling techniques and simulation tools are necessary to accurately represent these interactions and predict system behavior under different conditions.

2.1.6.3 Major Challenge 3: Supporting the increasing lifespan of devices and systems and embedded intelligence

2.1.6.3.1 State of the art

Supporting the increasing lifespan of devices and systems can mainly be based on three main principles:

- Upgradability
- Modularity
- Reuse

By extension, this means that devices and systems have to increase their scalability and interoperability.

Upgradability

This requires hardware that can accommodate for example software upgrades, ensuring that devices remain functional and up-to-date over extended periods. This is the drive for approaches such as Software Defined Vehicle. 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.

Hardware requirements for edge processing devices that support software upgrades must address several critical factors to ensure that these devices remain functional and up-to-date over extended periods. The hardware must have sufficient computational power and memory flexibility or capacity to handle the evolving complexity of software applications and some level of flexibility and reconfigurability that allows it to be used in ways that were not originally intended without compromising performance.

Secondly, hardware for edge processing devices must be compatible with various operating systems, RTOS and software ecosystems, providing the flexibility needed to adapt to different applications and use cases over time. This is an important point that should also happen in the other domains of edge computing.

Modularity

Enhancing interoperability and modularity allows different generations of devices to work together, extending their usability and reducing electronic waste. It would lead to systems which are more eco-designed and with greater sustainability. The hardware should be **designed with modularity in mind**, enabling easy replacement or upgrading of individual components. This implies a long-lasting chip-to-chip communication protocol between units (like I2C, SPI, PCI-e, USB, Ethernet, MIPI, AXI, etc.).

Interoperability, modularity, scalability, virtualization, 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.

Reuse

The last aspect of increasing lifetime is to reuse a system in an application framework less demanding in terms of performance, power consumption, safety, etc. Developing the concept of a second life for components further contributes to sustainability by repurposing older hardware for new applications. Another approach is to combine "old" devices to share their hardware resources to create a more powerful virtual computing device. This idea is already present in operating systems like Harmony OS and its European open-source counterpart Oniro[29] as explained before.

2.1.6.3.2 Key focus areas

Ensuring Long-Term Functionality and Up-to-Date Operation

A fundamental aspect of supporting the increasing lifespan of devices is ensuring that they remain functional and up-to-date over extended periods. This may incur over-specification to be able to be future proof.

- Dynamic reconfiguration and Self-X techs
  Intelligent reconfigurable concepts are an essential key technology for increasing the re-use and service life of hardware and software components.
  - 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.
  - 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-reorganize while preserving the key parameters of a system (performance, power consumption, real-time constraints, etc.). Thanks to AI, when some malfunctioning parts are identified, it may be possible to assess, relying on AI and the data accumulated during system operation, if it affects the behaviors of the system regarding its real operating conditions. It would then extend its lifetime "in place". The second case is to better understand the degraded part of a system and then identify its new operating space. This can decide how it could be integrated in another application making sure that the new operating space of the new part is compatible with the operational requirements of the new hosting system.
  - Self-learning techniques are promising. Many domains can benefit from AI in mobility, smart building, and communication infrastructure. LLMs show interesting properties in this field, such as few-shot learning.

[29] https://projects.eclipse.org/projects/oniro.oniro4openharmony

- Monitoring the devices and systems' health

  Dynamic reconfiguration and Self-X Techs also need data to be as efficient as possible. It means that monitoring of devices and systems' health are necessary to acquire those data. Several techniques exist.

  - Distributed monitoring: continuous monitoring and diagnosis also play a crucial role for the optimization 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 predictively manipulate the operational strategy, e.g., to extend service life or optimizing energy. This also allows to detect shifting behavior or faulty conditions in the systems, 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 characterize and adjust to ageing and environmental effects and adjust operations accordingly.
  - Distributed predictive optimization 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 mostly processed, condensed, and evaluated locally thus relieving both communication and computational infrastructure.
  - The other area of lifetime extension is how AI could identify very low signals in a noisy data environment. for predictive maintenance, for instance, it is difficult for complex machinery to identify a potentially failing part well in advance. Thanks to AI and collecting large datasets it is possible to extract some very complex patterns which could allow for very early identification of parts with a potential problem. AI could not only identify these parts but also give some advice regarding when the exchange of a part is needed before failure, and then help with maintenance planning.

- Artificial Intelligence challenges

  Secure software upgradability is now essential. Hardware, software stacks, tools and data must therefore be co-developed for plasticity, interoperability and long life, supported by virtualization and standards. Like power management, lifetime extension must be designed in from the start.

  One challenge for the AI edge model is upgradability of the firmware and new learning/training algorithms for edge devices. The related security questions regarding model confidentiality, data privacy etc. need to be addressed specifically for such fleets of devices.

  The novelty with AI systems is to upgrade while preserving and guaranteeing the same level of safety and performance. 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. 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.

Designing with Modularity and Extensibility in Mind

To achieve long-term functionality, devices need to be designed with modularity and extensibility as core principles. For this to be practically usable means that a specific chip-to-chip interface should be added and internally connected to ensure this modularity at board/system level. This design philosophy supports easier maintenance and enables incremental improvements, which can significantly extend the device's lifespan.

- Advancing Modularity at the Chiplet Level

  While the concept of modularity is well-established at board and system level, achieving it at the level of chiplets is an emerging challenge that has not yet been fully realized. This approach promises greater flexibility, improved scalability, and easier integration of new technologies.

- Virtual Modularity

  Virtual Modularity refers to the dynamic integration and seamless interaction between multiple devices within an interconnected ecosystem, enabling them to function as a unified system.
  Virtual Modularity can increase the lifespan of devices by distributing workloads and optimizing resource usage across a network of connected devices, rather than relying on a single device to handle all tasks. Older devices can have their lifetime extended thanks to the extra computing and storage resources delivered by other devices in the pool.

Reuse of components or systems in a downgraded or requalified use case

Re-use: One concept called the “2nd life” is actually the re-use of parts of systems. 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 to fit the “2nd life” similar use case, going for example from smart manufacturing to smart home. 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.

2.1.6.4 Major Challenge 4: Ensuring European sustainability of embedded intelligence

2.1.6.4.1 State of the art

Edge computing and Artificial Intelligence are quickly becoming more and more tied together, converging towards the unified concept of Embedded Artificial Intelligence.

Economic and environmental sustainability represents two key factors when defining actions and investments promoting the coverage of the value chain and of the technology stack. e.g., cloud computing, based on data centres, plays a fundamental role for the digitalisation process.

Data centres and transmission networks consume roughly 2–3% of global electricity and account for about 1% of energy-related greenhouse-gas emissions, although efficiency gains have moderated demand growth (Figure 2.1.19). The IEA reported in January 2024 that data-center electricity demand could double by 2026; cryptocurrency processing may still consume more electricity than AI that year (Figure 2.1.20).

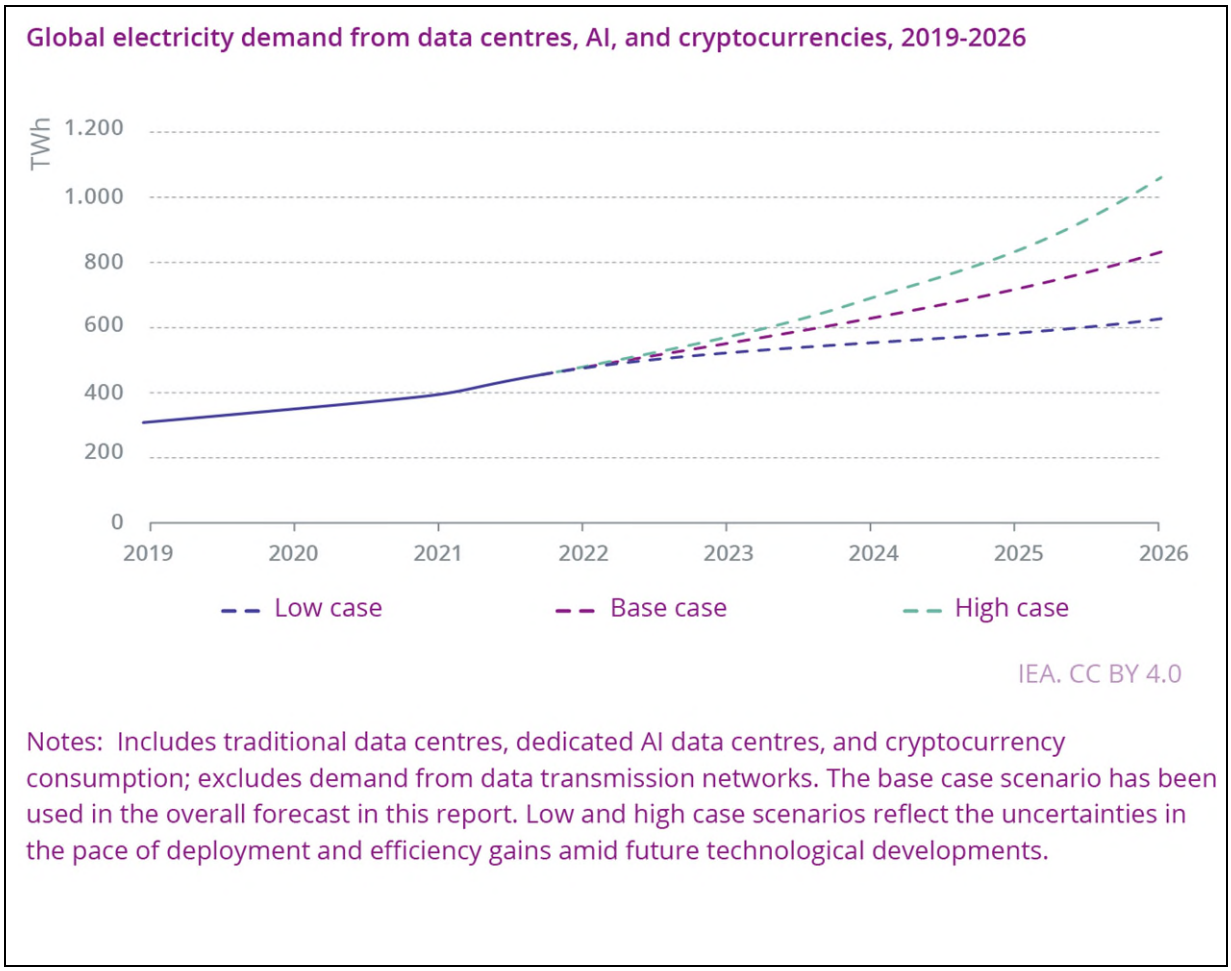

Figure 2.1.19: Forecast of global electricity demand from data centres, AI and cryptocurrencies, 2019–2026 (source: IEA, Electricity 2024)[30]

[30] https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks#tracking, captured in August 2024

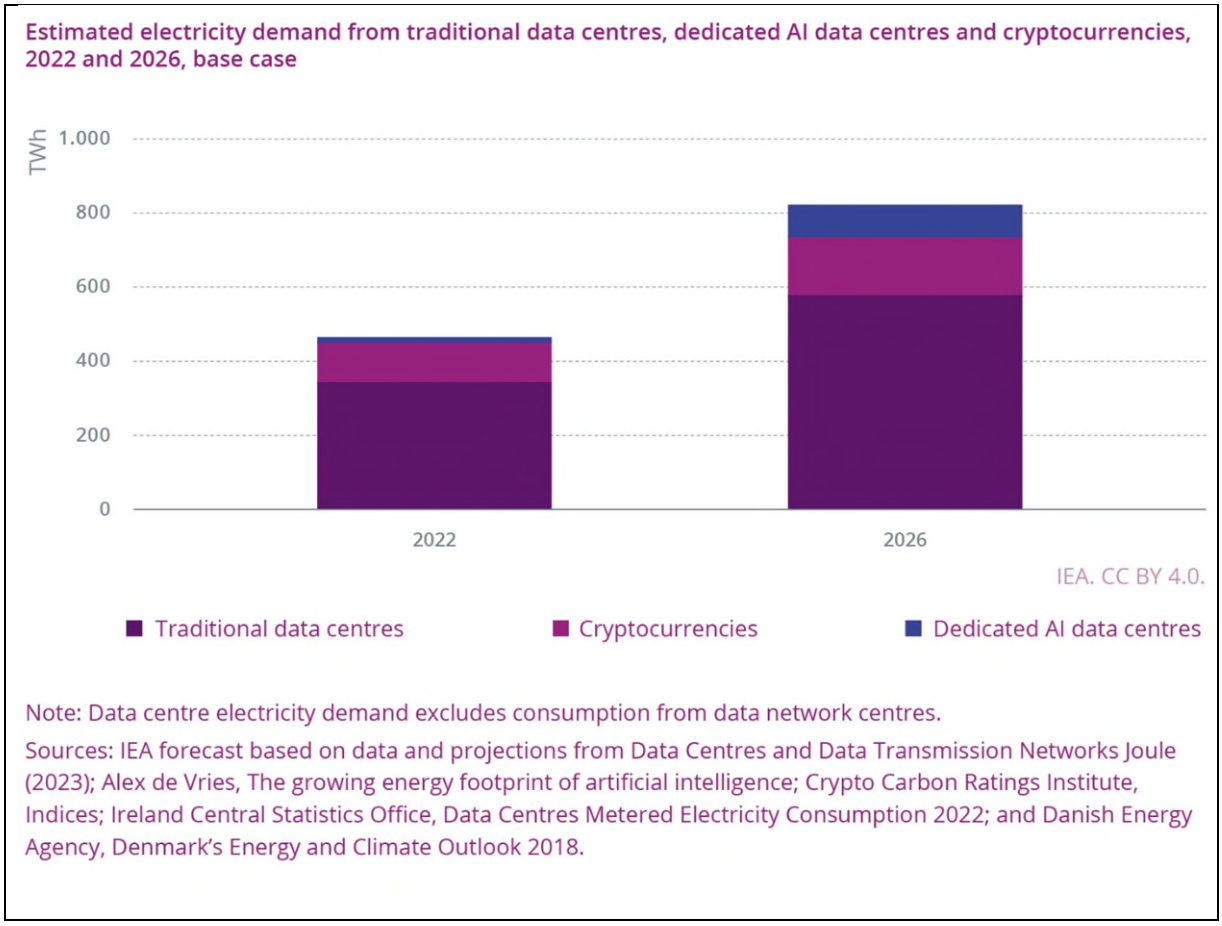

Figure 2.1.20: Estimated electricity demand of traditional data centres, dedicated AI data centres and cryptocurrencies, 2022 and 2026 (source: IEA, Electricity 2024; see footnote 32)

Data centres are progressively becoming more efficient, but shifting the computing to the edge, for example, allows to reduce data traffic, data centres storage and processing.

Shifting to green energy is certainly a complementary approach to ensure sustainability, but the conjunction of AI and edge computing, the Embedded AI, has the potential to provide intrinsically sustainable solutions with a wider and more consolidated impact. These solutions also bring other important benefits such as real-time data analysis, reduced memory and storage capacity and better data protection. To avoid such drawbacks, new AI algorithms specifically tailored for embedded systems, in conjunction with new HW components (e.g., based on neuromorphic architectures), should be designed and developed.

Sustainability of Edge Computing and AI is affected by many technological factors, which require investments to consolidate and strengthen EU global positioning, generating a potential positive impact on the sustainability of future digitalization solutions and related applications.

Ensuring sustainability for Embedded AI in Europe involves several key initiatives: open-source hardware can drive innovation and reduce costs, while energy efficiency improvements are critical for sustainable development. Engineering support represents the third key factor. It is necessary to advance sustainable Embedded AI from several perspectives: optimize the energy profile of Embedded AI solutions (technical and environmental levels), tackle the lack of expertise and of human resources (operational/engineering level), and keep the costs of these solutions sustainable (economic). For example, by mastering the adoption of new Embedded AI techniques, such as

transformers and large language models (LLMs) with a focus on federation of smaller specialized models developed in Europe[31], and integrating them with efficient accelerators and algorithms, Europe can maintain a competitive edge. This is crucial for many vertical domains that are key for Europe: for example, in the domain of autonomous systems, Europe has the potential to lead in the development of autonomous vehicles and robots, leveraging advanced AI and embedded intelligence. The necessity to ensure an efficient engineering process, with consequent short time-to-market, is motivated by the speed of global market evolution: for example, the emergence of cheap Chinese RISC-V microcontrollers emphasizes the necessity for fast development, robust, cost-effective computing solutions made in Europe.

Sustainability can also be measured in terms of democratizing technology use, to make it more accessible to a broader community of users and facilitate market entry to startups and SMEs: natural language interfaces for example could contribute to facilitate the access to digital technologies. It is also crucial to support the research into new computing paradigms, like neuromorphic and analog computing based on a diverse set of technologies that include spintronics, photonics and memristors, and to ensure they can reach high TRL levels (i.e. 7, 8 and 9).

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, especially on the edge. This is particularly challenging in the European landscape, which is dominated by small and medium enterprises (SMEs) with only some large actors that can invest and support larger-scale projects.

2.1.6.4.2 Key focus areas

Leveraging Open-source Hardware and Software for Innovation and Cost Reduction

Open-source Hardware and Software are drivers of innovation and cost reduction in the fields of Edge Computing and Embedded AI, allowing democratization of design and creating a collaborative environment where innovation can emerge and making the development of cutting-edge solutions that are both affordable and highly effective possible.

Developing and Federating Smaller Specialized AI Models

The federation of smaller specialized AI models developed in Europe represents a strategic approach to harnessing localized expertise and enhancing the efficiency of AI applications at the edge. These models, when federated (in “Agentic AI”), can work together to tackle complex tasks as, or even more effectively than monolithic models. Specialized agents can be derived from few foundation models (made by few European companies or from Open Source) by fine tuning that can be achieved by SMEs or start-ups on specialized datasets, as this specialization requires less computing power and data than the creation of a completely new foundation model.

[31] For example, see https://mistral.ai/

Training Models with European Data and Ethical Compliance

For AI models to be truly sustainable and beneficial to Europe, they must be trained on data that covers European languages and reflects the diverse cultural and social contexts of the continent.

- Finding solutions which ensure privacy, fairness, and transparency in AI systems, thereby aligning technological advancements with the core values and regulations of Europe.
- Allowing those AI to work at the edge, hence promoting the development of specialized AI chips for edge AI, this will facilitate access to digital technologies to a broad audience.
- Supporting natural language interfaces which enable users to interact with technology in intuitive ways, breaking down barriers to adoption and use, in a continent characterized by cultural, societal and language diversity.
- Increasing the re-use and sharing of knowledge and models generated by embedded intelligence, improving the energy- and cost-efficiency of AI training, and adopting a new benchmarking AI approach oriented to sustainability.

Deploying Efficient and Sustainable Embedded AI-oriented ECS

Efficient ECS like new memories, accelerators and algorithms specifically conceived for Embedded AI are fundamental to the performance and sustainability of the domain. This will require for example:

- New materials and substrates oriented to low power consumption.
- New generations of embedded ultra-low power electronic components.
- 3D-based device scaling for low power consumption and high level of integration.
- Chiplet-based solutions promoting modularity and reuse (sustainability by design).
- Strategies for self-powering nodes/systems on the edge and efficient cooling solutions.
- Policies and operational algorithms for power consumption at edge computing level.
- Efficient and secure code mobility.
- Advanced Neuromorphic components.
- Generative AI for the edge.
- Inclusion of existing embedded systems on the edge (huge market opportunity).

Accelerating Development of Robust, Cost-Effective Solutions

There is a pressing need for the rapid development of robust, cost-effective computing solutions made in Europe. These solutions must be designed to meet the specific demands of European markets and regulatory environments.

- Engineering process automation for full lifecycle support of Embedded AI solutions.
- Edge Computing and Embedded AI security and sustainability by design.
- Engineering support for Embedded AI verification and certification, addressing end-to-end edge solutions.
- Support for education and professional training to enable, facilitate, improve and speed-up the design, development and deployment of Embedded AI.
- Engineering process automation based on generative AI.

2.1.7 Timeline

The timeline indicates expected high-TRL operational prototypes or early commercialisation. The 2027–2031, 2032–2036 and 2037-and-beyond bands are conditional maturity estimates, particularly for adaptive and multi-paradigm systems.

Legend:

- (EC): edge computing
- (eAI:) Embedded Artificial Intelligence

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2027–2031	**2032–2036**	**2037 AND BEYOND**
Major Challenge 1: increasing the energy efficiency of computing systems	**Processing data locally and reducing data movements: towards the computing continuum**	Energy-aware edge/cloud orchestration demonstrated with measured data-movement costs, shared-memory interfaces and secure local processing.	Dynamic compute/storage placement qualified under latency, availability, energy and privacy constraints.	Federated compute placement qualified across operators with verified energy/latency trade-offs and resilient local fallback.
	Co-design of algorithms, hardware, software	HW/SW/algorithm co-design demonstrated for embedded generative AI, with measured accuracy, memory, latency and energy trade-offs.	Specification-driven accelerator and software generation qualified for selected workloads and multi-paradigm packages.	Lifecycle co-design automation qualified across successive heterogeneous platforms with independently verified resource and functional constraints.
	Efficient management of storage resources	[32]Memory-efficient edge inference demonstrated using quantisation, caching, streaming and parameter-efficient adaptation, with measured end-to-end energy.	Qualified near/in-memory AI platforms and heterogeneous memory management, including retention, endurance and software support.	Adaptive memory hierarchies qualified across device generations with reproducible energy, endurance and numerical-accuracy evidence.
	Energy proportionality	Workload-aware accelerators demonstrated with power gating, voltage scaling and measured energy proportionality across operating modes.	Adaptive power control qualified across heterogeneous compute resources while preserving real-time and safety constraints.	Distributed energy-proportional control qualified under changing workloads, ageing and coordinated fault recovery.

[32] It seems that Apple is doing something similar in its « Apple Intelligence »

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2027–2031	**2032–2036**	**2037 AND BEYOND**
	Ultra-low standby current	Event-driven sensing and always-on wake-up systems demonstrated with measured standby, wake-up energy and false-trigger rates.	Energy-harvesting nodes qualified for intermittent workloads, state retention and safe recovery under variable supply.	Long-lived autonomous sensor systems qualified under seasonal energy variation, component ageing and secure intermittent operation.
	Development of innovative hardware architectures	Neuromorphic and in-memory accelerator prototypes demonstrated with usable toolchains, measured accuracy and system-level energy benefits.	Hybrid computing platforms qualified for selected workloads with interoperable runtimes and validated device variability.	Multi-paradigm embedded platforms qualified where lifecycle energy and application benefits justify integration.
Major Challenge 2: managing the increasing complexity of systems	**Balanced mechanisms between performance and interoperability**	Machine-readable resource characteristics demonstrated for offline composition and validated performance/energy trade-offs.	Bounded runtime reconfiguration qualified against changing requirements, with monitored constraints and rollback.	Cross-vendor resource partitioning qualified through interoperable capability descriptions and conformance tests.
	Developing distributed edge computing systems	Distributed edge platforms demonstrated with standard APIs, secure orchestration and measured communication overhead.	Agent-assisted orchestration qualified across selected platforms, including fault isolation and safe fallback.	Federated edge orchestration qualified across independent administrative domains.
	Scalable and Modular AI	Modular AI compute prototypes demonstrated with chiplets, package-level reliability and interoperable software interfaces.	Manufacturing-qualified embedded AI chiplet platforms with tested interoperability and reusable toolchains.	Composable AI hardware qualified across successive chiplet generations with maintained interfaces, thermal integrity and software compatibility.
	Easy adaptation of models	Transfer and federated learning demonstrated with application-specific evaluation, privacy controls and labelled validity limits.	Automated model adaptation qualified against drift, forgetting, latency and safety constraints.	Model adaptation services qualified across defined application families with maintained evidence.

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2027–2031	**2032–2036**	**2037 AND BEYOND**
	Easy adaptation of modules	Portable execution demonstrated across selected CPU/accelerator platforms with performance and numerical-conformance tests.	Cross-platform migration qualified using virtualisation and validated compiler/runtime mappings.	Lifecycle module replacement qualified across heterogeneous device generations with verified behavioural equivalence and rollback.
	Realizing self-X Self-optimize, reconfiguration and self-management	Self-assessment and bounded optimisation demonstrated with monitored operating envelopes and recovery.	Resource self-reconfiguration qualified against explicit goals, fault conditions and stability criteria.	Twin-supported self-management qualified across evolving edge deployments.
	Using AI techniques to help in complexity management	AI-assisted architecture exploration demonstrated with reproducible requirements, objective functions and independent validation.	Architecture generation qualified for defined application domains and verified resource constraints.	Bounded AI-assisted lifecycle engineering qualified for changing architectures with independent verification and traceable decisions.
	Safeguarding emergent behavior of interacting edge AIs	Interacting edge-AI agents demonstrated with bounded authority, conflict detection and systemic safety tests.	Multi-agent coordination qualified against emergent failure scenarios and monitored operating limits.	Federated agent coordination qualified across independent operators with assured containment, authority transfer and recovery under evolving interactions.
	Using AI techniques modeling of interactions among system components	AI-assisted interaction models demonstrated against measured component and communication behaviour.	Agent-supported simulation workflows qualified with model provenance, uncertainty and independent checks.	Lifecycle interaction models qualified under changing compositions using physical feedback, uncertainty bounds and monitored validity.

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2027–2031	**2032–2036**	**2037 AND BEYOND**
Major Challenge 3: supporting the increasing lifespan of devices and systems	**HW supporting software upgradability (eAI)**	Updatable edge-AI hardware/software platforms demonstrated with versioned interfaces, compatibility testing and rollback.	Long-lived platforms qualified for successive model generations with revalidation and maintained security support.	Successive hardware and model generations qualified within maintained update ecosystems with transferable assurance and security support.
	Realizing self-X Also partially in ***Managing the increasing complexity of systems (eAI)***	Health-aware adaptation demonstrated with bounded retraining, ageing indicators and verified operating margins.	Lifetime-extension control qualified using degradation evidence, safe reconfiguration and monitored model change.	Coordinated lifetime-extension strategies qualified across ageing fleets with independent evidence of safety, residual life and recovery.
	Improving interoperability (with the same class of application) and between classes, modularity, and complementarity between generations of devices. (EC) Also, partially in ***Increasing the energy efficiency of computing systems***	Open interfaces demonstrated for interoperability between selected current and legacy device generations.	Qualified reusable function modules and virtualisation preserving compatibility across successive platforms.	Cross-generation interoperability qualified across independently maintained device families with governed interface evolution.
	Improving interoperability of AI functions (with the same class of application) and between classes, modularity, and complementarity between generations of devices. (eAI) Also, partially in ***Increasing the energy efficiency of computing systems***	Portable AI interfaces demonstrated across selected model/runtime families with numerical and resource-conformance tests.	Reusable AI modules qualified across device generations with traceable behaviour and update compatibility.	Federated AI-function replacement qualified across application families with monitored semantic compatibility and maintained assurance.

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2027–2031	**2032–2036**	**2037 AND BEYOND**
	Developing the concept of 2nd life for components (EC) (Link with sustainability)	Second-life edge modules demonstrated with health histories, secure sanitisation and use-case-specific requalification.	Reusable component libraries qualified with remaining-life evidence and traceable functionality.	Second-life qualification workflows validated across supply chains, including retraining and safe reuse.
Major Challenge 4: ensuring European sustainability of embedded intelligence	**Leveraging Open-source Hardware and Software for Innovation and Cost Reduction**	Maintained open embedded-AI software, models and hardware designs demonstrated with reproducible builds, licences and benchmarks.	Open hardware/software platforms qualified with verified interfaces, security maintenance and industrial support.	Sustained European open-platform ecosystems qualified across product generations with reproducible builds, long-term maintenance and verified reuse.
	Developing and Federating Smaller Specialized AI Models	Specialised small-model federations demonstrated with measured task quality, energy, communication cost and failure handling.	Cross-domain model federation qualified with auditable routing, interoperability and bounded actions.	Federated specialised models qualified across independently operated domains with controlled routing, drift management and auditable resource benefits.
	Training Models with European Data and Ethical Compliance	European-language/data adaptation demonstrated with provenance, representative evaluation, privacy controls and measured training energy.	Qualified cross-domain datasets and adaptation workflows with validated bias, privacy and energy trade-offs.	Continuously maintained European data/model ecosystems qualified with traceable rights, population coverage and independent fairness evaluation.
	Deploying Efficient and Sustainable Embedded AI-oriented ECS	Low-power edge-AI platforms demonstrated with event-driven processing, energy management and measured lifecycle benefits.	Qualified 3D/chiplet and neuromorphic platforms with secure code mobility and demonstrated application-level efficiency.	Successive embedded-AI technologies qualified through measured lifecycle resource benefits, repairability and maintained security.
	Accelerating Development of Robust, Cost-Effective Solutions	Reproducible continuous-engineering flows demonstrated for secure, modular edge AI with independent model and software checks.	Lifecycle engineering environments qualified for deployment, update assurance and evidence reuse across embedded-AI products.	Cross-organisational engineering services qualified across successive product generations with reusable assurance and measured lifecycle cost benefits.

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 layers is motivated by the Major Challenges that characterize them (see Figure 2.2.1).

2.2.1.1 Scope for OSI layers 1, 5 and 6

The scope covers the following types of physical-layer connectivity:

- Cellular:
  - Beyond 5G
  - 6G
  - Direct-to-cell (Supplemental Connectivity from Space scenario)
- Satellite communication
  - Low Earth orbit and geostationary orbits
  - Non-Terrestrial Networks
- Low-power wide-area:
  - Cellular: narrowband IoT, RedCap, LTE, 6G, etc.
  - Non-cellular: Sigfox, LoRa, M-Bus, etc.
- Low-power short-range:
  - Wireless: existing (Bluetooth, Wi-Fi, etc.) or innovative technologies (mmW, etc.).
  - Wired: covering both high-speed optical glass and plastic fibers, mmW plastic fibers, and copper interconnect (USB, DOCSIS, PCIe, UCIe, AIB, etc.).
- High-speed:
  - Wireless: point-to-point mmWave.
  - Wired: high-speed optical (800 Gb+, etc.) and copper interconnect (Ethernet, etc.).
- Very high-speed
  - On chiplets and SoCs, e.g. die-to-die connections

The main challenge will be to ensure European leadership in terms of connectivity technologies (for example, standards) as well as associated software and hardware technologies supporting the development of connectivity solutions (e.g. chipsets, modules, protocols, etc.). For genuine digital sovereignty, it would also be important to have user devices (phones, wearables, Physical AI devices) with secure connectivity based on EU or strategic partners' chips.

2.2.1.2 Scope for OSI layers 5 and 6

The scope addressed in this context is application-to-application interoperability 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, authentication, authorization, certificates, tokens and key distribution.
- Data semantics: supporting application-to-application understanding of transferred data/information.

LAYER		DATA UNIT	FUNTION
HOST LAYERS	7. Application		Network process to application.
	6. Presentation	Data	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	ENERGY	DIGITAL INDUSTRY	HEALTH AND WELLBEING	AGRIFOOD AND NATURAL RESOURCES	DIGITAL SOCIETY
	3.1	3.2	3.3	3.4	3.5	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 Application breakthroughs

Improvements in connectivity technology will have an impact on all ECS application areas. For health and well-being, connectivity and interoperability can enable faster translation of ideas into economically viable solutions, which can then be scaled up in everyday healthcare 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 in adopting technology-enabled care.
- Data communication technologies enabling interoperable wireless data infrastructure.
- E2CCC contributes to faster deployment and business uptake.

Connectivity for heterogeneous and chiplet integration enables European research, prototyping and large-scale production addressing market needs in key application domains such as automotive (SDV/RISC-V), HPC and industry.

Improved, secure and interoperable connectivity will further support healthcare and well-being application breakthroughs regarding, for example:

- Healthcare deployment through digital health platforms.
- A healthcare paradigm shift from treatment to 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 personalized and participative treatments for chronic and lifestyle-related diseases.
- Enabling more years of healthy life for an ageing population.
- Reducing digitalisation risks through highly secure solutions, including secure connectivity for digital healthcare solutions.

In the AI 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 program.
- Strengthening the competitiveness of the European industrial mobility digitization value chain.
- E2CCC contributes to faster deployment and business uptake.
- Enabling Physical AI use cases, e.g. for connected robots, drones, IoT devices and AI agents.

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 the connectivity required for integrating future heterogeneous energy grids.
- “Plug-and-play integration” of ECS into self-organized grids and multi-modal systems.
- Solving safety and security issues of self-organized grids and multi-modal systems.

- E2CCC contributes to faster deployment and business uptake.
- Reliable, low-latency communications for Physical AI devices and systems. Their connectivity must also be secure, e.g. through quantum-safe communications.

In the industry application domain, the provision of improved, robust, secure and interoperable connectivity will support closing gaps such as:

- Preparing for the 5G-Advanced and 6G era in communications technology, especially its manufacturing and engineering dimensions, and securing high-quality connectivity for Physical AI devices needed in Industry 5.0-type digital automation solutions
- Long-range communication technologies, optimized for machine-to-machine (M2M) communication, asynchronous event-based data exchange, a large numbers of devices, and ultra-low-bit-rate operation, are key elements for energy-autonomous and intermittently powered sensing systems, including distributed neuromorphic IoT infrastructures such as in smart farming.
- Addressing IoT cybersecurity and safety problems through attestation and security by design, as only safe, secure and trusted platforms will remain viable in industry.
- Interoperability-by-design at the component, semantic and application levels.
- IoT using cellular-network ISAC functionality, configuration and orchestration management to allow for the (semi)autonomous deployment and operation of large numbers of devices.
- E2CCC contributes to faster deployment and business uptake.
- Enabling efficient use of AI in Physical AI applications and placing AI inference at the network edge.

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, improving people’s employability and better protection against social or economic exclusion.
- Enabling European governments, companies and citizens to cooperate more closely and develop reliable societal emergency infrastructures.
- E2CCC contributes to faster deployment and business uptake.
- Boosting EU productivity and quality of life via scaled AI use and augmenting people’s actions with Agentic AI and connected Physical AI

In the agrifood application domain, the provision of improved, robust, secure and interoperable connectivity will support innovations addressing EU competitiveness, productivity and Green Deal objectives through:

- Improving European competitiveness and productivity for European sovereignty.
- Reducing the environmental impact related to transport, storage, packaging and food waste.
- Reducing water pollution and greenhouse gas emissions, including methane and nitrous oxide.
- Reducing the Europe’s cumulative carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agriculture and halting biodiversity loss.

2.2.3 Major Challenges

Five Major Challenges have been identified in the connectivity domain:

- **Major Challenge 1**: strengthening the EU connectivity technology portfolio (chips, products, systems, networks, AI cloud integrations, ISAC) to maintain leadership, secure sovereignty and offer an independent supply chain.
- **Major Challenge 2:** investigate innovative connectivity technology (new spectrum or improved spectral efficiency) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership.
- **Major Challenge 3**: autonomous interoperability translation for communication protocols, 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 from edge to cloud
- **Major Challenge 5**: network virtualisation enabling efficient and low-cost run-time and evolvable integration, deployment and management of edge-to-cloud network architectures.

2.2.3.1 *Major Challenge 1: Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain*

2.2.3.1.1 State of the art

Today's connectivity solutions require a highly complex electronic systems comprising various functions integrated into a wide range of technologies. This universe is currently being expanded by the advances in chiplet technology.

Note that advanced digital functions such as the application processor and the baseband modem are developed by a limited number of US and Asian players (MediaTek, Qualcomm and Samsung), and implemented in advanced complementary metal–oxide–semiconductor (CMOS) technology available by only two Asian companies (Taiwan Semiconductor Manufacturing Company, TSMC, and Samsung). On this last point, it is worth noting that through the US CHIPS Act, Intel, Samsung and TSMC will build new advanced logic (3 nm and below) 300 mm fabs in the US to further strengthen US sovereignty and supply chain.

The European Chips Act supports similar development but at a slower pace. Development of advanced nodes in Europe is still concentrated mainly in RTOs such as CEA-Leti and imec. Consequently, for the foreseeable future, Europe's most advanced semiconductor manufacturing capability will be limited to the 18/16 nm CMOS node, reflecting the products currently designed by European semiconductor players and required by key vertical sectors (automotive, industrial, ...). Europe would need to expand the market for connected end-user devices, which could also generate demand for advanced 2 nm fabs in Europe.

Cellular networks are one of the few European digital technologies with leading market positions (except China). For connectivity, European chip manufacturers (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. The cellular networks are provided by Nokia and Ericsson which have large, highly advanced system-on-chip design teams 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 standardization of future connectivity technologies. This point is crucial for securing European sovereignty in connectivity.

Moreover, over the past year, rising economic tensions 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 Tower Semiconductor) 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 a potential 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 offer connectivity chipset solutions (for example, Sequans Communications and Nordic Semiconductor in narrowband IoT) 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.

The use of chiplet technology to advance high-performance computing is well established. Here again, the US has a leading position supported by TSMC and Korean memory makers. In the connectivity market, European players such as Ericsson and Nokia are leading designers of very complex digital computational hardware for connectivity. This points to the potential value of supporting and engineering advanced chiplet technology in Europe.

2.2.3.1.2 VISION AND EXPECTED OUTCOME

To address identified connectivity technology challenges, we propose the vision described below, which can be summarized 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 Chapters 1.1 and 1.2):

- ***2 nm and more advanced system-on-chip design*** for 5GA and secure dual-use 6G networks including ISAC functionality (several advanced semiconductor technologies need to be developed in the EU for this purpose).
- ***Advanced BiCMOS***: targeting RF and sub-THz (i.e., 100–300 GHz) and THz front-end modules.
- ***RF SOI***: targeting <7 GHz and mmW front-end modules.
- ***GaN and GaN on Si***: 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 and K bands).

- ***InP & InP on Si***: targeting high-speed optical links (>800 Gb/s), mmW applications (6G sub-THz communication >100 GHz) and ultra-low-noise front-end modules in K band.
- ***Silicon Photonics***: targeting next-generation silicon photonics technologies (SiN waveguide, thin film LNO, magnetic optical isolator, etc.) to address both pluggable optics for data centre and AI-driven co-packaged optics solutions
- ***RF filters***: supporting the development of innovative European-based technologies (for example POI based TF SAW technologies below 5 GHz and spin-waves technologies above 5 GHz).
- Advanced logic in multiple-node technology chiplets for secure connectivity chips: RISC-V, AI inference, compute-in-memory and analogue computing.
- ***Advanced packaging***: enabling prototyping and medium-volume production capabilities in Europe to enable heterogeneous integration of differentiated technologies manufactured in Europe, helping European companies move higher in the value chain and capture more value.
- **Advanced high-speed chiplet technology for cost-efficient, medium-volume production in Europe.**
- Chiplet connectivity exploring standardised bus structures such as UCIe and AIB.

The main challenge will be to improve achievable performance while using less energy. To illustrate this, we refer to the historical 2025/2030 solid-state technology roadmap proposed by H2020 CSA project NEREID to serve as a connectivity roadmap (see Figure 2.2.3). The roadmap indicates 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 0.5 dB in the long term. The only parameter that differentiates the types of applications is the output power, which, for outdoor applications, 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 achieving the required frequencies. Technologies such as GaN/Si and RF SOI will deliver power but for applications operating at less than 100 GHz.

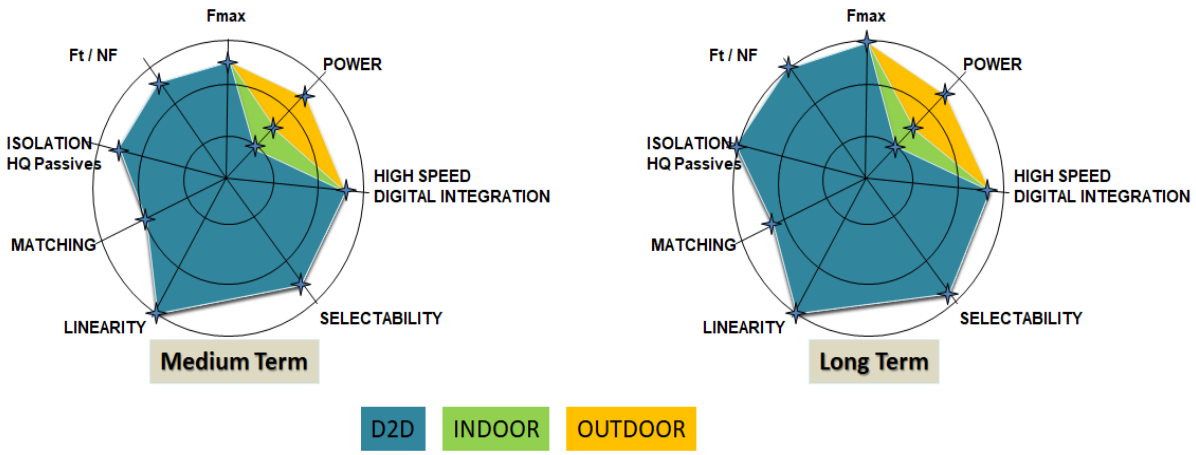

Figure 2.2.3 - Historical 2025/2030 solid-state technology roadmap proposed by H2020 CSA project NEREID[1]

Note that the vision presented in Figure 2.2.3 also applies to packaging, chiplet and printed circuit board (PCB) technologies. It is also worth noting that while Europe is playing a key role in innovative differentiated semiconductor and packaging technologies, R&D activity in heterogeneous packaging

[1] https://www.nereid-h2020.eu/

(chiplets) and PCBs needs further strengthening. This is a challenge that should be addressed to strengthen Europe's connectivity technology portfolio.

Securing Europe's differentiated hardware and heterogeneous packaging technology manufacturing

Beyond the development and enablement in Europe of innovative semiconductor, chiplet and packaging technologies targeting the connectivity market, it will be key to safeguard and promote European manufacturing capability to both secure Europe's economic interests (in terms of market share) and also address sovereignty concerns (since trade disputes can jeopardize the viability of Europe's industrial actors). To do so, in coordination with Chapters 1.1 and 1.2, the following topics should be supported:

- The enablement of pilot lines: the objective here is to support the deployment of additional manufacturing capabilities for technologies already available in Europe and to address chiplet and packaging technologies to better exploit the technology portfolio available in Europe.
- The rise of new semiconductor and packaging 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 also for advanced sub-3 nm semiconductors.
- Nurture a pan-European design ecosystem to tackle the new challenges involving More-than-Moore transistors, circuits and chiplet architectures with increased security and trustworthiness and new AI/ML chips arising in the digitalisation era (RISC-V, CiM, Analog).

Strengthening Europe's connectivity technology portfolio (hardware, packaging, protocols and software)

Leveraging the previously discussed portfolio of differentiated semiconductor and packaging technologies, innovative connectivity solutions should be encouraged to enable Europe to take full advantage of its technology and manufacturing assets. This action is crucial to secure Europe's position beyond 5G and 6G standardization and preliminary deployment activities. It also enables the development and manufacturing in Europe of highly integrated connectivity modules and 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 in the value chain, in coordination with Chapter 1.2 Components, Modules and Systems Integration.

In targeting systems and applications, it is important to consider the interconnection between subsystems, and focus should be on the development of individual component technologies according to needs identified at the system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous and chiplet integration is key.

Heterogeneous and chiplet 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, 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 slowing of traditional Moore's-law scaling. It is in the interconnection of the transistors and other components in the integrated circuit, chiplet, package or PCB, and at the system and global network levels that future limitations in terms

of performance, power, latency and cost reside. Overcoming these limitations will require heterogeneous chiplet integration of different materials (silicon, III-V, SiC, magnetics, etc.), devices (logic, AI, DSP, accelerators, memory, sensors, RF, analogue, etc) and technologies (electronics, photonics, MEMS, spin-waves and sensors).

2.2.3.1.3 Key focus areas

To support the vision presented in the previous paragraph, we propose to focus effort on the following key focus areas:

- Chiplet design, engineering and manufacturing for very-high-speed applications using polymer materials.
- Materials (GaN, InP, etc.) and large-diameter wafer technologies (POI, InP on Si, GaN on Si, garnets on Si, InP etc.) supporting the development of innovative connectivity technology solutions.
- Differentiated semiconductor technology development targeting connectivity applications.
- Pilot line enablement to support the strengthening of European manufacturing capability.
- Connectivity solutions engineering through virtualization of the different connectivity layers.
- Ensure EU leadership in 5G-Advanced and 6G secure critical infrastructure.
- Connectivity for very-high-speed, low-energy heterogeneous and chiplet integration.
- Ultra-low-power transceivers with low eco-footprint.
- Power- and cost-efficient transceivers including data conversion (ADC-DAC), up & down frequency conversion (LO & mixers), and RF transmission and reception (PA-LNA).
- Advanced system-on-chip design for CMOS and new technologies such as GaN, InP, InP on Si, GaN on Si.
- Innovative EDA solutions leveraging AI capability.
- Enabling an EU fabless ecosystem which could leverage advanced semiconductor manufacturing in Europe and strengthen the EU position in the value chain starting from a significant boost in secure-connectivity chip design activities.

2.2.3.2 Major Challenge 2: Investigate innovative wireless connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership

2.2.3.2.1 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 advantages of using new spectrum (especially the 6–15 GHz band and mmW frequencies >100 GHz)

With the ongoing deployment of 5G below 6 GHz, the R&D currently focuses on on the spectrum considered for 6G development targeting the 2030-time horizon with early launches in 2028. Three main frequency bands are today discussed in the telecommunication industry (following the recent decision of WRC-23 in December 2023):

Low band (6.425 GHz – 7.125 GHz):

One of the significant outcomes of WRC-23 was the identification of the 6.425 GHz – 7.125 GHz band for potential licensed mobile use while the lower 6 GHz spectrum (5.925 GHz – 6.425 GHz) will remain available for unlicensed usage (namely Wi-Fi). WRC-23 thus gave a balanced decision which supported both services. We can note that while this new spectrum will be the main 6G one identified by most regions to start deployment around 2030, the USA has adopted a different position. While China is considering allocating even the lower 6 GHz spectrum for IMT services, the US did the opposite and the FCC allocated the full 5.925 GHz – 7.125 GHz band for Wi-Fi (raising the question of which low frequency spectrum may be used to deploy 6G in the USA). Development of wireless systems in the 6.425 GHz – 7.125 GHz will likely be incremental to previous one <6 GHz, however we can mention that PA efficiency (including potential GaN opportunities in handsets) and filtering technology (due to coexistence issues with Wi-Fi) seem to be the main challenges today.

Mid band (7.125 GHz – 8.4 GHz):

WRC-23 also set the agenda for the next World Radiocommunication Conference in 2027 (WRC-27) with a clear roadmap for future IMT spectrum allocations. One of the keys identified new spectrum bands to be evaluated is the 7.125 GHz - 8.4 GHz one since it seems to be the most likely solution to add new spectrum for 6G deployment in the US (a federal spectrum study working group started in March 2024 with the goal of releasing a final report on potential commercial access to the band by October 2026).
Since it may prove difficult to clear this entire spectrum from existing usage, we can note that the 7.75 GHz – 8.4 GHz band is attracting a lot of attention since such scenario poses less technical difficulty and has the advantage to be considered by regions other than the USA.
From a hardware technology point of view, working over 8 GHz will bring several challenges. From the PA perspective, we can wonder if GaAs HBT technology will remain relevant. From the filter perspective, it is not clear if existing filter technologies will provide acceptable performances. Agile, frequency-tunable, analogue spin-wave based RF devices (filters, delay lines, frequency-selective limiters) with low footprint might answer this challenge. 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 and for emerging agile spin-wave based technologies.

NTN in Ku & Ka bands:

In addition to new spectrum requirements previously mentioned, 6G envisages seamlessly integrating 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 Low Earth orbit satellite constellations being deployed to complement the cellular network coverage while offering performance (latency and data rate) suitable for real-time applications.

Two main challenges will have to be addressed: seamless integration and handover of satellite connectivity with cellular connectivity (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).

We should also note that, in the NTN context, Supplemental Connectivity from Space is a new trend to be kept in mind. The idea consists in reusing frequency bands used by cellular operators on the ground to complement their existing cellular network with a LEO satellite connectivity. The main ongoing development concerns what SpaceX and T-Mobile are doing in the US. The advantage here is to leverage an installed base of user equipment (4G smartphones) since the only new hardware is from the infrastructure side (the LEO satellite constellation). This development is today limited to what regulators authorise in their markets (for example the FCC in the US), but if successful this approach could disrupt the current 3GPP view on NTN.

While R&D developments currently focus on frequencies below 15 GHz, there is some interest in assessing achievable performances with a higher frequency (even if now standardisation activities are currently ongoing either from 3GPP or WRC side). D band (~140 GHz) remains a strong topic of interest. For regulatory reasons, the 275 GHz – 325 GHz range holds promise as it enables the widest available bandwidth. As an illustration, the US has facilitated 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[2]: "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 frequencies, new hardware technology may be required and InP is currently an important research topic to enable low-noise receivers and power-efficient power amplifiers > 100 GHz.

[2] https://www.ericsson.com/en/blog/2022/11/why-its-time-to-talk-6g

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 conceptualize AI-enabled 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 optimizing 6G architectures, protocols and operations and as basic technology used in 6G products and systems to enable secure, optimized communications.

For example, two key 5G technologies are software-defined networking (SDN) and network functions virtualization (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 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 much 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 to changing network dynamics. Some applications may use COTS semiconductors but for ultimate optimization also custom-made connectivity system chips will be needed.

Given the integration of wireless, wired and legacy industrial edge connectivity, heterogeneous network virtualisation is of increasing importance to the System-of-Systems (SoS) integration in all application domains. Manageable virtual heterogeneous networks from edge to cloud will become a strong competitive advancement in the near future. Given the expected network complexity, AI-assisted and partly autonomous management is clearly important.

2.2.3.2.2 Vision and expected outcome

To address identified connectivity technology challenges, we propose the vision described below, which can be summarized in the following three points (with associated expected outcomes).

Assess achievable connectivity performances using new spectrum

To maintain European leadership on connectivity technology and ensure sovereignty, the development of new electronics systems targeting connectivity applications in not yet standardised (or in the process of being standardized) spectrum should be supported. A special focus should be dedicated to the frequency bands listed below:

- ***6G connectivity enablement in the 6.425 GHz – 7.125 GHz band***: This band having been identified as the main one to be deployed in the short term for 6G, it is of strategic importance to ensure both sovereign European hardware development and a timely spectrum allocation to operators to secure the position of the EU in the 6G race.
- ***Investigation of additional 6G spectrum in the 7.75 GHz – 8.4 GHz band***: This band being the most likely one in the medium term to support 6G deployment in the US, and also being a serious option to offer additional 6G spectrum worldwide, the EU must ensure a pragmatic evaluation of this spectrum to both be able to play a role in WRC standardisation activities and secure the market share of EU wireless infrastructure players on the US wireless market.
- ***Investigation of Supplemental Connectivity from Space in existing 4G and 5G bands***: While NTN in Ku and Ka band is today a hot topic inside 3GPP, it cannot be excluded that the SCS

approach, pushed by SpaceX and T-Mobile, may disrupt the current NTN approach (in a very pragmatic way). Consequently, Evaluation of SCS scenarios in the EU leveraging existing cellular 4G and 5G spectrum should be encouraged and dedicated R&D activities supported to secure this technical option in EU and ensure both an EU-sovereign connectivity solution and possible business opportunities for EU actors.

- ***Investigate possible deployment of Wi-Fi 8 at 60 GHz***: In the context of Wi-Fi 8 standard definition, Intel and other players have been pushing the support of the 60 GHz band to enable mmWave-based Wi-Fi connectivity (and achieve higher data rates than Wi-Fi-7 in a power-efficient manner). The IEEE 802.11 Integrated Millimeter Wave Study Group (IMMW SG) has been specifically created in 2023 to investigate this scenario and decide on the addition of the 60 GHz band to the Wi-Fi standard. R&D activity on this topic in EU should be encouraged to ensure that if selected this licence-free frequency band could be leveraged in EU to enable affordable high-speed connectivity to the market.
- ***Sub-THz connectivity application in D band (~140 GHz) and > 200 GHz***: With THz communication being a hot topic in the international academic community (especially in the US and China), European activity in the spectrum > 200 GHz should be encouraged (with a special focus on high speed point-to-point wireless links). These investigations should help Europe play a role in the development of the new technology and assess its relevance for future standardization activities.

Integrate AI features to make connectivity technology faster, smarter and more power-efficient

The use of new spectrum or propagation media is not the only way to boost innovative connectivity technology. As mentioned, 5G has underlined the role of software to promote virtualization 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, where first chips are already in RDI phase).

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 the mobile device’s computing capabilities. Moreover, processing data locally reduces the need to stream and store large amounts 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 aim is to move towards an AI-empowered connectivity network to go beyond the concept of virtualization and achieve improvements in efficiency and adaptability. For example, AI could play a critical role in designing and optimizing 6G architectures, protocols and operations (e.g. resource management, power consumption and improved network performance).

2.2.3.2.3 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 spectrum.
- Investigation and standardization activity targeting 6G cellular application in the frequency band < 15 GHz with an early pre-2032 focus on 3-8 GHz bands
- Development of innovative connectivity technology using unlicensed frequencies in the 6–15 GHz band.
- Development of connectivity systems leveraging the concept of edge AI and AI-native chips and algorithms in 6G products and systems
- Evaluation of the AI concept to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability.

2.2.3.3 Major Challenge 3: Autonomous interoperability translation for communication protocols, data encoding, compression, security and information semantics

2.2.3.3.1 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 advanced by Industry 4.0/5.0 initiatives backed by the EC and most EU countries. In the automotive sector, the software-defined vehicle initiative is a driver of the autonomous and green car vision. 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 application-to-application connectivity, prepared for interaction in System-of-Systems (SoS) solutions and benefiting from Physical AI, is fundamental to market success in these and other areas.

Interoperability is a growing concern among numerous industrial players. An example is the formation of industrial alliances and associated interoperability project efforts. One approach is to converge on a few widely adopted standards. An example of this is showcased in Figure 2.2.4.

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 infrastructure, and AI-enabled engineering support.
- Novel, flexible and manageable security solutions.
- Standardization of the above technologies.
- Interoperability within chiplets and heterogeneous packaging.

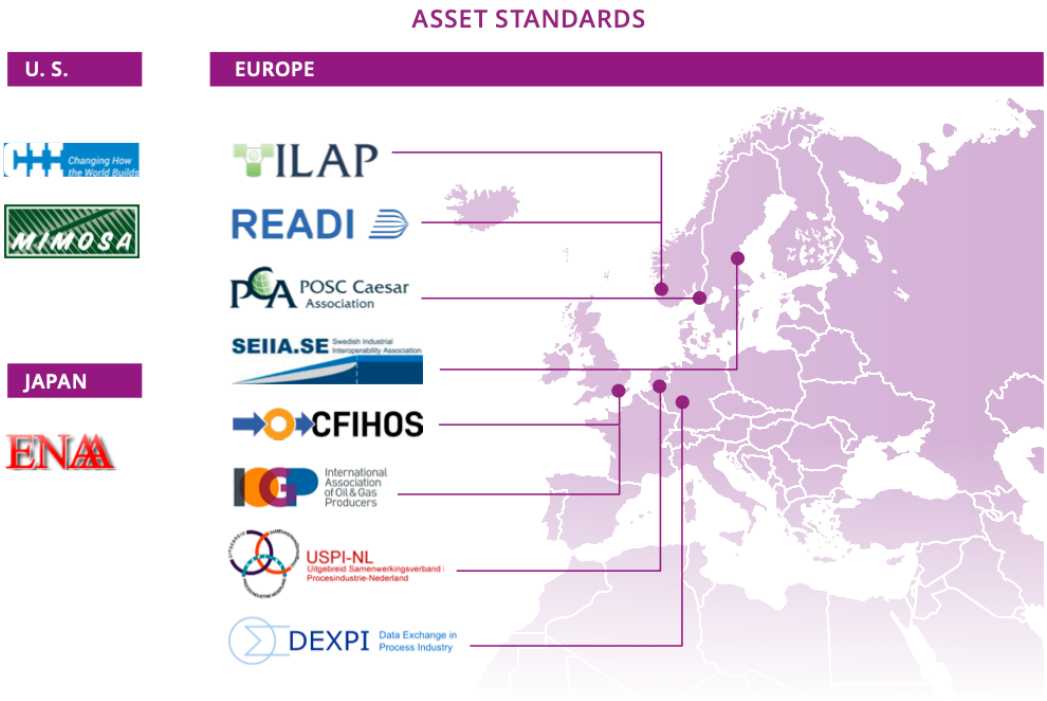

Figure 2.2.4 - ISO 15926 – Asset Standards worldwide (Source: Erik Molin, SEIIA)

2.2.3.3.2 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 the use of available data for all areas of application. To do so, dedicated software tools, reference architecture infrastructure 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 data semantics. Here, payload semantics interoperability is a primary focus, leading to architectures, ontologies, technologies and engineering tools that support application-to-application integration of SoS for all areas of applications at design time, at run time and throughout the lifecycle. This will include e.g. the integration of and 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 SoS architecture infrastructure with reference implementation supporting interoperability, security, scalability, smartness and evolvability from system-on-chip through chiplets to multiple technology platforms, such as Wi-Fi, 5G & 6G.
- Open-source engineering and implementation infrastructure for the de facto standard SoS connectivity architecture.

- SoC, chiplet and SOA architecture reference implementations with performance that meets critical performance requirements in focused application areas.
- Use of AI workflow automation, AI agents and Physical AI in the above concepts.

2.2.3.3.3 Key focus areas

The high-priority technical and scientific challenges in both design-time and run-time are:

- Semantic interoperability from application to application.
- Autonomous translation of connectivity protocols, encodings, security and semantics.
- Evolvable SoS connectivity architecture infrastructure and technologies over time and technology generations.

2.2.3.4 Major Challenge 4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

2.2.3.4.1 State of the art

It is clear that the US is the leader when it comes to wired IP-connectivity while Europe is the leader in cellular IP-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 integration of IP-connectivity with the vast industrial legacy edge connectivity needs a special focus. Such focus will foster a faster industrial and societal digitalization enabling the integration of efficient and optimizable flexible production value networks. Given the longevity of such IP and legacy connectivity, the lifecycle perspective across technology lifetimes and generations will need special considerations. In certain domains such as automotive and industrial automation, Europe is the major player. Market studies[3] indicate very substantial growth in the SoS market over the next five to ten years. This will provide a very strong market pull for all technologies and products upstream. Here, connectivity interoperability is an 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.

2.2.3.4.2 Vision and expected outcome

The enabling of SoS interoperable 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 establishing interoperable connectivity architectures, reference implementation and associated engineering frameworks.

[3] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.

The identified game changers are:

- Establishment of connectivity architecture infrastructure with associated reference implementation and related engineering frameworks and associated standardisation
- SoS application-to-application connectivity being interoperable, secure, scalable, smart and evolvable over technology generations.

Expected achievements

- Open-source implementation of reference architecture infrastructure supporting interoperability, security, scalability, smartness and evolvability across multiple technology platforms, from SoC and chiplets to Wi-Fi, 5G/6G, wired and optical connectivity.
- Open-source engineering and implementation frameworks for the de facto standard SoS connectivity architecture infrastructure.
- Architecture infrastructure reference implementations which meet critical performance requirements in focused application areas.

2.2.3.4.3 Key focus areas

The high-priority technical and scientific challenges are:

- SoS interoperable connectivity architecture infrastructure as a de-facto standard.
- Reference implementation of de facto SoS connectivity architectures.
- Engineering frameworks for de-facto standard SoS connectivity architecture.

2.2.3.5 Major Challenge 5: Network virtualisation enabling run-time engineering, deployment and management of edge-to-cloud network architectures.

2.2.3.5.1 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 including the vast industrial legacy edge connectivity. Current state of the art has large technological differences between legacy and IP-based connectivity. This also includes technological and operational competences in the industry and society. Thus, wide and flexible digitalisation of industrial and societal value networks is rather limited.

2.2.3.5.2 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, network orchestration, 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 SoC and chiplets to Wi-Fi, 5G and 6G while also supporting legacy connectivity.

The identified game changers are:

- Technologies for access, control and data network virtualisation across multiple hardware and software layers using heterogeneous devices based on SoC, chiplets and PCB systems.
- Engineering, integration and management tools and methodologies for engineering and operation of virtualized legacy, IoT and SoS networks and service components of technology and system lifecycles.
  Intelligent network orchestration supporting heterogeneous technology and multistakeholder integration from edge to cloud.
- Intelligent and run-time re-organisation of hardware platforms.

Expected achievements:

- Open-source implementation of reference architectures supporting virtualised connectivity across multiple technology platforms from industrial legacy to IP-based 5G, 6G, wired and optical.
- Open-source engineering and management frameworks for virtualised connectivity across multiple technology platforms from industrial legacy to IP-based 5G, 6G, wired and optical.
- Reference implementations with performance that meets critical performance requirements in focused application areas taking into consideration energy efficiency.
- Run-time re-organization of hardware and software platforms.

2.2.3.5.3 Key focus areas

The high-priority technical and scientific challenges are:

- Virtual connectivity architecture supporting multiple technology platforms.
- Reference implementation of virtual connectivity architecture supporting dynamic network orchestration enabling highly efficient application-level use.
- Engineering, integration and management frameworks with tools for virtual connectivity architectures.

2.2.4 Timeline

The timeline for addressing the Major Challenges in this section is provided in the following table.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 1: Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain	Topic 1.1: Materials (GaN, InP, etc.) and large-diameter wafer technologies (POI, InP on Si, GaN on Si, InP etc.) supporting the development of innovative connectivity technology solutions.	Qualified GaN, InP and POI RF process demonstrators with repeatable wafer-level performance and reliability data.	Selected RF processes transferred to production with validated yield, packaging and supply-chain capability.	Successive RF material and wafer generations qualified with transferable process, yield and lifecycle reliability evidence.
	Topic 1.2: Differentiated semiconductor technology development targeting connectivity applications.	Next-generation RF SOI and BiCMOS transceiver prototypes validated for target-band efficiency, linearity and integration.	Production-qualified RF platforms supporting evolving cellular and satellite connectivity requirements.	Reconfigurable RF platforms qualified across successive connectivity generations.
	Topic 1.3: Chiplet, packaging and PCB technology targeting connectivity applications.	Interoperable RF/digital chiplet and heterogeneous-package demonstrators with verified thermal, signal-integrity and test performance.	Manufacturable reference platforms with qualified die-to-die interfaces and multi-supplier integration.	Reconfigurable heterogeneous RF platforms qualified across successive die generations with maintained interoperability and thermal reliability.
	Topic 1.4: Connectivity solution engineering through virtualization of the different connectivity layers	Virtualised connectivity prototypes validated on COTS hardware against latency, energy and security requirements.	Cross-vendor virtualisation validated across hardware accelerators, radio and industrial-edge platforms.	Runtime reconfiguration qualified across independently operated connectivity domains.
	Topic 1.5: Connectivity for very high-speed low energy heterogeneous and chiplet integration	Integrated low-energy transceiver and interconnect demonstrators using European differentiated technologies.	Full-transceiver and chiplet-link platforms qualified against application-level energy and bandwidth targets.	Scalable heterogeneous connectivity platforms qualified for sustained operation under changing workloads.
	Topic 1.6: Ultra-low power transceivers with low eco-footprint	Ultra-low-power transceivers demonstrated in energy-constrained sensing systems, with measured link reliability and lifecycle energy use.	Manufacturing-qualified transceivers supporting secure, intermittently powered deployments at scale.	Long-lived sensing networks qualified for secure autonomous operation under intermittent energy, ageing and component replacement.
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	Topic 2.1: innovative connectivity system design using new spectrum	New-band RF demonstrators for centimetric spectrum and selected sub-THz point-to-point use cases, subject to spectrum availability.	Qualified transceivers for commercially viable new-band applications with validated range, efficiency and coexistence.	Selected sub-THz systems qualified for specialist deployments; no assumption of universal wide-area adoption.
	Topic 2.2: investigation and standardisation activities targeting 6G cellular application in frequency bands below 10 GHz	Standards-aligned first-generation 6G chipset and radio prototypes, including candidate mid-bands, subject to WRC-27 decisions and allocations.	Interoperable 6G products with improved RF efficiency, coexistence and integrated terrestrial/non-terrestrial operation.	Later-generation 6G platforms qualified for evolving bands and application requirements.
	Topic 2.3: development of innovative connectivity technology using unlicensed frequencies in the 6–7 GHz and 60 GHz bands	Wi-Fi 8 prototypes and early products focused on reliability, multi-AP coordination and coexistence; separate assessment of 60 GHz integration.	Interoperable low-energy Wi-Fi platforms validated in industrial and dense deployments. Wi-Fi 7 is an existing baseline.	Successive unlicensed-radio platforms qualified for dependable coexistence and coordinated operation in evolving industrial deployments.
	Topic 2.4: development of connectivity systems leveraging the concept of edge AI	Edge-AI connectivity systems demonstrated with local inference, reduced transmitted data and measured energy/privacy benefits.	Cross-vendor inference placement validated across devices and edge networks under latency, energy and security constraints.	Federated radio-edge optimisation qualified across operators with bounded autonomy, auditable policies and verified recovery.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
	Topic 2.5: 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	AI-assisted network control validated in operational trials with monitored decisions, bounded actions and safe fallback.	Closed-loop optimisation qualified across vendors and network domains, with auditable policies and stability checks.	Bounded autonomous network coordination validated across independently managed domains.
Major Challenge 3: Autonomous interoperability translation for communication protocols, data encoding, compression, security and information semantics	Topic 3.1: semantic interoperability from application to application.	AI-assisted semantic mappings validated for selected ontologies, with provenance, confidence checks and human approval for ambiguity.	Cross-standard semantic integration qualified in selected application domains with explicit loss and consistency checks.	Cross-domain semantic mediation validated under controlled vocabulary evolution and auditable governance.
	Topic 3.2: autonomous translation of protocols, encodings, security and semantics	Dynamic protocol and encoding gateways validated with explicit trust boundaries and preserved authentication and authorisation.	Runtime translation of selected ECS data models qualified with versioning, access-control and semantic validation.	Bounded translation across heterogeneous legacy models validated with explicit handling of unsupported semantics.
	Topic 3.3: evolvable SoS connectivity architecture infrastructure and technologies over time and technology generations	AI-assisted infrastructure migration validated against compatibility and security requirements.	Formal and AI-assisted tools qualified for controlled evolution across connectivity generations.	Continuous verification qualified for evolving, multi-operator connectivity infrastructures.
Major Challenge 4: architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	Topic 4.1: SoS interoperable connectivity architecture infrastructure as a de-facto standard	Service-oriented connectivity architectures validated within selected ECS domains, using open interfaces and conformance tests.	Cross-domain reference architectures qualified through multi-vendor deployments and measurable interoperability.	Federated connectivity architectures validated across industrial and societal services with independent governance.
	Topic 4.2: reference implementation of de facto SoS connectivity architectures	Open reference implementations demonstrated with secure discovery, configuration and legacy integration.	Reference implementations qualified for cross-domain deployment, operation and lifecycle updates.	Semantic-interoperability extensions validated across evolving reference implementations and data models.
	Topic 4.3: engineering frameworks for de facto standard SoS connectivity architecture	Engineering frameworks validated for automated configuration and conformance checking of selected connectivity platforms.	Reusable toolchains qualified across vendors, including regression tests for interface and security changes.	Engineering frameworks qualified for controlled semantic-model migration across domains.
Major Challenge 5: network virtualisation enabling run-time engineering, integration, deployment and management of edge-to-cloud network architectures	Topic 5.1: Virtual connectivity architecture supporting multiple technology platforms,	Distributed virtual connectivity management demonstrated from devices to edge and cloud on selected platforms.	Legacy and IP-based platforms integrated with verified performance isolation and policy enforcement.	Federated management validated across independently administered legacy and IP networks.
	Topic 5.2: Reference implementation of virtual connectivity architecture enabling very efficient application-level usage.	Programmable multi-platform connectivity demonstrated with measured application latency, energy and integration effort.	Accelerated edge-to-cloud reference systems qualified against realistic cost and workload baselines.	Cross-domain reference systems validated for legacy/IP coexistence and safe runtime reconfiguration.
	Topic 5.3: Engineering, integration and management frameworks	Engineering toolchains demonstrated for deployment and lifecycle management across selected connectivity technologies.	Toolchains qualified for repeatable multi-vendor deployment, monitoring and recovery in edge-to-cloud systems.	Runtime migration toolchains qualified across legacy and IP generations with verified continuity.

2.3



Cross-Sectional Technologies

ARCHITECTURE AND DESIGN: METHODS AND TOOLS

2.3 ARCHITECTURE AND DESIGN: METHODS AND TOOLS

2.3.1 Scope

Two assets are essential to strengthen European industry's potential to transform new concepts and ideas cost- and effort-effectively into high-value and high-quality innovations and applications based on electronic components and systems (ECS): 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. The trend towards Software-defined Vehicles in the automotive industry as well as to cloud- and edge-based architectures there and in other industries are major examples of such effective architectures and platforms; the increasing adoption of AI-enabled engineering technologies across all phases of design, modelling, simulation, verification, validation, test, configuration and commissioning leveraging frameworks in all application domains is transforming the efficiency of ECS development, as well as ECS operation.

Effective architectures and platforms and efficient engineering tools and frameworks are key enablers for producing ECS-based innovations that are: (i) beneficial for society; (ii) accepted and trusted by end-users; and thus (iii) successful in the market. Alongside these technologically driven advancements and benefits, the methods in this chapter also further the European goal of supporting sustainability (cf. Chapter 0), both by advancing the creation of sustainable components and systems, as well as by supporting their creation in a sustainable way.

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 a virtual integration platform leveraging Digital Twin and Industrial Metaverse technologies or a system of systems (SoS, cf. chapter 1.4). Their functionality will largely be 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 enable 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). 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 use of all cross-cutting technologies (cf. Part 2).

Design processes, methods, and frameworks

Engineers need to be able to create ECS-based products of ever-increasing functionality, complexity, and diversity that need to meet ever more demanding quality standards (i.e., with respect to safety, security, reliability, etc.), while still working cost- and effort-effectively. While the advent of AI-supported development methods at first sight seems to be helpful in this respect, the corresponding increase in testing effort offsets this effect considerably. Structured and well-defined design processes and methods are needed to ensure that high-quality standards can be met cost- and effort-efficiently. These design processes constantly need to be adapted and to incorporate new methods and tools, as well as completely new approaches to design and validation of ECS. One major change in design processes in recent years is that the essentially linear traditional processes that typically end at market

introduction are extended to so-called continuous design processes that: (a) span the whole lifecycle of a product, (b) leverage data and models of the supply chain for commercial components (Digital Thread), (c) use data collected from production, operation, and maintenance to improve on the original design, and (d) employ agile development methods and leverage novel AI technologies to move from AI-assisted engineering towards AI-enabled autonomous engineering.

The extension to cover the whole lifecycle, both for the initial design and development as well as for updates, enables additional product and production capabilities such as DPPs (digital product passports) and LCA (life-cycle assessment) and, generally speaking, all measures that help minimise environmental footprints. These non-technical challenges are becoming increasingly important and are at least demanded, if not even mandated, by society.

Collected data are used 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; and (iii) increase the effectiveness of validation and test steps by virtual validation methods based on this data. Apart from the technical challenges in collecting and analysing this data and/or using it for maintenance purposes, additional non-technical challenges include compliance with the applicable data protection regulations and privacy concerns of system owners (Intellectual Property) and users (personal data).

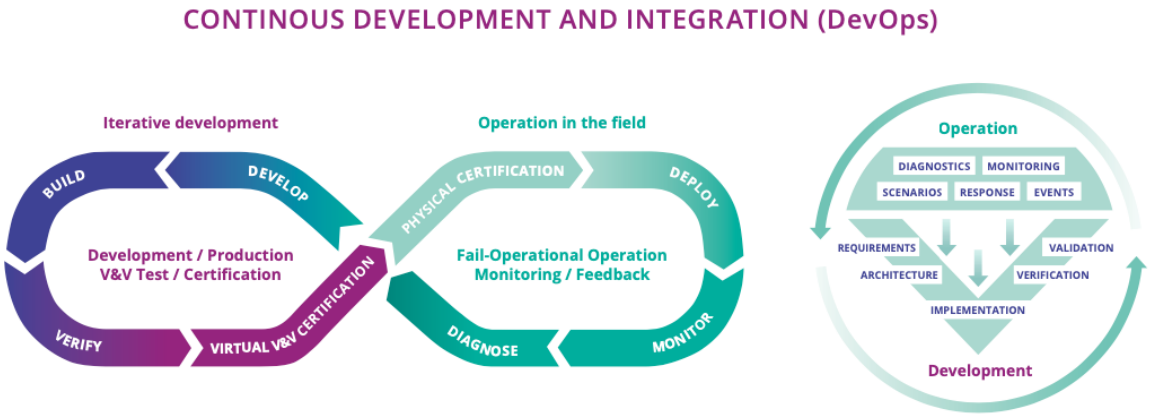

Figure 2.3.1 Simplified examples for continuous development processes (DevOps processes), employing agile development methods and leveraging novel AI technologies to transform from AI-assisted engineering towards AI-enabled autonomous engineering. Note that the 'deploy' activity is ideally possible for 'systems in the field', too, using over-the-air updates for both software modules and (chiplet-based) HW functionality.

Virtual Engineering

While model-based design techniques have long been a major instrument to decrease both design complexity and corresponding validation effort, they are now also a main enabler of the shift to virtual engineering and virtual validation (aka shift-left). This shift, in turn, is essential for cost- and effort-efficient design and is also mirrored in current regulations such as type approval and certification. With virtual engineering, much of the design effort can be done 'virtually' – i.e. by creating and using digital twins and formal models and/or simulation-based verification, test and validation methods. Additional supporting techniques are 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 organizational level – i.e. by employing open-source solutions such as RISC-V (cf. Appendix A) or the various open-source integration platforms (cf. Chapters 1.3 and 1.4), to increase interoperability and thus cooperation.

AI-support

The most impactful change is the transition to AI- and formal-method-supported engineering systems, not only enabling the offloading of work-intensive routines (like coding) to machines, but, more importantly, enabling autonomous execution of certain phases of system design and verification, and ultimately autonomous design and verification of systems directly from requirements. Both types of support free up engineering time for more advanced activities and thus reduce costs and time to market.

Trust

The resulting agile AI-supported continuous development processes employing virtual validation methods will ease assurance of quality properties 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 and test the features that those development methodologies support ("quality-by-design solutions"). The goal is to provide solutions and systems that one can trust to be of the highest quality, i.e. safe, secure, reliable, etc. 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) such as safety, security, dependability and reliability. Trustworthiness of ECS-based applications, however, 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 (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 tool chains providing engineers with the means to handle the complexity and diversity of future ECS-based systems.
    - Integrating these engineering frameworks with agentic AI technologies for orchestration, reasoning and the generative capabilities needed to design and verify 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 along the semiconductor and supplier value chains as trustworthy Digital Threads. Note that interoperability here has two aspects: (a) technical interoperability as a basis that the various parts and subsystems of the platforms can communicate at all and which is a prerequisite for (b) information interoperability (starting with semantic interoperability) which ensures that the subsystems can effectively exchange information (that they 'can understand each other'), see also Chpt. 1.4.

- 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 and security – 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, among 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.

2.3.2 Major Challenges

We have identified four major challenges within the transversal topic "Architecture and Design: Methods and Tools".

- **Major Challenge 1**: Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS. The ever-increasing functionality of ECS, emergence of new technologies, and the high demands for validation and testing to ensure their quality drive the need for efficient, AI-supported design and validation processes, frameworks and tools.
- **Major Challenge 2:** Sustainable Engineering for Sustainable ECS. Methods and tools to support the design and validation of sustainable ECS while also supporting a sustainable design and validation process.
- **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 the key objective of this challenge.

Together, these four challenges answer the need for software tools and frameworks for engineering support for sustainable high-quality ECS covering the whole lifecycle. These four challenges are highly interconnected, and can hardly be considered separately: First, advancements in one challenge often also imply advancements in other challenges. For example, techniques to reduce the complexity of the ECS-based system from Major Challenge 3 often also result in a decrease of cost and effort for validation and test within the design and validation process (and corresponding framework), as

described in Major Challenge 1. Second, solutions in one Major Challenge often also require at least partial solutions in other Major Challenges to be applicable.

This especially holds true for AI-enabled design technologies ranging from enhancing solvers and kernels for design synthesis and simulation (e.g., reinforcement learning technologies) up to the orchestration including analysis, decision making and adaptation (e.g., agentic AI technologies) transforming an engineer into a technical team leader for design and verification AI agents addressing all major challenges simultaneously.

2.3.2.1 Major Challenge 1: Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS.

2.3.2.1.1 State of the art

Future ECS-based systems need to be connected, intelligent, highly automated, and even autonomous and evolvable. This implies a huge variety of challenges, including: how to specify their behaviour in an open environment in terms that can be used as requirements for implementation and validation; how to validate autonomous systems at all; 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.

With the increased functionality of ECS and with the increasing demands on testing and validating them, engineers need tool support to enable them to design, build, test and validate, produce and maintain such complex systems; these tools need to be integrated into seamless design flows (frameworks) such that the effort and the cost associated with these tasks ideally remain constant even though functionality and validation demands increase. New functionality of ECS that cannot be handled by currently available tools requires new methods which, when successful, lead to additional design and validation tools. New technologies – or technologies that are new to ECS, like chiplets – often don’t have sufficient tool support, leading to the integration of stand-alone tools into frameworks.

Model-based Systems Engineering (MBSE) technologies will be disrupted by the latest AI technologies (e.g. generative AI and agentic AI), increasing design and verification productivity significantly. The fact that MBSE is becoming strongly connected to formally based languages, e.g., SysML v2, opens interesting interactions between formal and AI-based technologies, both in design and in validation and verification efforts. For ECS design, HW–SW-codesign is still limited by the capabilities of individuals. AI technologies will make collective expertise and collective data of whole industries available for an individual ECS design challenge. There are two scenarios to be addressed: (1) ECS design built upon commercial off-the-shelf (COTS) electronic components; and (2) ECS design down to new IC design. From an architecture design perspective, HW–SW-codesign requires virtual platform (VP) ready models for all COTS components to support architecture exploration and verification, as well as early SW development. For the latter, a VP-ready model of design IP is required for architecture exploration and verification, as well as early SW development. VPs integrated with established CI/CD pipelines for SW development ensure productivity and correctness of the development process.

To foresee the physical implementation of new ICs (and parts thereof, e.g., chiplets) in this early design stage of ECS, VPs need to be extended with additional attributes beyond functionality alone – such as timing performance, energy metrics, lifetime metrics, etc. AI technologies are expected to support the

design of architectures and take on the cumbersome generative tasks of engineers. Such capabilities are expected to serve as a kind of “copilot” for engineers in the first phase but will become increasingly automated in medium-term ECS design up to becoming fully autonomous. An important prerequisite for this increase in functionality is that testing, validation and verification functionality is also extended to include AI-generated artefacts. AI support can help here, too, especially by ensuring compliance-by-design and automated evidence generation, but care must be taken to ensure independence between a ‘executing’ AI (designer or implementer of the artefact) and a ‘testing’ AI (quality tester of the artefact). Functional integration technologies like chiplets open a new dimension of challenges in architecture exploration beyond conventional PCB design leveraging COTS components.

As with the architecture phase, the implementation phase of ECS will also be disrupted by AI technologies. AI-enabled design of functional models for SW and HW is already state-of-the-art, in spite of the increased challenges for ensuring quality aspects like safety and security in these designs. Copilots are widely used in SW development and have already begun to enter RTL design. The democratisation of IC design for ECS is the systematic enablement for design of optimised architectures and complete functional models of ICs. The downstream design flow steps for physical implementation require deep physical knowledge of manufacturing processes, which are standardised for PCB-based HW and enabled by the EMS ecosystem, but is highly sophisticated for ICs and deeply embodied in business models with foundries and IDMs as core stakeholders maintaining process technology and IP.

The Virtual Design Platform initiative at the European level is building an interface between proprietary process technology, open-source design IP, open-source EDA tools primarily addressing functional design and proprietary design IP and proprietary EDA tools, especially addressing the physical implementation phase of the design. Innovation is required at the interface to ECS system design through more complete, efficient and innovative design IP, as well as AI-enabled innovation for system design down to RTL as the formal specification for ICs for fully automated physical implementation, production and subsequent testing.

A rich and trustworthy ecosystem of design IPs, models, data and tools requires Digital Thread technologies to govern and ensure collaboration, as well as supporting design of compliant and certification-ready ECS products.

Both technology push, which enables new functionalities, and – even more – market pull (i.e. demand for new functions in products) are extremely strong in ECS. This is why design methods often lag behind current development methods. This holds even more true for validation tools, where there are prominent examples – like showing safety for systems with functions based on AI – for which even the methods used are not yet complete, let alone their implementation in appropriate tools. This leads to the absurd situation that although the technologies needed for specific functions are available and even though the market demands these functions, engineers cannot deliver them at all, or not in the required quality (i.e. safety) or not at an affordable price (because the effort, and thus the cost, for manufacturers to build and validate these systems is too high).

2.3.2.1.2 Vision and expected outcome

The vision is to enable European engineers to extend design processes and methods to a point where they allow engineers to handle future ECS-based systems with all their new functionalities and capabilities over the whole lifecycle. Such extended processes must retain the qualities of the existing processes: (i) efficiency, in terms of effort and costs; (ii) the design of trustworthy systems, meaning

systems that provably possess the desired quality properties of safety, security, reliability, dependability, etc; and (iii) be transparent to engineers, who must be able to completely comprehend each process step to perform optimisations and error correction. Last, but not least, to keep complexity – and therefore efforts and costs – within acceptable limits, tools and frameworks implementing these methods and processes will be highly automated themselves using AI to free engineers from burdensome and time-consuming 'menial tasks'.

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, see also Major Challenge 2). The main objectives to be reached here are the creation and extension of lifecycle-aware holistic design flows that especially allow continuous development and updates of systems by collecting data from operations and maintenance (and possibly other phases of the process), feeding it back into the design phase and allowing for continuous improvements and updates. Equally important is the switch to virtual engineering of ECS, where many of the test and validation efforts required are done by simulation and analysis methods, thereby considerably increasing the efficiency of these activities. Advances in System Design Methods, especially in Model-Based Design, and in V&V methods, complete the key research areas that are most important for this challenge. Innovation is required not only at the individual discipline-level (e.g., schematic design for PCB, RTL design for IC), but end-to-end to abstract away and manage the complexity of the design and verification flow (e.g., leveraging agentic AI technologies). Artefacts of such novel design and verification processes shall be models and data to be shared across the value chain upstream (e.g., models defining the requirement for supply chain partners as well as models replacing today's datasheets), as well as downstream to enable optimisation of manufacturing, operation and end-of-first-life circularity processes including repair/refurbish for second-life or recycling.

2.3.2.1.3 Key focus areas

This Major Challenge comprises the following key focus areas:

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.

Lifecycle-aware design shall include state-of-health and lifetime prediction technologies that enable extended use, repair, refurbishment, second-life applications and recycling.

Closing the loop includes data collected during the production and 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". On the one hand, this continuous development allows for shared learning, where in a system family (like a fleet of highly automated cars) all systems can be optimised based on the experience of each single member of the family. Combined with a strong monitoring concept – i.e. where unknown scenarios and

unknown use cases are detected before they actually arise and where corresponding safety measures like minimum risk maneuvers or evasive actions can be triggered – this 'learning in the field' concept can achieve significant advancements in safety assurance cases of such systems (online validation and verification).

All of these aspects must be supported within holistic design flows (frameworks) that also must support:

- Supply-chain-awareness: From requirements to optimised system architecture considering the supply chain and leveraging a seamless digital twin from component to design to manufacturing to operation.
- Complete traceability of products and processes in virtual engineering, supporting sensitivity analysis and robustness investigation, and their inclusion in the optimisation process and the system monitoring process.
- Design for optimised manufacturing and operation; awareness of physical effects and interferences; awareness of complete lifecycle, including energy, resource, CO_2 footprint, recycling, circular economy.
- Consistent methods and new approaches for (multi-level, multi-paradigm) modelling, analysis, verification and formalisation of the operational reliability of ECS and service life.
- Open (and inner) source in HW and SW for complete product lifecycle.

For EDA, an open-source EDA flow is a composable, licence-free toolchain that carries a design from requirements, RTL or schematics through verification, synthesis, place-and-route, sign-off checks, and tape-out, using community-maintained tools and open PDKs where available. A typical digital flow combines HDL linting and formatting (e.g. SystemVerilog front-ends and linters), simulation (cycle-accurate and event-driven), and formal verification, then proceeds through logic synthesis, static timing analysis, and physical implementation, including automated floorplanning, clock-tree synthesis, placement, routing, extraction, and timing closure. Sign-off-quality checks are achieved through DRC/LVS and basic IR-drop analysis, with standard data formats (Verilog, Liberty, LEF/DEF, GDSII/OASIS, and SDF/SPEF) ensuring interoperability. Analog and mixed-signal flows leverage schematic capture, SPICE-class simulators, layout editors, and LVS/PEX to integrate custom blocks with digital SoCs. The strength of this approach includes transparency, extensibility, reproducibility (via containers and pinned tool versions), and scalable compute without per-seat licences – making it ideal for education, research, early feasibility, and cost-sensitive production at mature nodes. Current limitations include partial SystemVerilog/UVM support, constrained DFT/ATPG capabilities, variable PDK coverage (stronger at mature nodes), and evolving sign-off fidelity for advanced effects (electromigration/IR, variability, and thermal), which may necessitate targeted use of commercial tools.

Open source is the predominant strategy for design IPs (e.g. RISC-V) and the early stages of the chip design flow addressing the capture of design intent, functional architecture exploration, functional modeling down to RTL and functional verification, as well as relevant Digital Twin technologies. These are the fundamental stages for the democratisation of the semiconductor value chain for potential users or customers who are not chip design experts. Later stages for physical implementation are deeply interlinked with semiconductor manufacturing process technologies and substantially more complex than the functional stages of the chip design flow. Semiconductor process technologies are fully controlled of quite a closed ecosystem of foundries, IDMs and EDA companies with significant continuous investment ensuring guaranteed quality of chips produced. Nevertheless, any open source

initiative is highly relevant for research developing the pool of resources for chip design experts and ECS design experts.

Operational efficiency improves when the open-source flow is wrapped in CI/CD and DevOps practices – i.e. if the loop is 'closed': every commit triggers lint, synthesis, and regression simulations; nightly or gated builds run place-and-route with timing/DRC/LVS checks; artifacts (netlists, constraints, Liberty, LEF/DEF, and GDS) are versioned; and benches, tool images, and PDKs are managed as code for reproducibility. AI can prioritise regressions, cluster failures, and guide floorplan/placement decisions or test selection, provided MLOps safeguards ensure datasets, models and metrics are tracked. Governance is essential: no internal data should be entered into external services or public repositories; run flows on approved on-premises resources, enforce IP sanitisation, and maintain auditable SBOMs for toolchains and PDKs.

As non-technical (or partly technical) challenges, all data collection activities described in this chapter also need to comply with privacy regulations (e.g. the EU General Data Protection Regulation (GDPR)) and must be conducted in a way that protects the Intellectual Property (IP) of the producers of the systems and their components.

Virtual engineering of ECS

Design processes for ECS must be expanded to enable virtual engineering at all levels of the hierarchy (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). This requires model-based design methods, including advanced modelling and specification capabilities, supported by corresponding modelling and specification tools. 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 and the following key focus area, "Advancing System and component design (methods and tools)").

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, for example using AI-supported, data-driven methods to derive (model) digital twins (see also Major Challenges 1 and 2 in Chapter 2.4 and "virtual prototypes" in Appendix A).

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 considerably enhanced 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. This includes overcoming limitations in realism of models and simulation accuracy, as caused for example by sensor phenomenology, vehicle imperfections like worn components, localisation and unlimited diversity in traffic interactions. Digital twin technologies built upon comprehensive modelling and high-performance simulation technologies at subsystem and system level should replace costly and time-consuming physical testing still widely used today. Of course, models have to be validated against the physical implementation of the system, and – especially on the system level – simulation environments have to be validated against the real, physical world, not only with respect to correctness but also completeness.

Advancing System and component design (methods and tools)

System and component design, validation and testing methods have to be continuously advanced and extended to keep up with the new functionalities of and new technologies used for ECS. Currently, advancement in the following topics is needed urgently to realise the potential that these new functionalities and technologies can bring:

- Model-based design technologies
    - Model creation/elicitation, modelling techniques, modelling tools, model libraries, using explicit models as well as data-driven models.
    - (AI-based) Model identification, synthesis, improvement and parameterisation with measurement data.
    - Techniques and tools to model behaviour, timing, functional and non-functional properties of: (a) components (incl. chiplets); (b) systems; (c) environment/real world; and (d) test cases/scenarios (physical rule-based as well as data-driven).
    - Executable models of sensors (including accuracy, confidence, etc).

- Test Management on all hierarchy layers
    - Automatic generation of test cases on all hierarchy layers (from physical sensor input via bitvectors up to concrete test scenarios for systems).
    - Means to efficiently process and analyse dynamic test results (traces, observations, loggings, etc) to derive tangible knowledge for design improvements.

- Augmented and virtual reality in design, development, manufacturing and maintenance processes.

- System Level Design for new System Architectures. The increasing diversity of OEMs and the complexity of modern E/E architectures demand a paradigm shift in system-level design. Traditional methods fall short in enabling seamless architecture exploration, HW customization (i.e., by chiplet-based design), HW/SW co-design, and mixed-signal modelling. A holistic design approach is needed – one that supports flexible adaptation to OEM-specific needs, integrates verification early in the process, and enhances quality, reusability, and development efficiency through consistent, tool-supported methodologies.

- Monitoring Techniques
  - V&V extended by life-time monitoring of security and reliability aspects.
  - Methods and tools for (automatically generated) monitoring of systems (based on their digital twins), including monitoring for anomaly detection (for both security and safety).

- Highly efficient digital signal processing
  - The growing complexity of modern sensor systems in the automotive and other domains demands highly efficient and scalable digital signal processing solutions. There is a clear need to develop a concept for architecture-independent, open-platform-based digital signal processing. This includes exploring how standardised, reusable DSP components and safety-compliant development and validation methodologies could be realised in a cohesive and adaptable framework. Measures for handling uncertainty in perception should be considered.

- Architectures and design technologies that support modular, updatable design (i.e., based on chiplets and software modules).

- Architectures and design technologies for post-quantum-secure architectures supporting crypto agility and field-update support for long operating lifetimes, including outside critical infrastructure.

- Design and V&V for emerging technologies and technologies newly introduced into ECS design, including neuromorphic technologies, quantum technologies, chiplet technologies, flexible electronics, textile electronics, magnetic sensors, spintronic systems, etc.

- Contract-based design methods and tool support should enable hierarchical and compositional design and assessment, component testing and monitoring, and interoperability testing of components and subsystems. Contracts should link functional and non-functional requirements to evidence used in V&V and assurance cases.

In addition, there are two research topics requiring special attention. The first is the handling of uncertainty. The higher level of automation – up to autonomy – of systems such as cars and other transportation systems, medical machinery, production plants and many others, implies that the level of uncertainty that the system has to cope with also increases and has to be handled. This is mainly the case in perception, where the system ‘observes’ its surroundings with sensors. Despite long-established techniques such as sensor fusion, there is always an inherent level of uncertainty as to the accuracy of the sensor data, which leads to ‘ghost artefacts’ – i.e. detection of objects that are not there in reality, and non-detection of objects that are. The other source of uncertainty is typically in prediction, where the system needs to predict how its surroundings will evolve over time to adjust its own behaviour accordingly. A key research topic here is therefore the advancement of design methods and V&V techniques for handling these uncertainties, where recent approaches implementing and guaranteeing bounds on these uncertainties have shown early success.

Second, the usage of Artificial Intelligence in Design and Validation promises a high potential for cost- and effort-efficiency, in a similar way as the use of AI in the systems themselves promises an increase in functionality of these systems (see the following key focus area).

AI support for Engineering (Design, Implementation, verification, validation, and testing)

The employment of AI-based methods and tools in all their forms – ML, AI, GenAI/LLMs, agentic AI, etc. – promises huge increases in efficiency and effectiveness of engineering tasks on all levels of the design hierarchy, from Systems-of-Systems down to EDA.

Large Language Models are becoming increasingly capable in many engineering sub-disciplines far beyond the generative extension of SW development. Theoretically LLMs can include the complete (published) knowledge of engineering tasks so that a designer should be able to use this knowledge automatically in their design. The idea is that once generative AI has learned enough structures and their functionalities in all relevant non-text-only engineering modalities, it should in principle be able to systematically assemble these structures at the transistor level, but also on higher levels such as software and systems— almost akin to formulating sentences – to realise certain functionalities. Therefore, the integration of EDA and software tools with agentic frameworks leveraging frontier models is a priority.

- The leading paradigms for AI-enabled design are replacing the intelligence of individuals with the collective intelligence of a relevant design community, including all published history.
- Replacing partly optimised design with systematically and holistically optimised design.
- R&D productivity will significantly increase.
- Full traceability and audit-compliant results.

However, the advancement of testing and V&V technologies able to handle AI-generated artefacts currently lags behind, even for pure SW development, especially where the highest quality requirements – like safety assurance cases in the homologation of automotive or medical systems – have to be demonstrated. Together, this results in calls for action on the following priorities:

- Open-source high-quality training data for research on AI-enabled tools for ECS design.
- Multi-modal AI models supporting specific ECS engineering modalities beyond text-only, such as timing diagrams, schematics, software libraries, etc.
- ECS design-specific benchmarks to assess the quality of AI-enabled design.
- Technologies ensuring completeness and correctness of AI-enabled design, up to a point where these can be demonstrated, e.g. for safety assurance. This specifically includes correctness by design and (quality) compliance by design
- Integration of AI (including generative AI) and AI-based tools into engineering and development processes on all levels of the design hierarchy to shorten development time, including metrics for the quantification of covered design space, etc.
- The key technologies here are Virtual Integration Platforms, Digital Twins and Digital Threads (see also Major Challenge 3 below), combined with ML/AI/GenAI/Agentic/AI-enabled Design Frameworks.
- Usage of AI and AI-based tools for V&V and development tasks, including for automated evidence generation.
- AI support for model identification, synthesis, improvement and parameterisation with measurement data (cf. model-based design technologies above).

- Using AI techniques in design and validation poses the additional challenge that these have to be either supervised (i.e. they need to be able to explain to their users why and how they achieved the results they produced) or have to be validated themselves ('Who validates the validator?'). One of the key techniques used in this regard – separating the 'doer', i.e., the designer or implementer from the 'checker', i.e., the tester, validator, etc. – and ensuring their independence becomes challenging if both are LLMs with essentially the same knowledge base.

Integration of new V&V methods

The required changes of current design processes identified above, as well as the need to handle the new system 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. Chapters 1.4 and 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 need to be implemented.

Third, V&V methods must be enhanced 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, among 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 leverage the added introspection techniques to establish an overall safety case for the system. In addition, generative AI methods based on LLMs or similar AI methods produce results based upon static dependencies and statistical heuristics. 'Hallucinations' – i.e. results that are possible but not aligned with factual reality – have to be identified and coped with, both to guarantee correctness and to avoid dependencies on (possible IP-protected) data used for learning.

All of these new methods will profit from the inclusion of AI methods (cf. previous key focus area).

2.3.2.2 Major Challenge 2: Sustainable Engineering for Sustainable ECS

2.3.2.2.1 State of the art

Sustainability is a major goal of the European ECS industry; as described in Chapter 0, there are two sustainability goals:

On the one hand, we need to produce *sustainable ECS*, i.e. products that contribute to sustainability by being highly energy efficient, by producing less or even no emissions; products that have a long lifetime and which are built from materials that can be recycled or reused in other contexts afterwards (second life).

On the other hand, we need to *produce ECS* in a *sustainable* way, i.e. by using less energy for design, validation and production, and by increasing the useful lifetime of systems and/or their components.

Together, and in combination with corresponding eco-design strategies, these actions contribute to eight of the 17 sustainability goals of the United Nations and the EU, namely SDG 3 Good Health and Wellbeing, SDG 6 Clean Water (and sanitation), SDG 7 Affordable and clean Energy, SDG 8 Decent work and economic growth, SDG 9 Industry, Innovation, and Infrastructure, SDG 11 Sustainable Cities and communities, SDG 12 Responsible consumption and production, and SDG 13 Climate Action.

This Major Challenge groups the most prominent Key Focus Areas contributing to these goals. It should be noted, however, that these two goals have been a driving factor for many of the advancements made in ECS Design and Validation over the last decades. Building engines that are better – stronger, more reliable, etc – while using less fuel or other resources, heavily contributing to the Smart Grid, the use of new materials (such as magnetic, spintronics, 2D, rare earth materials, polymers) and many other activities during recent years, aim to achieve sustainable ECS-based products as well as a sustainable way of designing and testing them. Thus, one can find sustainability goals behind many of the focus areas described in Major Challenges 1, 3 and 4, although the sustainability might not be the main driver, but a highly advantageous second goal of that topic area.

2.3.2.2.2 Vision and expected outcome

There is a strong technology push combined with a need raised by the increased functionality of ECS-based products to switch to lifecycle-aware design processes and continuous development of ECS-based products, including data collection from systems during production and operation, as described in Major Challenge 1. This switch perfectly matches the Lifecycle-aware Design Optimisations described in the following section. Together, these will enable the design of ECS-based products that are produced using progressively less energy and other resources, which are more easily repairable, and which are recyclable or reusable at the end of their initial lifetime. Continuous Design Flows also drive the need for updates and updatable systems, which perfectly matches the fact that updates also need to extend the useful lifetime of a product, thus increasing its sustainability. The two focus areas of 'Energy and resource-efficient test procedures and equipment' and 'Low power design' directly contribute to the sustainability of the design and test process, as well as the energy consumption of the system. Integration of energy-aware design, digital twins/virtual engineering, and lifecycle aware optimisation techniques will enable and support scalable, resilient, and environmentally sustainable ECS solutions.

2.3.2.2.3 Key focus areas

Lifecycle-aware Design Optimisations

Lifecycle-aware design optimisation is a collective term for procedures and methods that aim to design sustainable ECS. It comprises:

- 'Design for producibility' for designing ECS that can be produced resource-efficiently (i.e. with low consumption of energy and other resources). Note that this topic comprises a lot more than only thinking about production materials and changing them in a sustainable way: finding innovative ways to implement ECS' functionality – like switching from point-to-point communication between components to the use of buses – can decrease resource use – e.g., copper wires – substantially.
- 'Design for recycling/reuse', which is mostly concerned with the materials.
- 'Design for reparability', which comprises both architectural methods that enable or ease repairability of a system as well as design and management of spare parts.

All of them essentially face the same challenges, namely:

- Specification techniques for the corresponding requirements (of producibility, recycling/reuse and reparability).
- Requirement capturing.
- Implementation techniques for these requirements.
- Validation/Test methods for these requirements.
- Conflict resolution techniques for requirements (i.e. how to handle a situation in which, e.g., a safety requirement conflicts with a producibility requirement).

Especially for requirements capture and validation methods, these techniques profit from data collection during production and operation, as described in Major Challenge 1 under "Lifecycle aware holistic design flows", which enables a continuous design flow also for these aspects of the system.

Updates

Updates, with respect to a product being 'updatable', have the potential of significantly increasing the lifetime of a product and thus increasing its sustainability. An 'update' of an ECS is a change in the functionality and/or in the realisation (implementation) of some functionality of an ECS. Updates can be done by exchanging components or modules of a (sub-)system and by exchanging (parts) of the software running on it. The former requires physical access to the product, which can be carried out during regular or additional maintenance services, while the latter can also be done entirely 'over the air'. There are three reasons for updates. The first is error correction, i.e. when a hitherto unknown functional error or a security hazard is detected, it can be corrected via an update. The second is performance or usability optimisation and variation. If a function in an ECS can be implemented in different ways – for example, engine control in a car can be done 'smoothly' or 'sportively' or in many other ways – then a change in the implementation can be realised through updates. Updates initiated by one of these two reasons have already had a highly positive impact on sustainability. However, the main benefit for sustainability stems from the third reason for updates, which is adding functionality to an ECS already in use, thus avoiding replacement of the product in favour of 'newer, better versions'. The main challenges for updates are, first, ensuring the quality of the updated system. Taking safety as the major quality of an ECS again, it is difficult to analyse and guarantee all the existing safety

properties of a system for the new, updated system, given that the updated system is already in operation and thus no longer available for physical tests. The second challenge lies in the fact that there are typically many – sometimes even thousands – of variants of a product in operation, and the update has to fit all of them and quality has to be assured for all of them. The third challenge mostly concerns over-the-air software updates, for which safe and secure deployment has to be guaranteed.

Energy and resource efficient design and test

Testing and validation of ECS used to be a very energy-consuming task, with hundreds or thousands of physical tests taking place not only with the final product (or a prototype thereof), but also with all subsystems, components and modules of the system. The setup, maintenance and operation of the various test environments were also highly resource-intensive. With the shift to virtual engineering, including the use of digital twins and virtual testing (cf. Major Challenge 1), many physical tests can be avoided. However, the number of physical tests needed is still fairly large, and reducing their energy and resource consumption is still an important topic. In addition, virtual engineering itself requires energy for all the computers, servers, and simulation suites that are needed for it. Any technique that lowers power consumption for computers, servers, and clouds is therefore also beneficial here, as are methods that reduce the number of test cases needed for showing quality attributes. In addition, the increasing use of AI in all stages of the design flow incurs a high energy demand for running the respective AI components. Careful prompt design – that is, careful specification of the task the AI is supposed to solve – and techniques that minimize the number of iterations between 'doer' and 'checker' pairs will lead to more efficient design and test flows.

Ultra-low power design methods

The potential range of applications for ultra-low-power electronic systems is very broad 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 and home automation to condition monitoring of materials and 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 computing architectures (i.e. workload-aware architectures including AI training and inference), energy-optimised software structures or special low-temperature electronics (cf. Chapters 1.1, 1.2 and 1.3). Helpful here are automated system-level DSE (design space exploration) approaches able to fully consider energy/power issues (e.g. dark silicon and energy/power/performance trade-offs). 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. Design Technology Co-Optimisation

(DTCO) methods ensure implementation technology awareness in the design cycle in a way that the design best leverages physical properties, and the manufacturing parameter space of its physical realisation. Energy harvesting and the occurrence of parasitic effects must also be taken into account.

2.3.2.3 Major Challenge 3: Managing complexity

2.3.2.3.1 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 (cf. Part 3 and Sub-section 2.3.1 above). Increasingly complex environments in which these systems are expected to operate, and the more 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 achieve cost-effective solutions through high productivity. Four complexity-related action areas will help to master this change:

- Methods to enable efficient Safety Assurance Cases.
- Methods and tools to increase design efficiency.
- Complexity reduction methods and tools for V&V and testing.
- Methods and tools for advanced architectures.

2.3.2.3.2 Vision and expected outcome

The connection of electronic systems and the fact that these systems change in functionality over their lifetime continuously drive 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, which also handle 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 change over their lifetime (cf. Chapter 3.1). The innumerable combinations and variants of ECS must be handled and validated. To that end, new tools and methods are required to help test engineers create 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. 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.

2.3.2.3.3 Key focus areas

Assurance Cases

Safety Assurance Cases are a widely and successfully used method to show that a certain product possesses certain qualities (e.g. safety). Corresponding arguments for other quality properties (like security, dependability, etc) are also being used.

Safety Assurance Cases consist of a set of Safety Cases or Safety Arguments. ISO 26262 states that "the purpose of a safety case is to provide a clear, comprehensive and defensible argument, supported by evidence, that an item is free from unreasonable risk when operated in an intended context". According to the CAE principle, Safety Arguments comprise Claims, i.e. that the system fulfils a certain safety related requirement, and Arguments, i.e. an explanation – or proof – why a claim (or sub-claim) is valid. Arguments, in turn, comprise sub-claims – for which in turn an argument is needed – or evidence, i.e. analyses, test results or other findings from the implemented system that support the (sub-)claim.

Safety Assurance Cases remain a valid means for showing safety (or other qualities) of an ECS-based product. However, the following non-trivial extensions to the method are needed to be able to handle modern and future ECS-based products:

- ODD behaviour competencies: To construct safety cases, both the operational context as well as the functionality of the system need to be specified. While there has been considerable advancement in describing operational context by ODDs (Operational Design Domains), including first standardisation activities, there still is a lot of room for further improvement. Behaviour Competencies, which are used to formally describe the system's functionality, are still further behind. Together these two concepts need to be extended with means to describe reduced functional behaviour and minimal risk manoeuvers.
- Handling of unknowns: Both the definition of the operational context as well as the functionality of the system will contain uncertainties and unknowns (cf. Handling of Uncertainties in Major Challenge 1). To include these in the safety argument, statistical reasoning and/or three-valued logics need to be used.
- Quality metrics and guarantees: For highly automated (up to autonomous) systems, which may have part of their functionality implemented by Artificial Intelligence, it is sometimes infeasible to collect the evidence needed to support a certain (sub-)claim. For example, in the automotive sector for autonomous driving, test driving the number of miles required is infeasible. Sometimes, on the other hand, we do not even know what quality to measure or what guaranteed performance (e.g., bounded execution time, non-interference of concurrent execution using separation kernels) would be evidence to support a certain (sub-)claim. Again, as an example, for AI-based object detection, we cannot infer how much training and how many tests are required to guarantee this property. The challenge here is to find quality metrics and guarantees that: (a) are sufficiently strong to support the safety argument; and (b) can be measured or analysed with the needed efficiency.

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 these research topics:

- XIL testing (X-in-the-loop, with X = model, system, software or hardware, including mixed modes).
- XIL simulation techniques and tools, simulation speed and accuracy, multi-domain co-simulation.
- Efficient modelling, test and analysis for reliable, complex systems at different abstraction levels.
- Evaluation of architecture and design of the ECS SW/HW with real tests.

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 testing and V&V, ensuring compatibility and proper behaviour in networked 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. This includes the following research topics:

- Recommender-based guidance in the V&V process for complex ECS systems.
- Automated test planning starting from system requirements
- Automated generation of test cases from models/digital twins of ECS systems.
- Test coverage calculation by means of models and test cases (coverage-driven V&V).
- Minimising effort for V&V using models and AI techniques (e.g., automated fault triage and debugging).
- Advanced test methods, intelligent concepts for test termination, automated metrics/tools for testability, diagnosis, and extraction of diagnostic information.
- Methods and tools for consistent, hierarchical design, V&V and test.
- Energy- and resource-efficient test procedures and equipment.

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 changes in ECS over their 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 detection with respect to 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 “Open SoS architecture and infrastructure”, “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, enabling Digital Threads for data exchange along those value chains. Once these ecosystems reach a certain size and market impact, the platforms can serve as the basis for corresponding "platform economies" (cf. Major Challenge "Open SoS architecture and infrastructure" in Chapter 1.4). Thus, the following research topics are key:

- Architecture exploration and optimisation, including multi-aspect optimisation (e.g. safety, security, comfort, functionality, …) and AI-based optimisation methods.
- Architectures supporting advanced computation methods (AI, advanced control, etc).
- Methods and architectures for SDVs (software defined vehicles): The evolution toward SDVs introduces complex demands on SoC architectures, driven by diverse processor IP and stringent requirements for safety, scalability, and long-term viability. However, current design methodologies fall short in addressing these challenges holistically, and there is a pressing need for systematic evaluation methods and structured architecture exploration. The envisioned development framework aims to enable SDV-optimised SoC designs, foster standardisation within the RISC-V ecosystem, and integrate fault-tolerant mechanisms to ensure functional safety in future automotive applications.
- Architectures and tools for non-von Neumann and neuromorphic computing.
- Architectures supporting self-awareness, health and environment monitoring on all levels of the design hierarchy.
- Platform and middleware architectures, also for extremely distributed, multi-layered SoS and IoT applications.
- Reference architectures for continuous system improvement, i.e. across evolving system generations, both on software as well as on hardware level (using modular software for the former, chiplets or similar technologies for the latter).
- Architectures for V&V and certification, including automatic evaluation of computation and deployment decisions (i.e. on chip, edge, fog, cloud).
- Modular and evolvable/extendable architectures (supporting traceability of evolution, as well as modular updates, replacement and recycling for a circular economy).
- (SW-HW) architecture mapping, including resource mapping and tracing (communication, scheduling, etc.), such as requirements matching and tracing.
- Methods and tools to support design and validation for new architectures, e.g.:
    - The transition to electric mobility demands compact and highly efficient 48 V E/E architectures at the ASIC level. However, existing solutions are not yet sufficient to fully address challenges such as thermal management, EMC, and subsystem integration. There is a need to explore and develop robust, system-oriented design strategies that could meet the performance, efficiency, and reliability requirements of future vehicles. The aim is to investigate how optimised power management and

communication architectures might form the basis for scalable platforms and the integration of emerging technologies.

- Methods and tools are required for certifiable mixed-criticality execution environments, including deterministic scheduling, verifiable spatial and temporal isolation, separation kernels and time-partitioned virtualisation. These capabilities should support secure supply-chain-anchored software stacks, certifiable AI/ML pipelines, secure edge-to-cloud orchestration and interference-free real-time operation.

All the above topics need to be examined and developed in conjunction with corresponding changes in design and validation tools ('Design for Target Architectures', 'Design for (virtual) platforms') to leverage the complexity reduction they offer.

2.3.2.4 Major Challenge 4: Managing diversity

2.3.2.4.1 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), spintronics (memory, computing, communication, etc) systems, 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 in 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 at any level of the design hierarchy, and anywhere it occurs, is paramount, and a wide range of applications has to be supported.

2.3.2.4.2 Vision and expected outcome

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.

2.3.2.4.3 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 in 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 the following research topics:

- Consistent and complete Co-Design and 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, mechatronics integration, MEMS, …) and multi-paradigm designs (different vendors, modelling languages, …) and HW/SW co-design.
- Advanced Design Space Exploration and iterative Design techniques, including multi-aspect optimisation (performance vs. cost vs. space vs. power vs. reliability).
- Modular design of 2.5D and 3D integrated systems and chiplets and flexible substrates.
- Integration of III–V materials and MEMS (cf. Chapters 1.1 and 1.2).

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 the following methods and tools, which all need to take into account aspects of chiplet technology:

- Methods and tools for the design, modelling and integration of heterogeneous systems (including 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 variation 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 startup, floating node analysis ...).

Automation of analogue and integration of analogue and digital design methods

The area of automation of analogue design and integration of analogue and digital design methods comprises the following research topics:

- Metrics for analogue/mixed signal (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 – i.e. high-level description, synthesis acceleration and physical design, modularisation and the use of standardised components.

Analogue circuit design remains a manual, iterative process that challenges efficiency and scalability, especially when porting designs to modern technologies. The efficiency of the design process can be greatly increased by using techniques proposed under MC 1 in this chapter. To address this, a user-friendly and automated workflow is essential – one that streamlines design transfer, reduces development time, and enhances IP reusability. By integrating simulation, optimisation and layout into a cohesive process, the goal is to approach the automation level of digital design and ensure consistent, high-quality analogue development across technology nodes.

Connecting the virtual and physical world of mixed domains in real environments

The area of connecting the virtual and physical worlds across mixed domains in real environments is about the following research topics:

- Advanced analysis considering 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 heterogeneous, hardware, and integration of all of these into a continuous design and validation flow for heterogeneous systems, cf. Major Challenge 1 and 2 above).
- Novel More-than-Moore design methods and tools.
- Models and model libraries for chemical and biological systems for advanced/emerging technologies such as for spintronics, photonics, etc.

2.3.3 Timeline

Major Challenge	Topic / Key focus area	Short Term 2027-2031	Medium Term 2032-2036	Long Term 2037 and beyond
MC 1: **Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS**	**Topic 1.1:** Lifecycle-aware holistic design flows	Interoperable lifecycle design flows demonstrated with supply-chain data, production feedback and traceable models across engineering tools.	Qualified continuous-design frameworks linking manufacturing, operation, repair and recycling decisions to verified product requirements.	Lifecycle design automation qualified across organisational and tool boundaries, maintaining traceable evidence through successive product generations.
	Topic 1.2: Virtual engineering of ECS	Virtual engineering platforms validated with executable models, measured model fidelity and semi-automated artefact generation.	Domain-specific digital twins qualified for update assessment and mixed virtual/physical validation.	Federated lifecycle twins qualified across domains with explicit fidelity, synchronisation and uncertainty bounds.
	Topic 1.3: Advancing System and component design (methods and tools)	Validated sensor and environment models with uncertainty-aware design-space exploration and independent checking of AI-generated artefacts.	Qualified perception-chain design methods combining residual-risk analysis, uncertainty bounds and explainable optimisation.	Reusable design methods qualified for evolving heterogeneous platforms with compositional assurance and measured model validity.
	Topic 1.4: AI support for Engineering	Agentic engineering workflows demonstrated for selected design and verification tasks, with provenance, benchmarks and independent checks.	Qualified AI orchestration across defined development flows, with auditable decisions and verified tool interfaces.	Requirements-to-design automation qualified for bounded ECS classes, retaining independent assurance and sign-off.
	Topic 1.5 Integration of new V&V methods	Operational-design-domain monitoring and scenario-based V&V validated for defined capabilities and modular updates.	Update assurance qualified using validated twins, runtime monitors and guarded AI components.	Runtime assurance qualified for restricted updates and known operating envelopes, subject to applicable approval processes.
MC 2: **Sustainable Engineering for Sustainable ECS**	**Topic 2.1:** *Lifecycle-aware Design Optimisations*	Lifecycle optimisation demonstrated with measurable energy, material, repairability and lifetime objectives and traceable product data.	Qualified design-for-circularity flows linking health evidence, repair, refurbishment and second-life requalification.	Lifecycle optimisation qualified across successive product generations using traceable operational, repair and recovery evidence.
	Topic 2.2: Updates	Variant-aware update workflows validated for secure delivery, compatibility, regression testing and safe rollback.	Update assurance qualified across product variants using domain-specific twins and monitored field assumptions.	Adaptive update orchestration qualified across independently maintained systems with verified compatibility, rollback and evidence continuity.
	Topic 2.3: *Energy- and resource-efficient design and test*	cf. Topic 1.2 'Virtual Engineering for ECS' above as well as Major Challenge 1 of Chapter 2.1		
	Topic 2.4: *Ultra-low power design methods*	System-level energy-aware design-space exploration validated against measured workloads, harvesting profiles and intermittent operation.	Qualified low-power models capturing variability, fault tolerance, lifetime and application-specific quality constraints.	Lifecycle-aware ultra-low-power design flows qualified across heterogeneous technologies using measured energy and ageing behaviour.
MC 3: **Managing complexity**	**Topic 3.1:** Assurance Cases	Assurance cases validated for bounded operating domains, monitored assumptions and measurable scenario coverage.	Assurance methods qualified for uncertainty, rare events and safe degradation, with explicit limits on statistical confidence.	Lifecycle assurance qualified for defined autonomous-system classes and controlled evolution.
	Topic 3.2: *Methods and tools to increase design and V&V efficiency*	Correlated XIL and multi-domain simulation demonstrated with physical-test calibration and AI-assisted verification tasks.	Qualified simulation-driven V&V reducing physical tests within validated model envelopes and coverage limits.	Highly automated V&V qualified for selected domains, with independent evidence and retained physical validation where necessary.

Major Challenge	Topic / Key focus area	Short Term 2027-2031	Medium Term 2032-2036	Long Term 2037 and beyond
	Topic 3.3: Complexity reduction methods and tools for V&V and testing	Coverage-driven test generation and AI-assisted triage validated against requirements and independent reference cases.	Explainable test selection and verification guidance qualified with measured coverage and failure-detection performance.	Adaptive V&V qualified under changing designs with auditable coverage and diagnostic evidence.
	Topic 3.4: Methods and tools for advanced architectures	Modular architectures demonstrated with compositional assurance, mixed-criticality isolation and multi-objective exploration.	Evolvable reference platforms qualified for multi-level integration and controlled hardware/software updates.	Cross-domain architecture tools qualified for emerging computation technologies and lifecycle change assurance.
MC 4: **Managing diversity**	**Topic 4.1:** *Multi-objective design and optimisation of components and systems*	Integrated chip-package-board and HW/SW co-design demonstrated for heterogeneous and chiplet-based systems using correlated multiphysics models.	Qualified cross-domain optimisation linking electrical, thermal, mechanical and manufacturing constraints to application-level evidence.	Cross-domain optimisation qualified with quantified uncertainty, lifecycle constraints and independently checked trade-off evidence.
	***Topic 4.2**:* *Modelling, analysis, design and test methods for heterogeneous systems considering properties, physical effects and constraints*	Hierarchical heterogeneous-system models demonstrated with verified interfaces, co-simulation and measured physical correlation.	Qualified multi-scale models capturing operating variability, ageing and critical physical effects from component to system.	Compositional modelling and verification qualified for evolving heterogeneous systems with bounded cross-domain assumptions.
	Topic 4.3: Automation of analogue and integration of analogue and digital design methods	Automated analogue/RF design transfer and mixed-signal integration demonstrated for selected circuit families with independent sign-off checks.	Qualified AMS testability and diagnostic metrics, integrated with repeatable analogue/digital verification flows.	Analogue/digital co-design automation qualified across process and package generations with physical correlation and independent sign-off.
	Topic 4.4: Connecting the virtual and physical world of mixed domains in real environments	Mixed-domain design tools demonstrated with validated physical models and hardware-in-the-loop interfaces for selected technologies.	Qualified virtual/physical co-simulation with uncertainty bounds and reusable chemical, biological and other domain models.	Federated mixed-domain twins qualified for lifecycle adaptation with validated fidelity, uncertainty and physical feedback.

2.4



Cross-Sectional Technologies

QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

2.4 QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

2.4.1 Scope

2027 and beyond. The concurrent demand for increased functionality, uninterrupted availability of service, and continuous miniaturisation of electronic components and systems (ECS) confronts the scientific and industrial communities in Europe with many thorny challenges.

A key issue is how to enable the massive increase in computational power and low communication latency of ECS, with its hybrid and distributed architectures, without losing crucial properties such as quality, reliability, safety, or cybersecurity. It needs to be understood what would happen if any of those properties degraded, or if they were not correctly integrated in a critical product. In addition, what role will AI (artificial intelligence) play in addressing these challenges? Are the application of the EU Artificial Intelligence Act (AIAct) and the IEC standards on AI sufficient to ensure safety and cybersecurity of an AI-driven application?

All these problems form the core background to this chapter, which investigates the quality, reliability, safety, and cybersecurity of ECS by highlighting the required industrial research directions via six major challenges.

Related chapters. 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 cybersecurity within the levels of the design hierarchy.

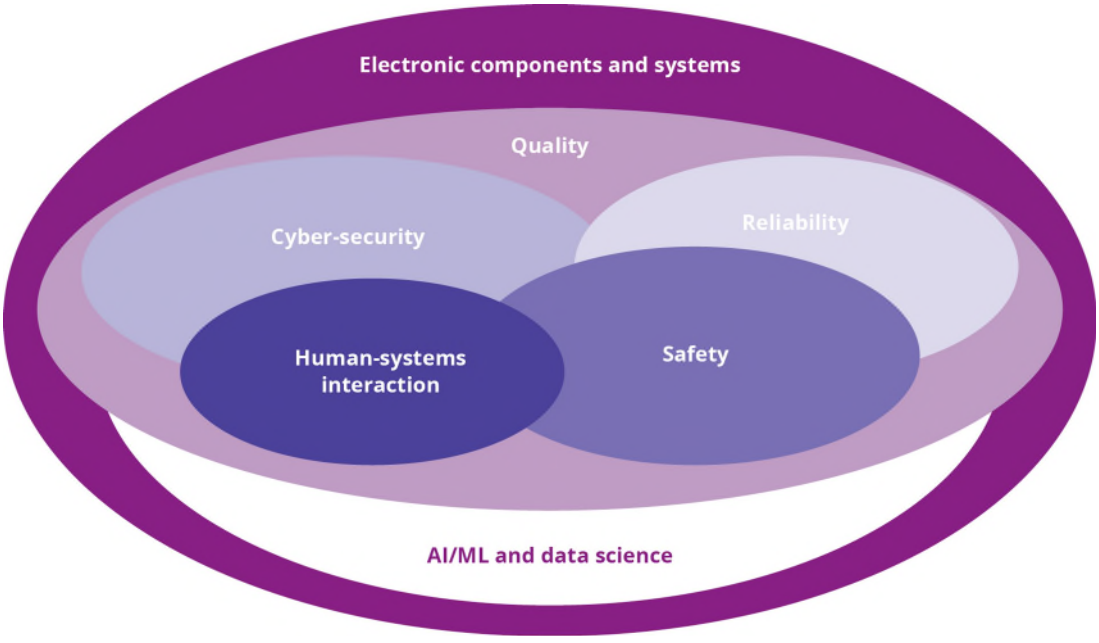

Figure 2.4.1 - Role of quality, reliability, safety and cybersecurity of electronic components and systems for digitalisation

2.4.2 Major Challenges

With the increasing dependence on multiple manufacturing nodes, accelerated by advanced packaging, heterogeneous integration, AI, and human-developed software, the need for verification of the authenticity of incoming components (HW and SW) has become critical. Numerous reports indicate that counterfeit components are entering production chains; however, an even greater concern is the risk of tampered devices that may introduce backdoors into critical systems.

This challenge is particularly relevant to applications in defence, automotive, communications and other safety-critical domains, but is not limited to these. The ability to verify authenticity and detect tampering in semiconductor components and electronic systems is therefore essential. This is especially important for sub-components manufactured outside the EU.

Robust tools and methodologies for verification and traceability are required to ensure the safe deployment of ECS in critical environments. These capabilities must guarantee the **integrity and trustworthiness** of components, uphold the **highest standards of quality and reliability**, and prevent vulnerabilities that could compromise system security.

Six Major Challenges have been identified:

- Major Challenge 1: Ensuring quality in ECS design and manufacturing
  - A compilation of the research needs for methods and tools enabling **quality assurance during design and manufacturing** of future European electronic components and systems. This spans the full front-end and back-end fabrication chain, starting from material growth and wafer processing to advanced packaging, assembly, and integration.
  - The focus is on **defect prevention, process control, and design-for-quality**, ensuring that ECS are built in accordance with specifications and meet stringent performance requirements of European standards from the outset.

- Major Challenge 2: Ensuring HW reliability during ECS Design and Use Phases
  - A compilation of the research needs for all methods required to assess and assure the reliability of the hardware of future electronic components and systems during design, fabrication, testing, qualification, and use – starting from single-crystal growth and wafer fabrication, proceeding through all wafer processes, covering all the diverse steps in the back-end-of-line, packaging and assembly, and including comprehensive studies of field-use conditions in order to prepare new products optimally for these conditions and to establish the most effective predictive health management.
  - The aim is to ensure that 'Made in EU' remains the label that stands for the highest quality and reliability, as well as for solutions at the highest level of functional safety so that these ECS can be used effectively for the most demanding applications in sectors such as automotive and mobility, industry and robotics, medical and healthcare, as well as energy infrastructure facilities and future quantum technologies.

- Major Challenge 3: Ensuring dependability in connected software
  - Ensuring dependability in connected software aims to make networked systems as reliable and predictable as traditional industrial applications. To achieve this, connected software components, architectures and technologies must treat dependability as an explicit operational property across the device-edge-cloud continuum. Future systems should detect and communicate relevant changes in network or platform conditions, such as bottlenecks, maintenance or degraded service states, and provide clear feedback on scope, expected duration and available degraded modes. For critical applications, redundancy and failover mechanisms must be considered in the software architecture.
  - Building a strong European ecosystem for dependable software will reduce reliance on US and Chinese ICT technologies, strengthening both resilience and technological sovereignty.

- Major Challenge 4: Ensuring cybersecurity and privacy

  This challenge aims to develop secure, resilient and trustworthy electronic systems by integrating cybersecurity and privacy measures across the entire digital ecosystem. It addresses cybersecurity and privacy in an increasingly connected digital environment. It considers how the growth of 5G, IoT, AI, and autonomous systems expands complexity, attack surfaces, and risks. Key issues include protecting sensitive data, countering hybrid and adversarial attacks, and ensuring trustworthiness, resilience and compliance across heterogeneous systems. The vision highlights robust trust frameworks, privacy-by-design, quantum-safe cryptography, and green, secure solutions. Expected outcomes focus on trustworthy AI, open-source hardware/software security, certification methods, and safety-security integration to protect critical assets and data through advanced, adaptable technologies and frameworks, ensuring compliance, reliability, and European digital sovereignty.

- Major Challenge 5: Ensuring safety and resilience

  This challenge highlights the need for continuous industrial research to enhance the safety and resilience of electronic components and systems as they increasingly integrate AI. It explores how evolving regulations, such as the EU AI Act and international standards, frame requirements for transparency, robustness, and traceability. The vision foresees autonomous and adaptive systems that remain dependable under physical, operational, and legal constraints, while supporting sustainability and interoperability. Key focus areas include dynamic adaptation, modular certification, trustworthy electronics, and safe human–machine interaction. Outcomes target improved resilience, liability traceability, and dependable deployment in real-world environments.

- Major Challenge 6: Human–systems integration

  It aims to ensure that the operational requirements of human stakeholders are sufficiently taken into consideration early on in the design and development of embedded systems. The goal is to reduce unintended consequences and risk exposure by ensuring that human requirements and oversight are built in from the outset. As systems become more complex, particularly with AI components, user integration and effective human oversight by design are essential. Key objectives are effective human oversight, calibrated trust, and acceptance.

2.4.2.1 Major challenge 1: Ensuring Quality in ECS Design and Manufacturing

2.4.2.1.1 State of the art

With the ever-increasing complexity and demand for higher functionality of electronics, combined with constraints on cost, power consumption, and miniaturisation, ensuring high quality in design and manufacturing has become a major challenge. Modern ECS rely on heterogeneous integration, advanced packaging, and multi-node fabrication, making process control and defect prevention significantly more complex.

Traditional quality assurance approaches based on post-process inspection are no longer sufficient. Instead, **in-line monitoring, real-time process control, and data-driven manufacturing approaches** must be deployed across the entire production chain.

Digitalisation of manufacturing, including the use of **AI, advanced metrology, and digital twins**, enables early detection of deviations, improved yield, and tighter control of variability. In parallel, **design-for-quality (DfQ)** and virtual verification approaches allow early identification of manufacturability and integration issues before fabrication.

The integration of data across the supply chain further enables a shift from isolated optimisation towards **collaborative, data-driven quality assurance**, ensuring that ECS meet stringent specifications from the outset.

2.4.2.1.2 Vision and expected outcome

The vision is to establish a **fully digitalised, data-driven and collaborative manufacturing ecosystem** that ensures ECS are built correctly from the outset, despite increasing complexity and heterogeneity.

Key outcomes include:

- Early detection and prevention of defects through **in-line monitoring and predictive process control**
- Integration of **digital twins and virtual verification** to minimise design and manufacturing risks before tape-out
- Enhanced **design-for-quality methodologies** supporting advanced integration technologies
- Improved **yield, manufacturability, and time-to-market** through model-based and AI-driven approaches
- Strengthened **supply chain collaboration and traceability**, enabling consistent quality across distributed manufacturing environments

This will ensure that *"Made in EU"* remains a benchmark for **manufacturing excellence and high-quality ECS**.

2.4.2.1.3.1 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 failures (failures immediately following the start of the use period), and prevent the early onset of wear-out failure modes.

Controlling the process parameters in the era of Industry 4.0 beyond traditional approaches will minimise deviations and improve the quality of the responses related to those parameters:

- Implement advanced sensor fusion and real-time data analytics to monitor process parameters across the entire manufacturing chain, from raw material input to final assembly.
- Develop and deploy AI-driven predictive process control systems that anticipate and automatically correct deviations, optimising parameters for material-specific characteristics and desired performance.
- Integrate in situ metrology and feedback loops directly into production equipment, enabling continuous adaptation of process conditions based on immediate material or component response.
- Establish digital twins of manufacturing processes to simulate and optimise process flows, identify bottlenecks, and predict the impact of parameter variations on final product quality.

Process and material properties (electrical, mechanical, thermal, chemical, etc) and their variability will have to be characterised to quantify their effects on hardware reliability, as well as to enable prediction of reliability in final products through combinations of empirical studies, fundamental RP models and AI approaches:

- Develop standardised methodologies for multi-scale characterisation of material properties (e.g. microstructure, composition, mechanical properties, electrical behaviour) and their inherent statistical variations.
- Conduct comprehensive empirical studies and accelerated stress testing to generate robust datasets on how specific material and process variabilities lead to degradation and failure mechanisms.
- Advance fundamental Reliability Physics (RP) models to accurately describe the propagation of material defects and process-induced weaknesses into macroscopic hardware failures.
- Utilise AI and machine learning (ML) models (e.g. Bayesian networks, Gaussian processes) to correlate complex multivariate material and process data with observed reliability outcomes, enabling robust prediction and risk assessment.

Advanced/smart monitoring of process output (e.g. measuring the 3D profile of assembled goods) for the detection of abnormalities (using AI for the early detection of standard outputs):

- Deploy high-resolution non-destructive testing (NDT) techniques such as advanced X-ray computed tomography (CT), high-frequency ultrasound, optical coherence tomography (OCT), and active thermography for comprehensive internal and external defect detection.
- Develop AI-powered image and signal processing algorithms to analyse complex NDT data, automatically identify anomalies, and classify defect types with high accuracy and speed.
- Implement predictive quality analytics that move beyond pass/fail criteria to identify subtle "signatures" in the process output that indicate potential future reliability issues, even if the current output meets specification ("early detection of standard outputs" that might degrade prematurely).

- Establish closed-loop feedback from process output monitoring to process control, enabling immediate adjustment of production parameters based on real-time quality insights.

Smart screening methodologies for critical latent defects, which include the use of intelligent, adaptive or automated techniques, such as machine learning, statistical analysis, or pattern recognition, within systematic procedures like inline inspection, stress testing, or predictive algorithms:

- Develop methodologies aimed at identifying latent defects that are not detectable through standard inspection, and typically do not cause immediate failure but may emerge under stress, ageing or specific usage conditions. When such defects are critical, they have a high likelihood of leading to significant or safety-related failures.
- Create and implement smart screening methods combining physical testing and virtual assessments based on physical and data-driven (AI-supported) approaches that enable comprehensive proactive detection of these hidden, high-risk flaws prior to product deployment without necessitating burn-in.

Early detection of potential yield/reliability issues by simulation-assisted design for assembly/design for manufacturing (DfM/DfA) as a part of virtual prototyping:

- Integrate multi-physics simulation tools (e.g. thermo-mechanical, fluid dynamics, electrical field analysis) into the DfM/DfA workflow to predict manufacturing-induced stresses, deformations, and potential failure points before physical fabrication.
- Develop virtual qualification and testing methodologies that simulate entire production runs, including assembly steps, to identify potential yield losses or reliability weak points stemming from design choices or material combinations.
- Utilise generative design and topology optimisation techniques, informed by manufacturing constraints and material properties, to create designs inherently more robust against common manufacturing defects.
- Establish digital threads from design to manufacturing, ensuring that material specifications, process tolerances, and quality requirements are consistently communicated and verified throughout the entire product lifecycle.

2.4.2.1.3.2 Design-for-quality and virtual verification

Design-for-quality and virtual verification approaches enable early detection of potential yield and manufacturability issues prior to fabrication, reducing development cycles and improving first-time-right success.

- Integrate multi-physics simulation tools (e.g. thermo-mechanical, fluid, electrical) into DfM/DfA workflows to predict manufacturing-induced stresses and process sensitivities
- Develop virtual qualification methodologies that simulate full production and assembly flows
- Apply generative design and optimisation techniques considering manufacturing constraints
- Establish digital threads linking design, materials, process parameters, and quality requirements across the lifecycle

2.4.2.1.3.3 Digitalisation: A paradigm shift in the fabrication of ECS from supplier/customer to partnership

Digitalisation is not possible without processing and exchanging 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).
  - Standardise the data exchange format, procedures and ownership, and create an international legal framework.
  - Conceive and validate business models creating economic incentives and facilitating data sharing, 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.
  - Standardised model-training and model-testing processes.
  - Standardised procedures for model maintenance and upgrade.

- Linking data from Industry 4.0 with model-based engineering:
  - Derive working hypotheses about system health.
  - Validate hypotheses and refine physics-based models.
  - Construct data models embedding (new) domain knowledge derived from model-based engineering.

- Identify significant parameters that must be saved during production to be re-used for design optimisation and manufacturing process improvement, 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 characterisation of ECS using end-of-line test data.

- Wafer fabrication (pre-assembly) online 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 technology nodes (e.g. thin dice for power applications – dicing and grinding).

2.4.2.2 Major challenge 2: Ensuring Hardware Reliability in ECS Design and Use Phases

2.4.2.2.1 State of the art

Progress in ECS technology means the continuous (i) increase in complexity and number of components integrated into one system, often shrinking in size and (ii) a growing share of highly safety-related applications being exposed to harsh service conditions, while at the same time (iii) global competition demands shorter development cycles and lower costs for fabricating and testing the new products. Meeting these conflicting challenges while still assuring ECS reliability necessitates a new generation of reliability methodologies that spans from the beginning of development to the end of the use phase of the ECS technologies and products. During development, design for reliability (DfR) needs to be implemented comprehensively along the entire value chain based on sound knowledge of the physics of degradation. During the use phase, reliability assessment requires *in situ* monitoring of the state of health at both local (e.g., the single IC package) and system levels. Hybrid prognostic and health management (PHM) supported by AI is the key methodology here. DfR concerns the total lifetime of a full population of systems under anticipated service conditions and its statistical characterization. PHM considers the degradation of the individual system in its actual service conditions and the estimation of its specific remaining useful life (RUL).

2.4.2.2.2 Vision and expected outcome

The trend towards interconnected, highly automated and autonomous systems will change the way we own products. Instead of buying commodity products, we will purchase personalized services. The vision of Major challenge 2 is to provide the tools and methods for novel ECS solutions to meet the ever-increasing product requirements in terms of product availability during use in the field. Both types of reliability methodologies will contribute, i.e., the continuous improvement of DfR methods and the development of new PHM techniques. They are the cornerstone of future developments in ECS. Hence, the main focus of Major challenge 2 will centre on the following topics:

- Digitalisation, by improving collaboration within the supply chain to introduce common DfR and PHM methods for faster market entry of better ECS.
- Continuous improvement of the DfR methodologies by applying compact models and AI.
- Data science and AI will drive technology development and pave the way for PHM implementation for ECS.
- AI- and PHM-based risk management, in situ mitigation, and active RUL extension.

2.4.2.2.3 Key focus areas

2.4.2.2.3.1 Reliability: Tests and modelling

Continuous improvement of physics-of-failure (PoF)-based methodologies combined with new data-driven approaches: tests, analyses, degradation and lifetime models (including their possible reconfiguration):

- Identifying and adapting methodologies to the main technology drivers.
- Methods and equipment for dedicated reliability assessments at the first level (component), second level (board), and third level (system with the 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 them 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), and new interdisciplinary system approaches and system integration technologies (e.g. micro-fluidics, optical input/output (I/O)).
- 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 prioritisation and design of testing.
    - Use of field, PHM and test data to build models for ECS working at the limit of the technology as accelerated testing is limited.
- Standardisation of how the mission profiles are deduced from multi-modal loading.
- Design to field – better understanding of field conditions through standardised methodology across the supply chain using a field-load simulator.
- Implementation of monitoring methods for the 10 most relevant failure modes in the field
- Replacement of burn-in by built-in sensors and AI/ML to screen out weak components (leading to early failures)
- New standards/methodologies/paradigms that evaluate the “ultimate” strength of systems – i.e. no longer test whether a certain number of cycles are a “pass”, but instead test to the limit to identify the actual safety margin of systems, and additionally the behaviour 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/HW reliability modelling: find ways to combine the modelling techniques (in other words, reconcile the different time domains).
    - SW/HW reliability testing: find ways to test systems with software and find the interaction failure modes.

2.4.2.2.3.2 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 twins as main drivers of robust ECS systems:
    - 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.
- Virtual design of experiments as a best practice at the early design stage.
- Realistic material and interface characterisation depending on actual dimensions, fabrication process conditions, ageing effects, etc., covering the critical structures, generating interface strength data with statistical distributions.
- 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 harmonised methods and tools for model-based engineering across the supply chain:
    - Material characterisation 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.
- Standardisation as a tool for model-based development of ECS across the supply chain:
    - Standardisation of material characterisation and modelling, including effects of ageing.
    - Standardisation of model exchange format within the supply chain
    - Simulation data and process management.
- Automation of model build-up (databases of components, materials).
- Use of AI in model parametrisation/identification, e.g. extracting material models from measurements.
- Virtual release of ECS through referencing.

2.4.2.2.3.3 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 combination 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.
- Standardised protocols and interfaces for PHM facilitating deployment and exploitation.
- Monitoring test structures and/or monitor procedures at 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.
- Distributed data collection, model construction, model update and maintenance.
- Concept of digital twin: provide quality and reliability metrics (key failure indicator, KFI).
- Development of AI-supported failure diagnostic and repair processes to improve field data quality.
- Development of AI-based asset/machine/robot life-extension methods based on PHM.
- AI-based autonomous testing tools for verification and validation (V&V) of software reliability.
- Implementation of hardware-based security tokens (e.g. physical unclonable functions, true random number generators) with optimised randomness, reliability and uniqueness.
- Lifecycle management. Contribute to the modelling of the HW cost across the lifecycle.

2.4.2.3 Major Challenge 3: Ensuring dependability in connected software

2.4.2.3.1 State of the art

Connected software applications spanning embedded devices, gateways, edge platforms and cloud services differ significantly from traditional industrial software that operates within a tightly controlled system boundary. In many deployments, connected functions reuse mainstream IT communication stacks, middleware, web technologies and open-source components that were not originally developed for stringent dependability or graceful degradation. For critical functions, transient network failures, overload, failed updates or platform outages must not lead to unpredictable behavior. Future connected software therefore needs to be engineered for dependable operation across the full device-edge-cloud continuum, including fault containment, diagnosability, redundancy where needed and controlled degradation under infrastructure failures.

2.4.2.3.2 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 requires connected software components, architectures and technologies that make dependability an explicit operational property. Future dependable connected software should detect and communicate relevant changes in network or platform conditions, such as bottlenecks, maintenance measures or degraded service states. If outages occur, the user or end application should receive clear feedback on scope, expected duration and available degraded modes so appropriate measures can be taken. For critical applications, redundancy and failover mechanisms must be considered in the software architecture. The availability of a European ecosystem for reliable software components will also reduce the dependence on current ICT technologies from the US and China.

2.4.2.3.3 Key focus areas

2.4.2.3.3.1 Dependable connected software architectures

In the past, dependable software was typically deployed on specialised, tightly controlled reliable hardware. With the increased use of IoT, edge and cloud computing, critical software functions now span devices, communications infrastructure and remote platforms. Dependable operation must therefore be ensured across the full operational continuum:

- Software reliability under connectivity loss, infrastructure instability and partial outages.
- Dependable edge and cloud computing, including AI/ML-enabled functions where relevant.
- Dependable communication methods, protocols and infrastructure.
- Formal verification of protocols, coordination mechanisms and safety-relevant decision logic (including those using AI/ML).
- Runtime monitoring, diagnosis and mitigation of communication and platform faults.
- Deterministic and time-sensitive communication where bounded latency is required.
- Increasing software quality by AI-assisted development and testing methods.
- Infrastructure resilience to maintenance events, overload and cascading failures.
- Reliable over-the-air (OTA) software and configuration updates.
- Controlled autonomy and self-adaptivity under explicit dependability constraints.
- Dependable integration platforms.
- Dependable cooperation of Systems of Systems (SoS).

This Major Challenge is tightly interlinked with the cross-sectional technology in Chapter 2.2, Connectivity, 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.

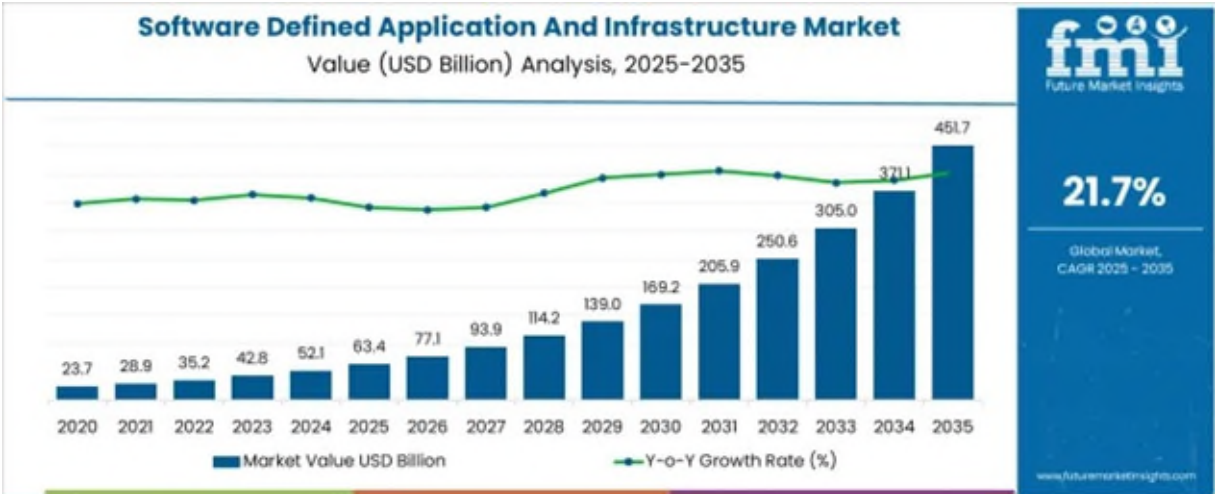

Figure 2.4.2 -Current and expected market value and year-on-year growth rate for the software-defined application and infrastructure market (Ref: Software Defined Application And Infrastructure Market | Global Market Analysis Report - 2035, Future Market Insights, 2024

2.4.2.3.3.2 Dependable softwarisation and virtualisation technologies

Changing or updating software while retaining existing hardware is common in many industrial domains. However, keeping dependable software while changing the execution platform or underlying hardware remains difficult, especially for critical applications. By decoupling software functions from specific hardware, softwarisation and virtualisation bring flexibility and shorter deployment cycles, but they also introduce new dependability concerns because critical software is increasingly executed on shared or general-purpose computing platforms:

- Dependability of software-defined communication stacks and programmable networking components in critical systems.
- Reliability of virtualised execution platforms, orchestration layers and resource management.
- Reliable containerisation and virtual machine technologies.
- Resilient multi-tenancy environments with fault containment and isolation.
- 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.

2.4.2.3.3.3 Combined SW/HW test strategies

Unlike hardware, software does not physically wear out, but connected products are modified frequently through updates, reconfiguration and continuous deployment. Dependability therefore requires reducing latent defects and controlling change-related regressions across software, platforms and hardware. Software reliability growth models (SRGM), i.e. statistical models that estimate how software reliability improves as faults are detected and removed during testing, combined with Bayesian statistics, merit further attention within the hardware-oriented reliability community over the coming years:

- HW failure modes are considered in the software requirements definition.
- Design characteristics must not cause the software to overstress the HW, or adversely change failure-severity consequences when failures occur.
- Establish techniques that can combine SW reliability metrics with HW reliability metrics.
- Develop efficient (hierarchical) test strategies for combined SW/HW performance and update validation of connected products.

Dependability in connected software is strongly connected with other chapters in this document. In particular, additional challenges are examined in the 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.

2.4.2.4 Major Challenge 4: Ensuring cybersecurity and privacy

2.4.2.4.1 State of the art

The pervasive deployment of connected digital products — accelerated by 5G infrastructure and the emerging development of 6G networks — has dramatically expanded attack surfaces across personal, industrial, and critical-infrastructure domains.

In this context, the largest and most exposed attack surface increasingly resides at the level of deployed systems and end-user environments, where devices interact with users, applications, and dynamic software ecosystems. While hardware-rooted security mechanisms are essential, vulnerabilities and attacks often materialize at runtime within software layers operating above the hardware.

Connectivity provides better flexibility and usability of these products in different sectors, with tremendous growth in sensitive and valuable data. Moreover, the variety of deployments and configuration options, and the growing number of sub-systems with increasing dynamism and variability, increase the overall complexity. In this scenario, new security and privacy issues should be addressed, and the continuously evolving threat landscape must also be considered. These should include both software and hardware approaches towards data security. New approaches, methodologies and tools for risk and vulnerability analysis, threat modelling for security and privacy, threat information sharing and reasoning are required. Artificial intelligence (e.g. machine learning, deep learning and ontologies) not only promotes pervasive intelligence supporting daily life, industrial developments, the 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. This is particularly relevant in critical sectors such as energy, healthcare and digital infrastructures, where the convergence of IT and OT has increased attack surfaces. In these domains, cybersecurity research must address the protection of vital assets from both conventional and hybrid attacks, approaching solutions with a dual-use perspective considering threats that could affect civilian and strategic infrastructure alike. This requires strong perimeter defence against external threat actors and advanced intrusion detection mechanisms.

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 the device level. Therefore, resilience to cyber-attacks is of utmost importance. AI can have a direct effect on the behaviour of a device, possibly affecting its physical operation and 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.

At the same time, the dynamic nature of modern ECS requires continuous, runtime-aware security approaches capable of detecting, analysing, and responding to evolving threats throughout the operational lifecycle of systems. This includes the ability to monitor system behaviour, identify anomalies, and support adaptive security responses in deployed environments, particularly at the edge and at the interface with end users.

The rapid proliferation of large language models (LLMs) introduces additional attack vectors — including prompt injection, model extraction, and LLM-assisted malware generation — while simultaneously offering new capabilities for automated vulnerability discovery and security testing. To address this issue, adaptable protection mechanisms and robust security measures at both device and network levels should be deployed, allowing integration of current and future technologies. For

instance, advances in embedded machine learning should be considered, for example, lightweight AI models deployed directly on ECS for real-time intrusion detection and anomaly detection (e.g. TinyML), providing real-time, on-device threat detection without dependence on cloud connectivity. 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). In addition, the tremendous increase of computational power and reduced communication latency of components and systems, coupled with hybrid and distributed architectures, require a rethink of many of the “traditional” approaches and expected performance concerning safety and security, exploiting AI and ML. Data protection should not only rely on complex software encryption algorithms, but also hardware-level safeguards leveraging emerging materials and techniques to protect information at that level.

Approaches for providing continuous evaluation of the compliance of systems of systems with given security standards (e.g. IEC 62443, which uses technical security controls*) will allow a homogeneous level of security across a multi-stakeholder ecosystem, challenging tech giants with platforms providing overall levels of security but often resulting in vendor lock-in.

More recently, the EU Cyber Resilience Act (CRA, Regulation 2024/2847), entering into force in December 2024, introduces mandatory cybersecurity-by-design requirements and vulnerability handling obligations for all products with digital elements placed on the EU market, creating new compliance imperatives directly relevant to ECS manufacturers and integrators.

Early tools have demonstrated the feasibility of continuous compliance evaluation for specific policy sets. However, the rise of powerful language models and code generation may allow for the dynamic creation of evaluation machinery to support the evaluation of compliance against any given standard.

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 by exploiting different types 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 vehicles, infrastructure and the environment around them, exchanging basic safety messages to avoid collisions and, according to the evolution of 5G standards, 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 guarantee the 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 on-board action or remotely by law enforcement in the case of any failure, security breach, sudden obstacle, crash, etc.

In the scenario described 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 dynamism and variability of systems.
- Developing novel privacy-preserving identity management and secure cryptographic solutions.
- Novel approaches to hardware security vulnerabilities including side-channel attacks, microarchitectural exploits, attacks on Trusted Execution Environments (TEEs), and hardware supply chain integrity threats.
- Understanding and addressing the interdependencies between hardware-level security properties and the software security ecosystem operating above them, ensuring that secure components are effectively integrated into resilient, system-level cybersecurity architectures
- Developing new approaches, methodologies and tools empowered by AI in all its forms (e.g. machine learning, deep learning, ontology).
- Investigating a deep verification approach also for open-source hardware in synergy and implementing the security by-design paradigm.
- Investigating the interworking among safety, cybersecurity, trustworthiness, privacy and legal compliance of systems.
- Evaluating the energy and environmental footprint of deployed security solutions, in line with European sustainability objectives.
- Developing advanced data protection techniques that take advantage of unique physical phenomena – such as physical unclonable functions (PUFs) – to address the inherent vulnerabilities of conventional password-based systems to hacking.
- Strengthening consumer-facing and endpoint-level cybersecurity, including capabilities for continuous threat detection, behavioural anomaly identification, and response mechanisms operating within deployed systems and user environments.

2.4.2.4.2 Vision and expected outcomes

The vision for this major challenge is anchored on a chain of trust that provides continuous, uninterrupted security from device level up to the application layer, including AI-enabled components operating in dynamic and unpredictable environments.

This chain of trust must extend beyond design-time and component-level assurances to include runtime protection mechanisms and the software layers interacting with end users, ensuring that security is maintained throughout the full system lifecycle and across all operational contexts.

This foundation is especially critical for mission-critical systems where reliability, quality and safety and security are tightly connected. Building on this, the vision emphasises the protection of EU citizens' privacy and security while safeguarding usability, market competitiveness, industrial intellectual property. Technical solutions should be designed for energy efficiency and reduced environmental impact, contributing to EU sustainability objectives. Ultimately, the development of proof-of-concept demonstrators should simultaneously guarantee defined levels of security and privacy and be capable of evolving into reference designs providing reusable, adaptable implementations for industry.

End-to-end encryption of data, both in transit and at rest, is maintained 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. Following the 2024 NIST finalisation of post-quantum cryptography standards (FIPS 203/204/205), the priority now shifts to migration strategies, hybrid classical/PQC deployments, and hardware-accelerated implementations suitable for resource-constrained ECS

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.

Putting together security and privacy requirements seamlessly is a difficult challenge that also involves some non-technical aspects. The human factor can often cause security and privacy concerns, despite the technologically advanced tools and solutions. Security and privacy requirements must also address socio-technical dimensions, including user behavior and organizational practices, which remain significant attack vectors. Another aspect relates to security certification versus certification cost. A security certification that does not mitigate risks and threats increases costs with minimal benefits. Therefore, all techniques and methodologies to reduce such costs 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. The relevant regulatory frameworks are the EU Cyber Resilience Act (CRA, Regulation 2024/2847) and the AI Act (Regulation 2024/1689).

In addition, the NIS2 Directive (2022/2555), has extended mandatory security and incident-reporting obligations to a broader set of critical entities and their supply chains, reinforcing the regulatory imperative for sector-specific cybersecurity frameworks.

Particular attention should be given to sectors like health, energy, and digital infrastructures due to their strategic importance and increasing exposure to sophisticated hybrid attacks. These sectors demand advanced, sector-specific cyber-defense frameworks capable of protecting data, operational continuity, and public safety, including through dual-use technologies that support both civilian and critical mission resilience. The vision includes prioritising external threat hunting, robust perimeter security, and proactive defense against adversarial intrusion.

2.4.2.4.3 Key focus area

2.4.2.4.3.1Trustworthiness

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 technologies, regulations, compliance, legal and economic issues. To this end, the main expected outcomes can be defined as follows:

- Defining different methods and techniques of trust for a system, and proving compliance with a security standard via certification schemes.

- Defining methods and techniques to ensure trustworthiness of AI algorithms, including explainable AI (XAI) (cf. Chapter 2.1 “Edge Computing and Embedded Artificial Intelligence”)
- Developing methodologies and techniques spanning trustworthy hardware and trustworthy software layers (cf. Chapter 1.3 “Embedded Software and Beyond” and Chapter 1.4 “System of Systems”). Trustworthiness should also focus on trustworthy architectures with security and privacy by design as follows.
- Support the adoption of secure virtualisation and dependable software update mechanisms.
- Defining methods and tools to support the composition and validation of certified parts addressing multiple standards (cf. Chapter 1.4 “System of Systems” and Chapter 2.3 “Architecture 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.
- Implementing risk-based security testing and threat modelling for ECS systems.
- Targeting end-to-end transparency and resilience in global ECS supply chains and developing component authentication and firmware integrity verification mechanisms for the ECS supply chain, addressing risks of hardware Trojans, pre-compromised firmware and counterfeit devices entering critical system assemblies.
- Definition of architectures that provide mitigation, remediation and restoration against physical and software cyber threats, ensuring integrity in data, software and systems.

2.4.2.4.3.2 Security and privacy-by-design

The main expected outcome is a set of solutions to ensure 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 mechanisms (cf. Chapter 1.4 “System of Systems” and Chapter 2.3 “Architecture and Design: Method and Tools”).
- Ensuring performance in AI-driven algorithms (which need 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 trustworthy architectures.
- Establishing advanced data security devices based on neuromorphic/probabilistic computing approaches, utilising advanced spintronic/nanomagnetic materials.
- Extending confidential computing paradigms – based on hardware-enforced Trusted Execution Environments (TEEs) – to resource-constrained ECS and edge nodes, ensuring data confidentiality and code integrity during processing, not only at rest or in transit.

2.4.2.4.3.3 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's safe level of behaviour when the system's security is breached or there are accidental failures.
- Guaranteeing information properties under cyber-attacks and adversarial AI (quality, coherence, integrity, reliability, etc).
- Ensuring safety, security and privacy of embedded intelligence (cf. 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 to offer a possibility to create transparent, auditable processes for ensuring safety and security (cf. Chapter 3.1 "Mobility").
- Assess complex System-on-Chip implementations and a chiplet approach assembling functional circuit blocks with different functions (e.g. processor, accelerator, memories, interfaces, etc) with regard to security functionalities, focusing on scalability, modularity as well as Edge paradigm.
- 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).
- Development of hybrid-attack resilient strategies integrating cyber and physical defence layers.
- Asset protection frameworks addressing dual-use technologies to ensure both civilian and critical infrastructure safety. The aim is to define integrated frameworks ensuring both safety and security properties.
- Continuous monitoring and adaptive response mechanisms for sector-specific threats.
- Integrating rapid vulnerability detection and incident-analysis processes to provide real-time feedback for R&D, accelerating remediation, and strengthening overall system resilience.

2.4.2.5 Major Challenge 5: Ensuring safety and resilience

2.4.2.5.1 State of the art

In 2027 and beyond, why is it still important to finance European industrial research on safety? Have not decades of studies and applications already addressed this major challenge? What key issue still demands our attention?

The recent spread of AI applications is forcefully and naturally making its way into the digitalisation of ubiquitous electronic components and systems (ECS), and is stretching traditional safety analysis. To govern this, over the last couple of years the international community has published and updated a series of standards, technical specifications and regulations related to safety and AI.

In 2024, the European Parliament and the Council of the European Union published the EU AI Act. Although this regulation does not apply to “any research, testing or development activity regarding AI systems or AI models” [Art. 2 Pf. 8], it indirectly applies to industrial research if the product is deployed on the market. Moreover, the AI Act highlights the importance of guidelines and principles for safety, linking this latter to the risk-based AI classification system as well as to robustness, resilience, transparency, traceability and explainability [e.g., art. 27].

At the same time, the international standardisation group ISO/IEC JTC 1 42 published a set of standards and technical specifications that are focused on domain-independent applications. Even in the nuclear domain, and certainly among the most restrictive and conservative ones, the related industrial community is investigating, amid active internal debate, how to use AI-based techniques, identify the limits and study their impacts on safety (see, e.g., the activities and works of IEC TC 45 SC 45A and the International Atomic Energy Agency).

The current landscape of regulations and standardisations concerning safety and AI underlines the need for ongoing industrial research into the safety and resilience of ECS, to deliver answers and innovations. This major challenge is therefore devoted to understanding and developing innovations that are required to increase the safety and resilience of systems in compliance with the AI Act and other related standards – by tackling key focus areas involving cross-cutting considerations such as legal concerns and user abilities, and to ensure safety-related properties under a chiplet-based approach (cf. Introduction).

2.4.2.5.2 Vision & expected outcomes

The vision points to the development of safe and resilient autonomous systems in dynamic environments, with a continuous chain of trust from the hardware level up to the applications involved in the accomplishment of the system’s mission. Our vision considers 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, for example, via open-source hardware), and considers optimising energy usage and system resources of safety-related features to support sustainability of future systems.

Civilian applications of (semi-)autonomous mobile systems are increasing significantly. This trend 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 systems.

Civilian applications thus inherently entail safety, and in the event of an accident or damage (for example, in uploading a piece of software to an AI system) liability and the certification/qualification of AI systems should be clearly traceable.

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, as are those in Chapter 1.3 on Embedded Software and Beyond

2.4.2.5.3 Key focus area

2.4.2.5.3.1 Dynamic adaptation and configuration, self-repair capabilities, (decentralised 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 adaptation 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 those based on RISC-V 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 optimisation.
- Develop explainable AI models for human interaction, systems interaction and certification.
- Resource management of all system components to accomplish the system mission in a safe and resilient way. Consideration should be given to minimising 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 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.

2.4.2.5.3.2 Modular certification of trustable systems and liability

The expected outcome is clear traceability of liability during integration and in the event 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, fault identification and failure analysis (FIFA), 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.
- Having a workflow for guaranteeing compliance with the AI Act.

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.

2.4.2.5.3.3 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 6 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 humans can safely interface with machines in complex systems and SoS, and also that the machine can prevent unsafe operations.
- New self-learning safety methods to ensure safe system operations in complex systems.
- Ensuring safety in machine-to-machine interaction.

2.4.2.6 Major Challenge 6: Human systems integration

2.4.2.6.1 State of the art

This ECS SRIA roadmap aligns RD&I for electronic components with real-world deployment contexts in which the resulting technologies will be operated, maintained, and overseen. In practice, technological benefits only materialise when systems are designed to fit their intended use environment and operational workflows, so that the people interacting with them can use them effectively, safely, and with acceptable effort. Only under these conditions can the promised benefits be realised at scale. It is common for human users and beneficiaries to remain mostly invisible during subsystem development. Only once subsystems are assembled into an operational system do 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, the key challenge is to integrate the human into the technological system throughout the innovation cycle. This means making user and beneficiary needs visible during subsystem development, so that interaction constraints, operational realities, and foreseeable misuse can shape architectures, interfaces, and safeguards before they become costly to change. Approaches from Human Factors, Human-Centred Design, and User Research offer practical means to do so. Building on psychological scientific research methods, they enable the systematic elicitation of stakeholder needs, the study of real-world use, and the evaluation of prototypes and concepts early and iteratively. These activities must therefore be planned and coordinated alongside technological maturation to support effective human oversight, calibrated trust, and acceptance. As this is currently only rarely done in most industrial R&D activities, this chapter describes the challenges and outlines a vision to address them.

There are three high-level challenges in integrating the human into ECS-based technological systems along the product lifecycle:

- The first challenge is to design products that are acceptable, trustworthy, and support effective human oversight, so that they are likely to be used safely and sustainably to realise the expected individual, organisational, or societal benefits. In practice, the overall vision for how a product will be used by real users in their operational context is often still unclear at the time the technological specification is defined. Instead, innovation efforts frequently prioritise assembling available capabilities to demonstrate technical feasibility, while leaving operational use, roles, workflows, and constraints under-specified. As a consequence, sufficiently detailed operational knowledge about the environment, organisational processes,

user characteristics, tasks, and failure modes is not available early enough to shape technology development. Therefore, achieving technologies that users accept and can effectively oversee often becomes a trial-and-error outcome rather than the result of strategically planned development.

- The second challenge is to bridge engineering-led innovation with operational fit: while technological leaps originate from engineering excellence, they only translate into real-world value when systems also work reliably for the people and processes that operate, supervise, and maintain them. In practice, specialised teams often optimise within their domain, and cross-cutting requirements that arise from human interaction in operation are not consistently carried into subsystem specifications and early architecture decisions. As automation and AI-enabled functions increase interaction complexity and shift responsibilities between human and system, it becomes increasingly important to integrate established, empirically grounded human-factors knowledge into design choices, e.g., limitations of human attention and vigilance in supervision tasks, workload and situation awareness effects, typical error modes, and interaction design principles. The situation is further amplified by technical unknowns (often pronounced in AI) where not all behaviours and corner cases can be characterised upfront; even then, systems must communicate capabilities, limitations, and confidence in ways that support appropriate user understanding and responsibility. Accordingly, engineering excellence should be complemented by user-centred excellence by intentionally bringing together applied user research, human-factors expertise, and engineering to translate operational realities into integrated requirements and architecture decisions.
- Third, continuous maintenance and updates are turning many technical solutions into dynamically changing systems, which can undermine effective human oversight, calibrated trust, and sustained use across all usage situations if change is not managed well. Frequent, often automated, software and model updates (including over-the-air updates) are now commonplace to maintain security levels, roll out new capabilities, and allow adaptive or self-learning functions to adjust to user preferences, usage history, and environmental changes. However, when changes occur without clear notice, are hard to interpret, or alter behaviour in subtle ways, users may become confused about what the system will do, what it can be relied upon for, and when intervention or caution is required; this can lead to inappropriate use and, in turn, additional safety, security, and acceptance risks. This challenge is intensified in ecosystems with server-hosted components and rapidly iterated services where “the product” may change without an obvious change in the user-facing tool, and where versioning is not transparent or easily traceable (e.g., AI assistants/chatbots that look identical while their underlying settings and change). Therefore, maintenance and update cycles must be designed as part of the full product lifecycle to preserve user understanding and control, through predictable change management, meaningful release communication, and user-facing transparency about capabilities, limitations, and relevant version/state, so that oversight remains feasible and trust remains appropriately calibrated beyond initial design and fielding.

2.4.2.6.2 Vision and expected outcome

The vision and expected outcome are that these three human-centred 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 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 psychologists and human-factors researchers who are also familiar with 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 organisational 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 products that are safe, capable of being overseen in operation, and trusted and adopted in a calibrated and sustainable manner. In this way, 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 fertilisation. This also requires sufficiently large, multi-disciplinary research environments for active collaboration and enablement of sufficient interaction 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 is 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 standardised update policies. This will be addressed by bringing the end-users, workers, and operators towards 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 multidisciplinary areas of knowledge, expertise, and capabilities within sufficiently interdisciplinary research and development environments where experts can interact with stakeholders to jointly design, implement, and test novel products. Early and iterative stakeholder involvement is established to link the various tasks: users and beneficiaries are engaged through interviews, contextual inquiries, and targeted studies, and emerging concepts are explored and validated with low-fidelity prototypes and early demonstrators; where simulation and modelling are used, they incorporate parameters explicitly derived from observed human behaviour and user studies to ensure realism and relevance. Involving experts on the "human factor" ensures that these activities are methodologically sound and that results are integrated into development through well-founded interpretations and requirement formulations.

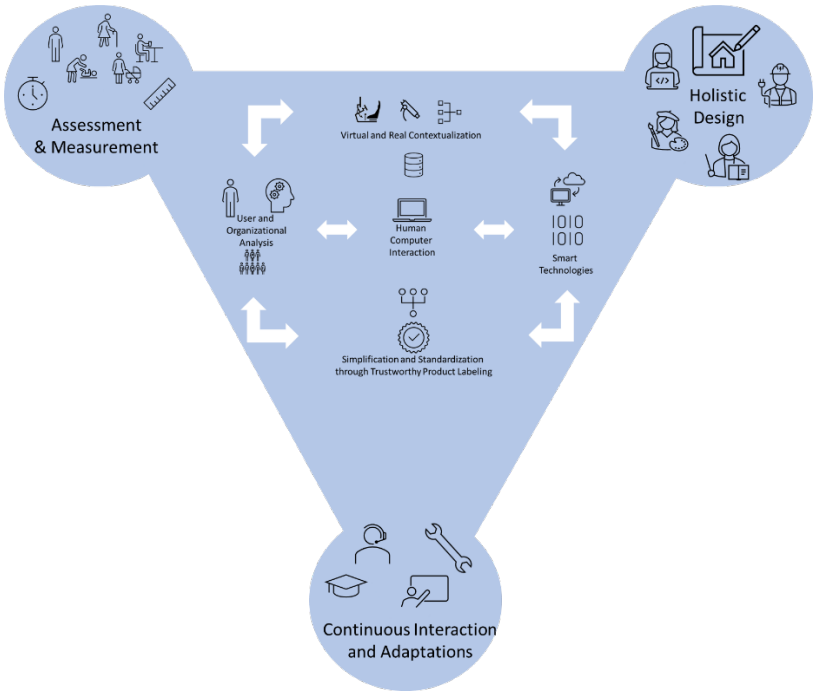

Figure 2.4.3 – Human–Systems Integration in the ECS SRIA

2.4.2.6.3 Key focus areas

- Systematise methods for user, context, and environment assessments, and the sharing of information for user-requirement generation. Such methods are necessary to allow user-centred methods to achieve an impact on overall product design.
- Integrate parameters derived from empirical human-behaviour research into simulation and modelling, enabling virtual assessments that reflect realistic user behaviour and constraints and that can be traced back to evidence. This supports early requirements and design decisions as well as lifecycle updates, and helps align researchers, developers, and stakeholders.
- Establish multi-disciplinary research and development centres and sandboxes. Interdisciplinary research and development centres allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support.

2.4.3 Timeline

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027-2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 1: Ensuring Quality in ECS Design and Manufacturing	**Topic 1.1: Q**uality: *in situ* and real-time assessments	- In-line quality monitoring validated with traceable process data, anomaly detection and measured reduction of latent defects.	- Production-to-field feedback qualified for corrective design and process changes, with validated causal models.	- Cross-supplier quality prediction qualified using governed, IP-protecting data exchange.
	Topic 1.2: Design-for-quality and virtual verification	- Correlated multiphysics DfM/DfA workflows demonstrated with virtual qualification and design-to-production traceability.	- Cross-supplier virtual verification qualified against physical fabrication and yield data.	- Virtual-first manufacturing qualification demonstrated for selected technologies with retained physical correlation.
	Topic 1.3: Digitalisation: A paradigm shift in the fabrication of ECS from supplier/customer to partnership	- Secure data-sharing and model-training workflows demonstrated across selected manufacturing partners.	- Closed-loop manufacturing, field and design data integration qualified with common semantics and model maintenance.	- Bounded autonomous quality decisions qualified across lifecycle partners, with audit trails and override.
Major Challenge 2: Ensuring Reliability and Lifetime Performance of ECS	**Topic 2.1:** reliability: tests and modelling	- System-level reliability models validated against mission profiles, interacting failure mechanisms and accelerated tests.	- Reliability monitoring qualified against field data, with quantified detection coverage and uncertainty.	- Coverage-based failure assessment qualified for evolving autonomous-system hardware and new failure mechanisms.
	Topic 2.2: design for (EoL) reliability: virtual reliability assessment prior to the fabrication of physical HW	- Virtual reliability models demonstrated with validated material data, ageing and interoperable model exchange.	- Degradation twins qualified for individual assets under measured field loading.	- AI-assisted reliability engineering qualified against independent test evidence and model-validity limits.
	Topic 2.3: PHM of ECS: increase in functional safety and system availability	- Condition monitoring validated for prioritised failure mechanisms with quantified false-alarm and missed-detection rates.	- Hybrid physics/data-driven PHM qualified with uncertainty-aware remaining-life estimates under field loading.	- Interoperable PHM services qualified across supply chains with traceable evidence and validated maintenance decisions.
Major Challenge 3: Ensuring dependability in connected software	**Topic 3.1:** dependable connected software architectures	- Connected-software architectures demonstrated with fault containment, monitored dependencies and predictable degradation under connectivity loss.	- Dependable coordination qualified across device, edge and cloud, with tested recovery and update compatibility.	- Federated dependable architectures qualified across independent operators and evolving infrastructure.
	Topic 3.2: dependable softwarisation and virtualisation technologies	- Shared execution platforms demonstrated with verified isolation, bounded interference and failure recovery for selected critical workloads.	- Cross-domain virtualised platforms qualified against real-time, safety and security requirements.	- Dependable workload migration qualified across heterogeneous platforms with verified continuity and rollback.
	Topic 3.3: combined SW/HW test strategies	- Combined SW/HW reliability metrics and fault-injection tests validated for updates and reconfiguration.	- Hierarchical lifecycle V&V qualified for interacting software, hardware ageing and platform changes.	- Continuous SW/HW assurance qualified across component replacement and adaptive updates with traceable fault coverage and independent validation.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027-2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 4: Ensuring privacy and cybersecurity	**Topic 4.1:** trustworthiness	- Hardware-rooted identity, attestation and authenticated updates validated across component and software supply chains.	- Crypto-agile trust chains qualified for constrained ECS, including post-quantum migration and legacy interoperability.	- Continuous trust evaluation qualified across evolving hardware, software and cryptographic generations.
	Topic 4.2: security and privacy- by-design	- Privacy-preserving edge/cloud data flows demonstrated with explicit access policies, risk assessment and verifiable data handling.	- Confidential and privacy-preserving computation qualified for constrained ECS and cross-organisational AI workflows.	- Federated data governance and privacy controls qualified across independently operated, changing systems.
	Topic 4.3: ensuring both safety and security properties	- Joint safety/security assessment validated against defined cyber-physical attacks and accidental faults.	- Safe degraded operation and recovery qualified under breached security assumptions and changing environments.	- Compositional safety/security assurance qualified across selected autonomous and critical-infrastructure domains.
Major Challenge 5: Ensuring safety and resilience	**Topic 5.1:** safety and resilience of (autonomous AI) systems in dynamic environments	- AI-enabled safety functions demonstrated with resource limits, fault injection and monitored operating envelopes.	- Context-aware safety assurance qualified for defined dynamic environments with explicit fallback and residual-risk evidence.	- Lifecycle resilience qualified for bounded adaptive systems, with maintained evidence under operational change.
	Topic 5.2: modular certification of trustable systems and liability	- Contract-based modular assurance demonstrated with traceable interfaces, responsibilities and independent component evidence.	- Modular qualification methods validated for restricted changes under specified assumptions and applicable standards.	- Cross-domain assurance evidence qualified for reuse, with traceable responsibility for system changes.
	Topic 5.3: dynamic adaptation and configuration, self-repair capabilities (decentralised instrumentation and control for), resilience of complex systems	- Dependable adaptation demonstrated using fault containment, digital twins and monitored assumptions, including legacy integration.	- Runtime reconfiguration qualified with contract checks, safety constraints, rollback and coordinated recovery.	- Coordinated self-repair qualified across heterogeneous systems with bounded authority, independently assessed recovery and maintained safety evidence.
	Topic 5.4: safety aspects related to HCI	- Human-system interfaces validated for workload, foreseeable misuse, intervention and safe degraded operation.	- Cross-domain interaction methods qualified in representative operational studies and lifecycle updates.	- Adaptive human-machine interaction qualified through lifecycle field evidence, preserving effective intervention and safe operation as users and tasks change.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027-2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 6: Human–systems integration	**Topic 6.1:** Skills & competences for user/context/environment assessments	- User-context assessment workflows validated in ECS projects, translating empirical needs, oversight roles and competence into traceable requirements.	- Reusable human-factors methods qualified across sectors, with measured operational fit and oversight effectiveness.	- Lifecycle human-systems assurance qualified across changing roles, updates and organisational contexts.
	Topic 6.2: Simulation and modelling for early integration of humans and technologies.	- Behavioural models and user-study datasets demonstrated with provenance, uncertainty and validation against observed tasks.	- Curated cross-domain model repositories qualified for safety, workload and oversight simulation.	- Behavioural-model maintenance qualified under changing populations, tasks and system behaviour.
	Topic 6.3: Establish multi-disciplinary research and development centres and sandboxes	- Existing labs and sandboxes demonstrate repeatable interdisciplinary ECS evaluations with stakeholder participation and shared evidence.	- Federated test facilities qualify reusable evaluation protocols, data governance and transfer of results across domains.	- Cross-sector assessment services qualified for sustained lifecycle evaluations and professional competence development.

3

Strategic Research and Innovation Agenda

ECS KEY APPLICATION AREAS

3.1



ECS Key Application Areas

MOBILITY

3.1 MOBILITY

3.1.1 Scope

The mobility industry **is currently navigating a period of unprecedented volatility and structural change**. However, mobility remains a fundamental human need and a cornerstone of the European economy, supporting **13.8 million jobs** (6.1% of total EU employment)[1]. While the core objectives of **Decarbonization** (Green Deal/2Zero) and **Digitalization** (CCAM/Automated Driving) remain, they are now viewed through a lens of global competitiveness and resilience.

The Shift to Software-Defined Vehicles (SDVs)[2]: Value creation has shifted from mechanical hardware towards software stacks. Consumers now prioritize "software freshness"—continuous updates for infotainment, Advanced Driver Assistance Systems (ADAS), autonomous driving (AD), and connectivity—over traditional performance metrics. The research challenge is to redesign vehicle E/E architectures to support high-performance computing systems (SoCs) needed for the new software features and lifelong cybersecurity via over-the-air updates.

Strategic Autonomy and Semiconductor Sovereignty: A major strategic shift is the pursuit of **European sovereignty** in automotive semiconductors and embedded software development for mobility. While Europe currently leads in traditional automotive chips, global competitors (specifically China) are catching up rapidly through massive subsidies and vertical integration. Research must focus on securing the supply chain for next-generation chips and advanced power electronics to reduce dependency on non-European providers. The same applies to the growing volume of software in mobility, including safety- and security-critical functions and AI platforms.

Global Competition and Market Pressures: The competitive landscape has shifted. European OEMs and Tier-1 suppliers are facing aggressive competition from new entrants who integrate battery technology and software more rapidly. To remain a global innovation driver, European research must reduce the time to market for innovations in sensor fusion, control algorithms, and computer vision.

Multimodal Decarbonization: While automotive remains the primary driver, the scope has expanded to include aeronautics, shipping, and light mobility (e.g., e-bikes). Research is increasingly focused on cross-sector synergies—such as using automotive software components or power electronics in drones, aerospace, maritime or rail applications—to achieve a CO_2-neutral ecosystem by 2050.

Bridging the Digital and Regional Divide: There is a growing risk of a "digital divide" between smart cities with dense infrastructure and rural regions. Research must address how automated and connected mobility can provide mobility services to ageing people, persons with special needs, or isolated populations without requiring prohibitive infrastructure investments, ensuring mobility remains inclusive.

AI-Driven Acceleration of the Development Lifecycle: The complexity of achieving "zero fatalities" in mobility applications such as autonomous driving makes physical testing alone insufficient. A key research focus is now on **AI-assisted simulation** and **digital twins** for verification, validation and homologation, which are essential to manage development costs and ensure the safety of complex

[1] Internal Market, Industry, Entrepreneurship and SMEs, https://ec.europa.eu/growth/ sectors/automotive_en
[2] https://federate-sdv.eu/wp-content/uploads/2024/04/2024-04-12-SDVoF-Vision-document-ver017-final.pdf, April 2024

automated systems. To compete with agile global entrants, Europe is integrating AI to move from slow, iterative processes to rapid, data-driven engineering:

Automated Verification & Validation (V&V): AI-powered testing tools now automate the identification of "edge cases" in software and ADAS/AD systems. By using machine learning to generate and run millions of critical virtual scenarios, the time required for safety certification is significantly reduced. AI is also needed to identify the tests required for software-defined vehicle (SDV) systems before distributing improved or advanced software versions via over-the-air (OTA) updates; otherwise, the enormous and continuously increasing testing effort would make the rapid updates expected by users impossible.

Generative Engineering: AI-driven design tools optimize hardware components for weight and thermal efficiency, while AI-assisted coding (LLMs for code) speeds up the development of complex "Software-Defined Vehicle" stacks. The validation, verification and testing of AI-generated artefacts are challenges in themselves, now aggravated by the sheer volume of output: the quantity and speed of AI-generated artefacts far exceed our current testing capabilities.

Predictive Maintenance & Digital Twins: By integrating AI with digital twins, research enables vehicles to predict component failures before they occur. This not only enhances reliability but also creates a feedback loop where real-world performance data is used to optimize the design of the next generation of components.

Overall, the focus of mobility research has evolved from purely technical improvements to **systemic resilience**. The goal is no longer just to build a vehicle, but to develop a secure, sustainable, and software-driven ecosystem that can withstand global geopolitical shifts.

Leveraging Cross-Domain Synergies in Mobility

While the automotive sector remains the primary volume driver for innovation, the current global situation demands a "system-of-systems" approach. Research must move beyond silos to exploit synergies between automotive, aerospace, maritime, rail, and industrial sectors to ensure European competitiveness.

Unified Electronics and Power Components: The high development costs of next-generation semiconductors (e.g., silicon carbide and gallium nitride) can only be amortized by applying automotive-scale innovations to other sectors. Synergies are being explored in high-efficiency power electronics that serve both electric vehicles (EVs) and light aircraft or harbor vessels, as well as in standardized sensor suites used across automotive and industrial robotics.

Transferable Software Architectures: The "Software-Defined" trend is not limited to cars. The move toward modular, updateable software stacks (SDx, for example SDV stacks) creates a massive opportunity for cross-domain reuse. For example, robust middleware and cybersecurity protocols developed for autonomous cars can be adapted for autonomous trains (ATO) and unmanned aerial vehicles (UAVs), reducing development timelines across the board.

The Hydrogen and Battery Ecosystem: Decarbonization research is converging. Advances in high-density battery storage and hydrogen fuel cell stacks are being co-developed to serve heavy-duty road transport, regional rail, and short-sea shipping. This cross-sector demand stabilizes the supply chain and accelerates the establishment of a European hydrogen infrastructure.

Multimodal Data Sharing: Digitalization allows for the integration of data across different modes of transport. Research into **connected, cooperative and automated mobility** (CCAM) is increasingly looking at how **vehicle-to-everything** (V2X) communication can synchronize road traffic with public transit and freight logistics, creating a seamless, energy-efficient "**Mobility-as-a-Service**" (MaaS) ecosystem.

Production and Automation Synergies: The manufacturing techniques perfected in the automotive industry—such as advanced robotics, AI-driven quality control, and digital twins—are acting as a blueprint for the "Factory of the Future" in other mobility sectors like aerospace and farming machinery, enhancing the overall industrial resilience of Europe. By treating mobility as a single, interconnected research domain, Europe can bridge the gap between high-volume automotive production and highly specialised sectors like aerospace. This horizontal integration is essential to outpace global competitors who are already leveraging cross-industry tech giants to dominate the market (see also Chapter 3.3, Digital Industry in this SRIA).

Impact of advances in mobility: Mobility products are used by people in all places and at all times. Their impact can be considered from different perspectives:

- Human: equity, inclusivity, health
- Safety, (cyber)security
- Accessibility: affordability and availability
- Environment: sustainability, circularity

Each perspective is a powerful innovation driver, requiring novel ECS solutions. This impact also leads to new regulations and policies at EU or national level which need to be considered from the earliest stages.

3.1.2 Strategic Focus: User-Centric Innovation, Resilience, and Sustainability

Driving Competitiveness through User-Oriented Innovation: The primary driver of competitiveness in the mobility sector is the rapid translation of advanced **electronics- and software-based systems** into user-oriented innovations. The goal is to bridge the gap between cutting-edge technology and innovative use cases that deliver maximum "visible value" - enhancing safety, comfort, and seamless connectivity for the end user while also improving environmental sustainability.

Environmental impact is a core consideration within the Strategic Focus on mobility research. The strategic research agenda on mobility prioritizes the necessary software and semiconductor features required for the reduction of emissions, resource use, and lifecycle environmental footprints across mobility systems by advancing energy-efficient technologies, electrification, alternative fuels, and circular design principles. By integrating environmental metrics into user-centric innovation and resilient system design, research aims to support sustainable mobility solutions that deliver high performance and societal value while contributing to climate goals and long-term ecological balance.

Managing Fleet Heterogeneity and Circular Economy: Future mobility must account for a heterogeneous landscape. Research must address next-generation vehicles while ensuring compatibility with legacy fleets.

- **Legacy Integration:** Developing scalable solutions that bridge the gap between "conventional" vehicles and evolving smart infrastructure.
- **Circular Economy:** A key focus is the **sustainability of the product lifecycle**. This includes modular designs for easy hardware upgrades, the **remanufacturing and recycling** of mobility-grade semiconductors and batteries, and "retrofitting" technologies that extend the operational life of existing fleets, reducing the overall environmental footprint.

Cyber-Resilience and Trustworthy Systems: As mobility becomes increasingly software-defined and connected, **Cyber-Resilience** is an essential prerequisite.

- **Security-by-Design:** Research must prioritize architectures that are inherently resistant to cyber-attacks across the entire Edge-to-Cloud continuum.
- **Operational Integrity:** This includes robust encryption, real-time threat detection, and fail-operational systems to ensure the safety of passengers and goods, maintaining public trust in automated and connected mobility.

Comprehensive Research Scope: From Hardware to Cloud: The research scope covers the entire value chain—from silicon to services—across all mobility modes:

- **Core Hardware:** Energy-efficient, mobility-grade semiconductors, advanced sensors, and high-performance actuators designed for longevity and reuse.
- **AI-Enabled Platforms:** Robust hardware and embedded software platforms leveraging **Edge-to-Cloud** service-oriented architectures for real-time, secure data processing.

Cross-Modal Application: While automotive remains the volume driver, the scope extends to **smart farming and off-road mobility** with specialized autonomous machinery, **maritime transport with intelligent**, cyber-secure ships and vessels, **aerospace with aircraft**, helicopters, and UAVs/drones with high-integrity flight controls, **rail transport** with advanced, energy-efficient systems for regional and high-speed trains.

By integrating these pillars, European innovations in ECS and AI provide a **secure, sustainable, and unified backbone** for the movement of people and goods in an increasingly volatile global environment.

3.1.3 Dual-Speed Software Development Model

To balance safety, reliability, and regulatory compliance with the demand for rapid innovation, many OEMs are adopting a **two-speed software delivery model**[3]:

- **Fast SW Update Cycle (DevOpsSec)**
  The fast cycle focuses on consumer-facing and data-driven features such as infotainment, connectivity, advanced driver assistance, automated driving, and comfort functions. Leveraging hardware abstraction, agile methodologies, and AI assisted CI/CT/CD pipelines (see Challenge 5), software is developed in short iterations and deployed through OTA updates. Many of these functions are implemented as edge-to-cloud services, with components distributed between vehicle and cloud infrastructures.
- **Slower SW Update Cycle (Systems Engineering / V-Model)**
  The slower cycle addresses safety-critical, real-time, and production-dependent software tightly coupled to mechatronic systems, including brakes, powertrain, batteries, thermal management, and body systems. Development follows rigorous systems-engineering processes, such as the V-model and shift-left strategies, to ensure functional safety, cybersecurity, quality, and production readiness aligned early with manufacturing systems.

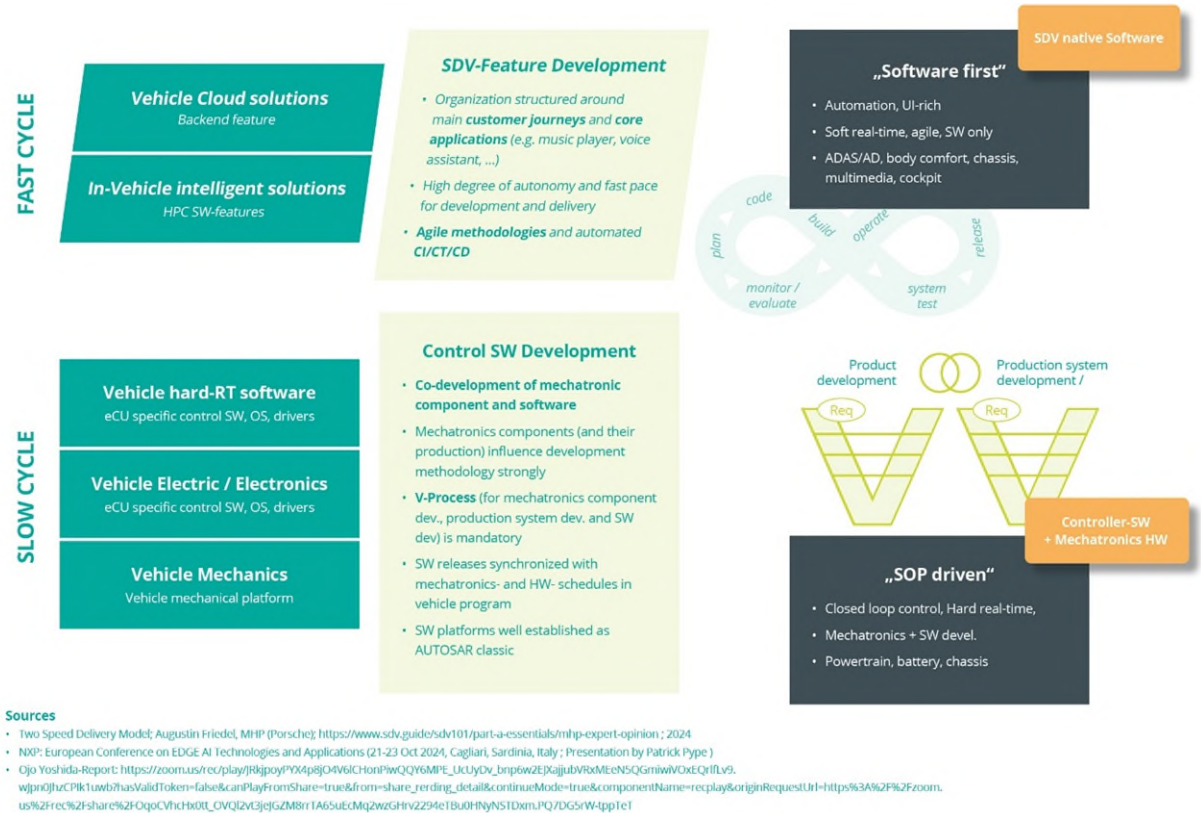

Figure 3.1.1: Two-speed automotive software model [4], [5]

[3] Two Speed Delivery Model; Augustin Friedel, MHP (Porsche); https://www.sdv.guide/sdv101/part-a-essentials/mhp-expert-opinion ; 2024 NXP: European Conference on EDGE AI Technologies and Applications (21-23 Oct 2024, Cagliari, Sardinia Italy ; Presentation by Patrick Pype)

[4] Two Speed Delivery Model; Augustin Friedel, MHP (Porsche); *https://www.sdv.guide/sdv101/part-a-essentials/mhp-expert-opinion* ; 2024

[5] NXP: European Conference on EDGE AI Technologies and Applications (21-23 Oct 2024, Cagliari, Sardinia Italy ; Presentation by Patrick Pype)

This dual-speed framework allows OEMs to combine rapid feature delivery with robust platform and lifecycle management. However, increasing functionality, tighter coupling of vehicle and cloud, and shared compute resources across domains are driving a sharp rise in software complexity.

3.1.4 Closing the Gap Between Complexity and Productivity

The automotive industry faces a widening and increasingly unsustainable gap between software complexity and development productivity. Fragmented and incompatible software platforms create significant redundancy and non-value-adding effort across development, integration, and maintenance. To remain globally competitive, the automotive software operating model must evolve along several dimensions:

- **Architecture and Platforms**: Adoption of end-to-end software platforms with standardized interfaces, enabling reuse across vehicle families and decoupling software lifecycles from hardware.
- **Open-Source Collaboration**: Systematic development of non-differentiating building blocks (e.g. middleware, hardware abstraction) based on open-source software, leveraging community innovation and shared investment.
- **Development Methodologies and Toolchains**: Scalable agile methods, advanced testing, continuous integration, and deployment pipelines across the full SDV lifecycle.
- **AI-Assisted Development**: Use of AI to automate design, code generation, integration, and testing, while preserving safety, security, and regulatory compliance.
- **Organizational Transformation**: Adaptation of organizational structures, skills, locations, and partnerships to support software-centric development without losing hardware excellence.
- **Towards a European SDV Ecosystem and Strategic Autonomy**

To reinforce European leadership and strategic autonomy in the digital vehicle value chain, European automotive, embedded-software, and semiconductor industries—together with the European Commission—are aligning complementary initiatives around a shared SDV vision.

A core objective is the creation of a **European SDV ecosystem** based on reusable, application-oriented, and largely open-source software building blocks, supported by shared toolchains and active participation of start-ups and SMEs. Agility and development speed are critical success factors, making systematic reuse of proven components and close cooperation across initiatives essential to avoid duplication of effort and reduce time-to-market.

Key initiatives contributing to this ecosystem include **ECAVA[6], AUTOSAR[7], Catena**-X[8], **COVESA[9]**, **Eclipse SDV[10], FEDERATE[11], SOAFEE[12], 2Zero[13], CCAM[14]**.

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[6] ECAVA (European Connected and Automated Vehicles Alliance), ECAVA – A European Alliance for Connected and Automated Mobility, European industry alliance supporting coordination on architecture, safety, and validation of connected and automated vehicle technologies, 2023–present. Available at: https://www.ecava.eu
[7] Home AUTOSAR: https://www.autosar.org
[8] Catena-X: https://catena-x.net/en/
[9] COVESA: https://covesa.global/
[10] Software Defined Vehicle | The Eclipse Foundation: https://sdv.eclipse.org/
[11] FEDERATE: https://federate-sdv.eu/
[12] Soafee: https://www.soafee.io/
[13] 2Zero: https://www.2zeroemission.eu/
[14] CCAM - European Partnership on Connected, Cooperative and Automated Mobility: https://www.ccam.eu

3.1.5 The Role of ECAVA

ECAVA provides strategic and architectural coordination for the European Connected, Automated, and Virtualized Automotive ecosystem. It supports alignment across SDV, CCAM, and data-space activities, bridges research and industrial deployment, and promotes consistency between industry-driven initiatives and European policy objectives.

ECAVA contributes in particular by:

- Promoting coherent reference architectures across vehicle, edge, and cloud layers
- Supporting collaboration on non-differentiating building blocks
- Strengthening links between SDV platforms, AI technologies, virtualized compute infrastructures, and data spaces
- Enhancing Europe's capacity to industrialize software-defined mobility solutions

3.1.6 Layered SDV Hardware/Software Stack

European initiatives converge on a layered SDV hardware/software stack that structures complexity and supports reuse:

- **Layer 1 – Hardware and Virtualization**
  High-performance compute platforms, domain and zonal controllers, and abstraction of compute, sensor, actuator, and communication resources as well as hard real-time controllers.

- **Layer 2 – SDV Software Platform (Middleware, OS, Hardware Abstraction)**
  The core enabling layer, consisting largely of open-source, non-differentiating building blocks that decouple hardware and software lifecycles and enable efficient collaboration across OEMs, suppliers, SMEs, and IT companies. This layer is critical for portability, scalability, and edge-to-cloud integration.

- **Layer 3 – In-vehicle SDV Applications**
  Differentiating vehicle applications, including infotainment, automated driving, ADAS, cockpit HMI, charging, routing, powertrain, chassis, and comfort functions.

- **Layer 4 – Cloud SDV applications**
  Many SDV applications require cloud services and data, such as traffic and weather information, billing services for tolls, parking and charging, parking availability, and infotainment services.

- **Layer 5 – AI Assisted Engineering Automation and Processes**
  Modular toolchains supporting model-based design, simulation, testing, integration, and deployment, increasingly leveraging AI to improve productivity and quality. (see also SRIA Chapter 2.3).

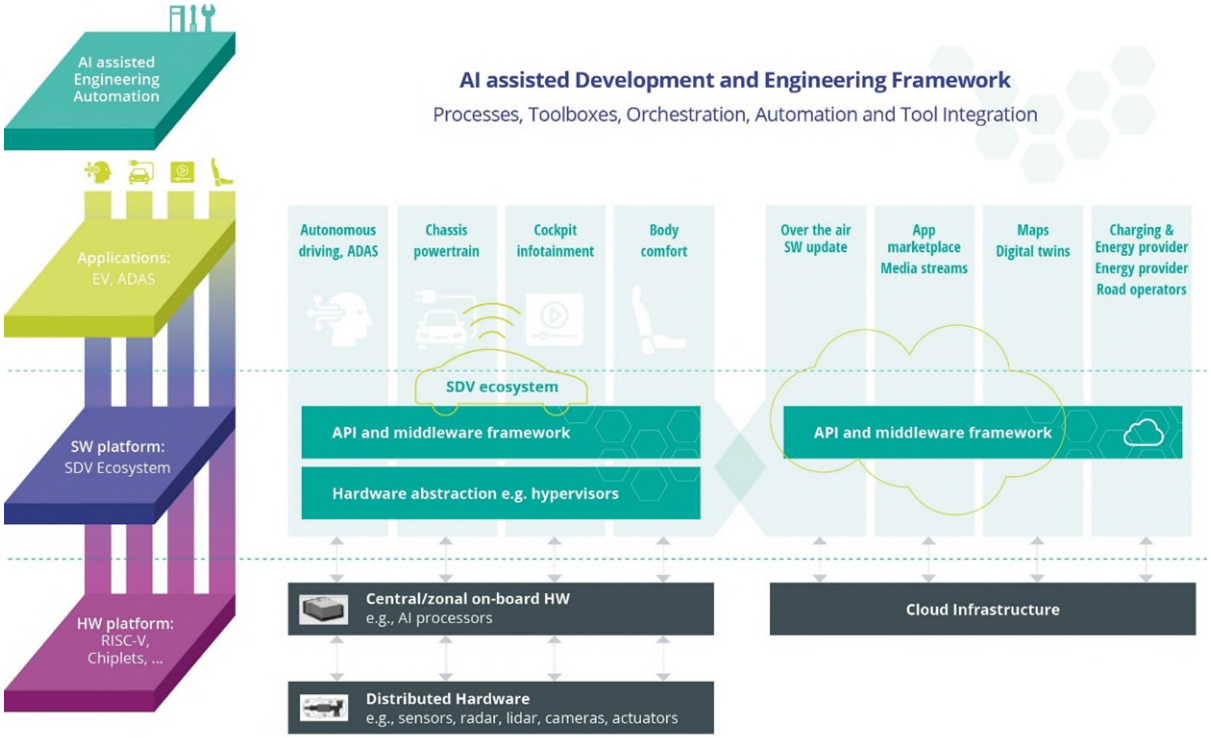

Figure 3.1.2: SDV Layer model

Standards play a central role in ensuring interoperability, semantic consistency, diagnostics, data governance, and ecosystem integration. Continued contribution to and evolution of relevant standards is essential to support the SDV ecosystem.

By aligning with alliances such as **ECAVA, Eclipse-SDV, Catena**-X, **COVESA**, **SOAFEE, 2Zero, CCAM and AUTOSAR, Europe aims** to create a shared ecosystem that reduces time-to-market and fosters a vibrant startup and SME landscape for mobility applications.

These layers of SDV mobility systems form an integrated framework consisting of hardware, software and AI.

3.1.7 Major Challenges

The ongoing transformation of the mobility landscape defines the following six core RDI (Research, Development, and Innovation) challenges, which are explained in the following sections:

Major Challenge 1: SDV Hardware Platforms – Developing modular, scalable, and flexible hardware architectures that ensure uncompromising safety and security.

Major Challenge 2: Software Platforms for the SDV of the Future – Engineering modular, reusable, and secure software environments that support seamless edge-to-cloud integration.

Major Challenge 3: The Green Deal – Advancing technologies to enable climate-neutral and energy-optimized mobility ecosystems.

Major Challenge 4: Digitalization – Implementing affordable, safe, and connected automated mobility solutions for both passengers and freight.

Major Challenge 5: Edge-to-Cloud Mobility Applications – Delivering enhanced end-user value through interconnected digital services and cloud-integrated functions.

Major Challenge 6: AI-Enabled Engineering Toolchains – Accelerating agile, collaborative software development and streamlining the validation of SDV and ADAS/AD systems through artificial intelligence.

3.1.7.1 Major Challenge 1: SDV hardware platforms: modular, scalable, flexible, safe & secure

Evolution of SDV EE-architecture

With code complexity projected to reach **1 billion lines by 2030**, current E/E architectures face critical bottlenecks in networking, latency, and wiring. This is driving a shift towards **software-defined vehicle (SDV)** architectures and a transition from distributed ECUs to centralized, high-performance computing for automation supported by zonal controllers mainly for data acquisition and safety-relevant real-time control tasks. *Figure* 3.1.3 below indicates the transition from **the classical distributed ECU architecture** to **the SDV central-zonal architectures**.

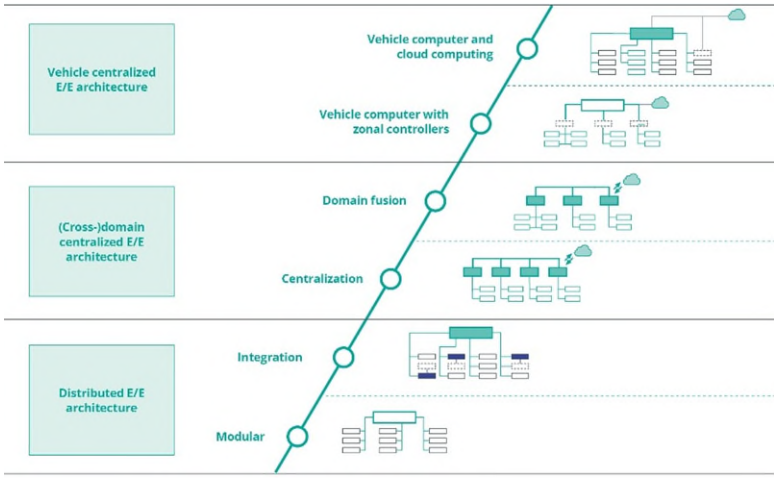

Figure 3.1.3: Electric and Electronic Architectures for SDV: Topologies and Networking [15]

[15] Springer Nature; accessed 2026-04; https://link.springer.com/article/10.1007/s42154-023-00266-9/figures/1

Layers and roadmap in SDV HW platforms

It is expected that there will be no single vehicle architecture, but that there will be different variants, based on the type of OEM and/or based on the type of car (low-end versus high-end), as depicted in the picture above. In addition, the growing complexity of both automotive software and E/E architectures (as illustrated qualitatively in the figure below) requires new families of high-end control units and application-specific processors with many system integration challenges.

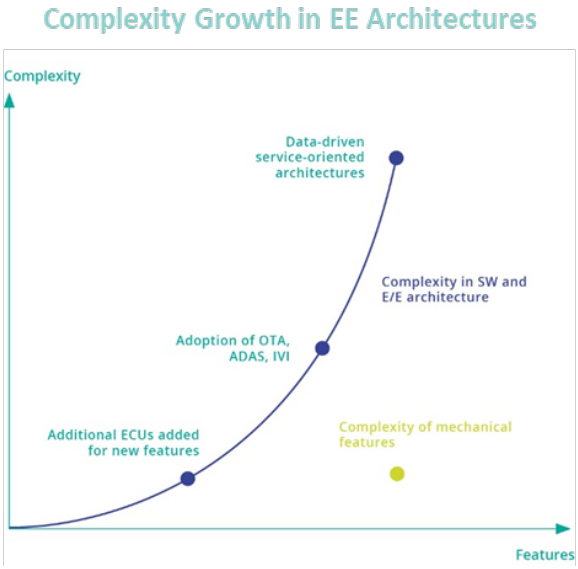

Figure 3.1.4: Complexity growth in EE architectures

RISC-V automotive roadmap

The Mobility hardware layer consists of the following major components:

- **High-Performance Computing (supporting edge-AI) and safety critical real-time controllers:** Serving as the foundational enabler for software stacks and SDV platforms
- **Power Electronics & Actuation:** Driving the transition to electric propulsion and energy efficiency (see also **Major Challenge 3**).
- **Actuator, Sensing & Perception:** Providing the essential hardware for real-time controllers, safety, security as well as environmental awareness and data acquisition (see also **Major Challenge 4**).
- **Reliable, high-performance communication** within vehicles and between vehicles, the cloud and other vehicles (see also **Major Challenge 5**).

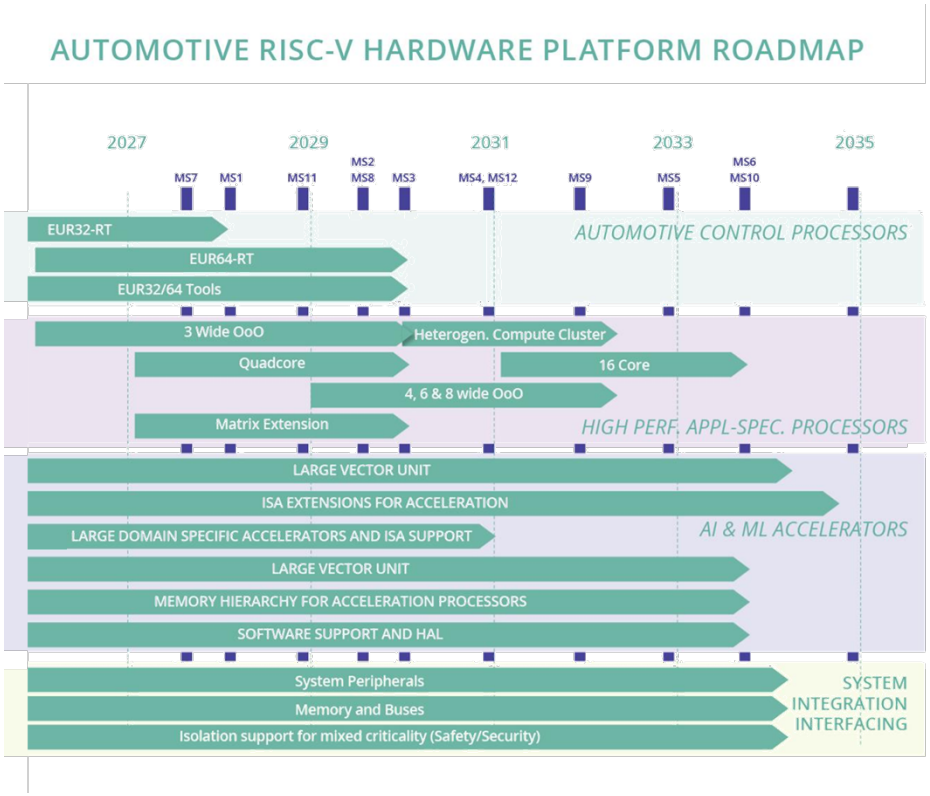

Figure 3.1.5: Automotive RISC-V hardware platform roadmap

To navigate the shift toward centralized architectures, a high-level roadmap was developed based on the **open-standard RISC-V ISA**. It offers a flexible reference platform for European innovation[16, 17, 18, 19, 20]. This framework ensures technological sovereignty by categorizing R&D into four pillars:

- **Scalable Control & High-Performance Processors:** Developing both real-time control and high-end application processors.
- **AI/ML Accelerators:** Integrated hardware for advanced perception and decision-making.
- **Next-Gen Interfacing:** Deploying high-speed fiber optics and wireless "plug-and-play" communication.

[16] European Working Group on RISC-V Automotive. The Road towards a High-Performance Automotive RISC-V Reference Platform. Annex 3 to: Roadmap for Future Automotive-driven RISC-V Developments in Europe. ECS SRIA / Chips Joint Undertaking, Brussels, Belgium, 2023 (updated final version 2024).
[17] European Commission. Recommendations and Roadmap for European Sovereignty on Open Source Hardware, Software and RISC-V Technologies. European Commission, Brussels, Belgium, 2022. Available at: https://digital-strategy.ec.europa.eu
[18] TRISTAN Consortium. TRISTAN: Expand, Mature and Industrialize the European RISC-V Ecosystem. Chips Joint Undertaking Project, European Union, 2023. Available at: https://www.tristan-project.eu
[19] ISOLDE Consortium. ISOLDE Project: Industrialising Open-Source Low-Power RISC-V Solutions. Chips Joint Undertaking Project, European Union, 2023. Available at: https://www.isolde-project.eu
[20] Cuomo, L.; Scordino, C.; Ottaviano, A.; Wistoff, N.; Balas, R.; Benini, L.; Guidieri, E.; Savino, I. M. Towards a RISC-V Open Platform for Next-generation Automotive ECUs. Proceedings of the 12th Mediterranean Conference on Embedded Computing (MECO), Budva, Montenegro, 2023, pp. 1–8. DOI: 10.48550/arXiv.2307.0414

- **System integration using chiplets addresses** the challenges of monolithic SoCs, such as suboptimal cost structures, reduced manufacturing yield and increasing development effort by decomposing a SoC into smaller, function-specific dies—such as CPU, AI acceleration, I/O, networking, and safety—connected via high-speed die-to-die interconnects[21].

Power electronics

The European semiconductor industry has a very strong footprint in power electronics, in particular for mobility. Cost and quality aspects drive the rapid development of new semiconductor technologies, packaging and system design.

Strong cooperation between automotive manufacturers, Tier-1 suppliers and semiconductor providers is essential for success.

The main development challenges are:

- New SiC technologies including vertical SiC architectures
- New GaN technologies for high-frequency applications with increased voltage levels
- Packaging aspects to increase the power per volume ratio and allow better cooling
- New standard packaging and interface solutions to decrease costs and increase reliability
- Synergies between different domains (aeronautics, automotive, industry) to allow economies of scale
- Data collection on a wider scale to allow in-situ predictive maintenance and input for new device developments
- Development of new technologies such as Ga2O3 or Diamond technologies
- Standardisation of quality requirements and checks for new technologies in new use cases to speed up adoption
- Better understanding of aging effects in order to enable the development of high-quality, high-performance products

Chiplets and SoCs in SDV hardware platforms

In automotive SDV platforms, chiplet architectures enable:

- **Heterogeneous integration**, allowing each function to use the most appropriate process node;
- **Performance scalability**, by adding or upgrading compute chiplets without redesigning the entire SoC (e.g. also for cybersecurity);
- **Improved yield and cost efficiency**, particularly for AI-heavy designs; and
- **Platform longevity and obsolescence management**, aligning long vehicle lifecycles with faster silicon innovation[22];
- **Energy efficiency**;
- **Miniaturisation**;
- **Supply Chain Resilience**.

[21] Chiplet-Marketplace, *CHASSIS: European Industry Initiative for Automotive Chiplets*, December 15, 2025. Available at: https://chiplet-marketplace.com/insights/news/chassis-chiplet-based-hardware-architectures-for-software-defined-vehicles

[22] Müller, B.; Foresi, J., Chiplet Architectures Can Solve Real Performance, Yield and Cost Challenges, ADT Media, March 25, 2026. Available at: https://www.adt.media/software-defined-vehicles/chiplet-architectures-can-solve-real-performance-yield-and-cost-challenges/2635105 [mckinsey.com]

For automotive adoption, chiplet architectures must rely on **standardized interconnects** and **automotive-grade safety mechanisms**. Technologies such as **UCIe (Universal Chiplet Interconnect Express)** and emerging automotive extensions enable:

- Deterministic, high-bandwidth die-to-die communication.
- Propagation of safety and isolation domains across chiplets; and
- Supplier interoperability without vendor lock-in [23].
- Open ecosystems—including **RISC-V-based compute and AI chiplets**—further enhance architectural flexibility and sovereignty by allowing OEMs and Tier-1s to customize instruction sets, accelerators, and safety mechanisms while retaining software portability [24], [25].

Critical infrastructure for hardware platforms

To support these high-performance clusters and ensure "freedom from interference" for safety-critical tasks, the roadmap prioritizes: (1) **Shared Cache Architectures:** Managing massive request volumes from out-of-order cores without serialization; (2) QoS-enabled **Interconnects:** High-bandwidth fabrics that prioritize safety-critical traffic; (3) Advanced memory controllers**:** High-throughput controllers designed to minimize contention and latency.

Hardware abstraction, virtualization and hard real-time controllers as part of the SDV hardware layer

In the SDV hardware layer, hardware abstraction, virtualization, and hard real-time controllers work together to reconcile mixed-criticality workloads on shared compute platforms. A standardized hardware abstraction layer (**HAL**) decouples vehicle software from underlying SoCs and accelerators, enabling portability, OTA updates, and long platform lifetimes despite heterogeneous silicon. On top of this, virtualization and partitioning technologies—including type-1 hypervisors, microkernels, and hardware-assisted isolation—allow multiple operating systems (e.g., POSIX/Linux, AUTOSAR Adaptive, and safety RTOSs) to coexist securely on the same hardware, with strict spatial and temporal separation to guarantee freedom-from-interference. This HAL connects the SDV-HW layer with SDV middleware layer.

Within this consolidated environment, hard real-time controllers (often implemented as dedicated cores, safety islands, or isolated partitions) execute time-critical control loops for braking, steering, powertrain, and body functions, ensuring deterministic latency and compliance up to ASIL-D, independent of best-effort or AI-heavy workloads. Together, these mechanisms enable SDV platforms to centralize compute without compromising safety, determinism, or upgradability, aligning long automotive lifecycles with software-centric development and heterogeneous hardware evolution.

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Key RDI Priorities:

- **Centralized E/E Architectures:** Consolidating functions into **Domain (DCU)** or **Zonal Control Units (ZCU)**, ultimately leading to centralized **System-on-Chips (SoCs)** that integrate autonomous driving, infotainment, and cabin control.
- **The RISC-V Open Standard:** Leveraging the **RISC-V ISA** to develop flexible, European-led reference platforms. This includes scalable control processors, high-performance application processors, and dedicated **AI/ML accelerators**.
- **High-Bandwidth Infrastructure:** Developing advanced shared cache memories, QoS-enabled interconnects, and memory controllers to manage high data throughput while ensuring **freedom from interference** for safety-critical applications.
- **Automotive Chiplets & Advanced Packaging:** Utilizing chiplet-based designs to balance performance with affordability. This involves mixing cutting-edge and mature technologies while defining clear boundaries between "open-source" and "proprietary" architectural zones.
- **Next-Gen Connectivity:** Integrating **fiber optics** and wireless communication (including plug-and-play software) to handle the massive data flow required for increased vehicle autonomy and security.
- **HW/SW abstraction and virtualization**

Strategic Impact: This modular hardware foundation ensures that European OEMs can manage escalating complexity while maintaining **technological sovereignty** and the ability to deliver continuous "software freshness" over the vehicle's lifespan.

3.1.7.2 Major Challenge 2: SW platforms for SDV of the future: modular, scalable, re-usable, flexible, safe & secure, supporting edge2cloud applications

Software-Defined Vehicles: Platforms, Architectures, and Ecosystems

Software has become the primary value driver for modern mobility, with software complexity increasingly outpacing development productivity. To remain competitive, the automotive industry is transitioning from hardware-centric designs to a **software-defined vehicle (SDV)** paradigm, in which functionality is continuously delivered, updated, and enhanced through software. This shift fundamentally changes how vehicles are designed, developed, produced, and operated over their entire lifecycle.

SDV mobility software leverages data acquisition, sensor fusion and connectivity to orchestrate vehicle actuation, data management, and the human-machine interface (HMI).

Paradigm Shift: Hardware/Software Abstraction and Edge-to-Cloud Integration

Regular over-the-air (OTA) software updates and cloud-integrated edge-to-cloud applications are reshaping vehicle lifecycles. Capabilities such as smart charging, automated parking, navigation, ADAS/AD (driving assistance up to autonomous driving) and predictive maintenance increasingly rely on close interaction between in-vehicle software and off-board cloud services. OTA updates significantly increase customer value by enabling continuous functional improvements after vehicle delivery.

These capabilities require a robust abstraction layer decoupling software from hardware. This abstraction uses the HAL functionalities and is enabled by comprehensive software platforms comprising virtualization, operating systems, middleware, and standardized APIs. Such platforms support "software freshness" throughout the vehicle's lifetime, allow independent evolution of hardware and software, and enable scalable edge-to-cloud integration.

Recognizing this transformation, the automotive industry has committed to strengthening collaboration and capability-building in open-source software, formalized through a memorandum of understanding[26] signed in June 2025.

The **Software-Defined Vehicle (SDV) software layer** comprises the full software stack that defines vehicle functionality independently of the underlying hardware and spans system software (safety-certified operating systems, hypervisors, and middleware), service-oriented communication frameworks, platform services for diagnostics, cybersecurity, and over-the-air (OTA) lifecycle management, as well as application software covering automated driving, infotainment, body, chassis, and energy domains.[27]

A central objective of this layer is the **systematic decoupling of software from hardware**, enabling portability, reuse, continuous deployment, and long-term maintainability across multiple vehicle generations.[28] In the European context, this approach is increasingly anchored in **open, standards-based software platforms**—such as Eclipse-SDV, SOAFEE, and COVESA—aimed at reducing fragmentation and strengthening digital sovereignty while preserving OEM differentiation.[29],[30]

The associated **research, development, and innovation (RDI) challenges** are substantial: ensuring deterministic real-time behavior and functional safety in mixed-criticality, virtualized environments; scaling verification, validation, and certification processes for software systems comprising hundreds of millions of lines of code; enabling secure, fail-operational OTA updates over vehicle lifetimes exceeding a decade; integrating DevOps and cloud-native development practices into safety-critical product lifecycles; and aligning open-source collaboration with automotive quality and regulatory requirements.[31],[32] Addressing these challenges requires coordinated advances in software architectures, tooling, governance, and validation methodologies and has become a strategic priority for maintaining the competitiveness and autonomy of the European automotive ecosystem.

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Available at: https://www.ecava.eu

Robust governance mechanisms for third-party software and services

Software-defined vehicles are evolving into open yet controlled platforms that extend beyond OEM functionality. This requires modular software architectures, OTA lifecycle management, and governance for integrating third-party services.

Standardized, credential-based trust and authorization mechanisms enable OEMs to certify providers, define execution policies, and control access to vehicle resources, while allowing users to transparently manage consent.

By combining SDV architectures with policy-bound authorization, vehicles can support dynamic mobility ecosystems while ensuring safety, cybersecurity, compliance, and data sovereignty across the lifecycle.

Key RDI Priorities:

- Scalable, cloud-capable SDV reference architectures supporting evolving domain- and zone-oriented E/E topologies;
- Vendor-neutral SDKs enabling hardware- and operating-system-independent application development and testing;
- Safe, secure, and reusable APIs abstracting hardware, middleware, kernels, and drivers;
- Systematic integration of safety and cybersecurity across the full SDV stack for rapid (re-)homologation, especially for OTA updates;
- Focus on energy efficiency in software as well (especially when using edge-AI)
- Usage of AI-enabled tools to increase software productivity without compromising compliance;
- Integrate and adapt the European GNSS technology into automotive applications to increase the resilience of the mobility in Europe
- Provide backward compatibility of middleware for easy updates
- Robust governance of third-party SDV SW applications and services

3.1.7.3 Major Challenge 3: Green deal: enable climate and energy optimised mobility

Strategic Context: Electrification and Defossilisation of Mobility

Global regulations targeting pollution and CO_2 emissions are accelerating the electrification of mobility across all transport modes. Passenger vehicles are increasingly based on battery electric (BEV), hybrid electric (HEV), or fuel-cell (FCEV) architectures. Scenario analyses (e.g. BIPE, France) show that regulatory stringency will determine the pace and structure of this transition. One possible pathway is the “Green Constraint” scenario, aligned with the European decision to ban new fossil-fuel vehicles by 2035. This decision creates a major industrial, technological, and societal transformation challenge.

Industry and politics in Europe predict that by 2035:

- The majority of cars sold in Europe will be electrified.
- Electrified vehicles will represent ~70% of global vehicle sales.
- Around one third of vehicles will rely on high-voltage architectures (400–1000 V) requiring on-board chargers.
- Fuel-cell systems may remain relevant for long-haul trucks, rail, maritime applications, and selected aviation use cases, although industrial commitment remains uncertain.

Convergence of Mobility and Energy Systems

Electrified vehicles are becoming integral components of the European energy ecosystem. Vehicle batteries will increasingly act as distributed energy storage through bidirectional charging (V2G), while on-board energy generation (e.g. photovoltaics, heat recovery) will partially feed energy back to the grid. This convergence imposes fundamentally new requirements on vehicle electrical and electronic systems.

Vehicle components traditionally designed for ~8,000 operating hours must now withstand continuous grid-connected operation over the full vehicle lifetime, increasing required durability by a factor of 5–15. This creates major challenges for reliability, safety, and validation, and requires systematic use of digital twins, advanced simulation, and lifecycle-oriented design methodologies.

Systemic Impact and CO_2 Reduction Speed

Electrification will profoundly reshape supply chains and competence distribution across the automotive and electronics ecosystems. However, achieving rapid CO_2 reduction requires solutions beyond new vehicle sales, whose impact unfolds only medium to long term. Measures targeting the existing global vehicle fleet offer higher short-term impact, including:

- Retrofit solutions and efficiency upgrades,
- Car-sharing and improved vehicle utilisation,
- Energy-efficient tires, improved lubrication,
- Digital solutions enabling teleworking and optimised mobility.

Electronics and digital technologies play a key role in enabling rapid deployment of such measures.

Key RDI Priorities

Components and Architectures

- Advanced semiconductor technologies (SiC, GaN, Ga_2O_3).
- Novel power electronics architectures exploiting wide-bandgap devices.
- Modular, scalable and flexible E/E platforms.
- Hardware upgradability, repairability, and component replacement with higher-efficiency modules.
- Low environmental impact across production, operation, and end-of-life.
- Reduction of critical raw materials and design for recyclability and circularity.

Software, Intelligence and Control

- Reconfigurable and updateable software architectures (including OTA).
- Embedded intelligence (AI-enabled control, real-time algorithms, cognitive perception).
- Fault-tolerant and fail-operational concepts.
- Predictive diagnostics, maintenance and recovery strategies.
- Cloud–edge–fog processing frameworks.
- Proof of robustness, trustworthiness, and quantification of operational risks.

Electrified Powertrains and Energy Management

- Advanced battery management systems for solid-state, sodium-ion, and high-silicon batteries.
- Accelerated lifetime testing, diagnostics and degradation-aware control.
- Smart batteries with sensing, communication, lifetime data logging and digital battery passports.
- Efficient, safe and fast charging and refuelling solutions (“plug and charge”).
- Integrated energy management linking vehicles, charging infrastructure and the power grid to minimise infrastructure investment.

Fuel Cell Systems

- Degradation-aware and efficiency-optimised control for fuel-cell vehicles, especially trucks and buses.
- Predictive control using route, traffic and weather data.
- State-of-health monitoring via virtual sensors and advanced sensing technologies.
- AI-enabled safety and IoT-based diagnostics.

Power Devices and Infrastructure

- AI-integrated power devices with enhanced functionality.
- Seamless interaction between vehicles, charging stations and energy infrastructure.
- Interoperability and communication standards (including spectrum and bandwidth management).

Connectivity, Safety and Automation

- Reliable, low-latency and resilient wireless communication combined with advanced sensing is essential for traffic efficiency, safety and fatality reduction. This drives stringent requirements on communication components, system architectures, and validation methods.
- Collaborative and self-organising multi-agent systems will enable new logistics concepts and cooperation across land, air and maritime domains.

Transport Modes and Application Scope (The addressed technologies apply across a wide range of platforms):

- Passenger cars (M1/M2), light vehicles and micro-mobility.
- Trucks, commercial vehicles, agricultural and non-road machinery.
- Ships and maritime systems.
- Aircraft, manned and unmanned air vehicles (including drones).
- Two- and three-wheel vehicles.
- Off-road and special-purpose vehicles (land, air, water).

Integrated Mobility Concepts and Societal Impact

- Cross-modal synergies between automotive, air and freight transport can significantly reduce costs and emissions
- Urban light personal and small freight mobility, including shared micro-vehicles interoperable with public transport for last-mile connectivity.
- Flexible multi-passenger vehicles, privately owned or shared, with enhanced safety and autonomous-ready features.
- Right-sized long-haul and commercial vehicles optimised for logistics, last-/first-mile delivery, and urban operation.
- Environmentally friendly mobile machinery for agriculture and construction, increasing efficiency and safety.

3.1.7.4 Major Challenge 4: Digitalisation: affordable and safe automated and connected mobility for passengers and freight

Regain European sovereignty and strengthen global competitiveness in embedded software for mobility

The four major mobility megatrends—**electrification, automation, connectivity, and shared mobility**—are fundamentally enabled by **advanced electronics, software, and artificial intelligence**. The rapid transition toward **software-defined vehicles and platforms (SDVs)** makes software, data, and AI decisive for safety, sustainability, competitiveness, and resilience. This challenge is therefore closely linked to European leadership in both hardware and software technologies.

Europe's ambition is to deliver **safe, sustainable, inclusive and affordable mobility**, while strengthening **digital sovereignty and open strategic autonomy** in critical technologies. This ambition is driven by major societal challenges such as climate change, urbanisation, demographic change, and increasing security risks, as well as by intensified global competition and geopolitical dependencies.

The overarching vision is to realise **always-connected, cooperative, safe, secure and automated mobility systems**—for passengers, freight and services—across **road, rail, waterborne, air** and **drone mobility**, based on **trusted, energy-efficient,** and **European-controlled hardware, software and data infrastructures**, combined with **advanced human–machine interaction**.

Automation Across Transport and Drone Domains

For road mobility, Europe pursues three core objectives:

1. **Eliminate road fatalities caused by human error by 2050**,
2. Ensure that increased automation introduces **no additional fatalities**, and
3. Reduce **validation and verification costs** from today's 70–80% of development effort to approximately 60% despite the increased validation effort caused by faster code generation with AI copilots.

Achieving these goals relies on **Key Digital Technologies** and is central to the **Horizon Europe Partnership on Connected, Cooperative and Automated Mobility (CCAM)**. Given the scale and safety-critical nature of the challenge, success requires **cross-sector collaboration**, shared operational data, and coordinated actions among industry, research, and public authorities.

Automation in **rail transport** enables driverless trains, optimised asset usage, higher capacity, improved punctuality, and enhanced safety. In **waterborne transport**, increasing automation and connectivity support condition-based maintenance, remote operation, and the progressive deployment of autonomous and unmanned surface and underwater vessels, improving efficiency, safety, and environmental performance.

In **aviation and aeronautics**, automation reduces pilot workload, enhances flight management, and enables predictive maintenance, contributing to safer and more efficient air transport. **Urban Air Mobility (UAM)** and **drone-based services** introduce a new layer of mobility above cities and regions.

Drones play a **strategic role for Europe's safety, security, and resilience**:

- Border and maritime surveillance,
- Infrastructure inspection and critical asset protection,
- Emergency response, search and rescue, and disaster management,
- Environmental monitoring and crisis assessment,
- Secure logistics and medical deliveries in hard-to-reach areas.

As such, **civil and civil-security drone capabilities must be considered a strategic technology domain**. Autonomous and connected drones depend on advanced ECS, AI, secure communications, and reliable control software, making them a key pillar of Europe's **open strategic autonomy**. Ensuring European control over drone platforms, autonomy stacks, communication systems, and data flows is essential for safeguarding sovereignty and public security while enabling civilian innovation.

Key Challenges for Connected, Cooperative and Automated Mobility

Connected, cooperative and automated mobility - including ground vehicles, rail systems, ships and drones - will profoundly shape future mobility and security systems. However, they introduce **multidimensional challenges**, especially in mixed environments where different levels of automation coexist with human-operated systems and vulnerable users.

Removing human operators (drivers, pilots) from platforms or supervision loops requires **fail-operational** in-vehicle HW and in-vehicle and associated cloud SW, robust tele-operation and tele-assistance, and dependable operation across extended operational design domains (ODDs). Both **stepwise automation ("conversion design")** and **purpose-built fully autonomous systems (SAE level 5 / unmanned aerial systems)** have reached pilot deployment stages but require significant R&I to ensure scalability, safety, certification, and public trust.

As electronics and software represent a growing share of system value, demands increase for:

- Cybersecurity, resilience and trustworthiness,
- Privacy-by-design and sovereign data handling,
- Safe degradation, redundancy and fallback strategies from component level to cloud services.
- Digital Sovereignty and Open Strategic Autonomy
- A European Autonomous and Drone Mobility Stack

A critical cross-cutting objective is to strengthen **Europe's digital sovereignty, security, and resilience** in automated mobility and drone systems. Today, essential parts of autonomy stacks—operating

systems, middleware, AI frameworks, perception algorithms, cloud platforms—are largely developed and controlled outside Europe, creating strategic dependencies.

Europe therefore needs to establish a **European Autonomous and Drone Mobility Stack**: a **modular, interoperable, certifiable and European-controlled ecosystem** spanning hardware, embedded software, AI, tools, and standards, applicable across road vehicles, trains, ships and drones.

Key Objectives

- Reduce dependence on non-European critical software and AI components in safety- and security-relevant mobility systems.
- Secure end-to-end European value chains, from chips and power electronics to autonomy software and validation toolchains.
- Embed **safety, security, trust and compliance-by-design** as competitive advantages.
- Enable reuse across transport and drone platforms, including dual-use civil and security applications.
- Strengthen European industry competitiveness and innovation capacity.

Core Stack Elements

- European-controlled SDV middleware, hypervisors and service-oriented architectures.
- Trusted, explainable and certifiable AI for perception, decision-making and control, including drone autonomy as part of a European controlled autonomous vehicle stack
- Standardised interfaces and reference architectures to ensure interoperability without vendor lock-in.
- Digital twins, simulation and verification frameworks for certification and operational assurance.
- Sovereign cloud–edge–vehicle–drone data spaces aligned with European data governance and security standards.

Key RDI Priorities:

- Robust perception and situational awareness, including integrated sensing and communication for protecting vulnerable users and enabling safe drone operations in dense airspaces.
- Real-time collaborative and multi-agent decision-making under uncertainty, across vehicles, infrastructure and drones.
- Energy-efficient and trustworthy AI, edge intelligence, continual learning and adaptive resource management.
- Cybersecurity, safety assurance and certification for highly autonomous and unmanned systems.
- Environmental and economic sustainability, including energy efficiency and lifecycle optimisation.
- Interoperability and standards, across vehicle, infrastructure and drone ecosystems.
- Dependable sensing, resilient localisation and V2X/U-space communication systems.
- Hardware–software co-design, digital twins and continual learning.
- SDV-centric and drone-centric ECS architectures with OTA, remote operation and monitoring.
- Advanced AI-based predictive control enabling new active safety paradigms.
- Predictive health monitoring and lifetime management of sensors, AI modules and control systems.

Regulatory and legal challenges (refer also to Chapter 2.4, major challenge 4)

- Regulatory frameworks and liability: Creating consistent regulatory frameworks that can keep pace with rapid technological advancements as well as determining liability and allowing for interoperable and fast deployment across Europe is challenging.

Ethical and social challenges

- Ethical decision-making: Autonomous vehicles must be programmed to make ethical decisions in situations where harm is unavoidable. Creating consensus on these ethical frameworks is difficult.
- Public acceptance: Gaining public trust and acceptance of autonomous vehicles is crucial. This involves addressing fears and misconceptions about the safety and reliability of the technology.
- Impact on employment: The widespread adoption of autonomous vehicles may impact jobs, particularly in sectors like transportation, logistics and digital industry.

Environmental and Economic Challenges

- Energy consumption: Autonomous vehicles, especially when equipped with multiple sensors and communication systems, can have high energy demands. Balancing energy efficiency with performance is necessary.
- Economic viability: The high cost of developing, testing, and deploying autonomous vehicles and the necessary infrastructure can be a barrier to widespread adoption. Ensuring economic viability for manufacturers, consumers, and municipalities is challenging.

Interoperability and standardization

- Interoperability: Ensuring that autonomous vehicles from different manufacturers can communicate and operate seamlessly with each other and with infrastructure is critical. This requires standardization of communication and data exchange protocols and systems.
- Standards development: Developing and implementing standards for autonomous vehicle performance, safety, and communication is a complex and ongoing process that requires coordination among industry stakeholders, regulators, and standards organizations.

Strategic Collaboration and Alignment

The required ECS and software innovations represent a structural shift driven by AI, data volumes, adaptability and multi-agent coordination. Close collaboration with the **European Connected and Autonomous Vehicle Alliance** (ECAVA) and European AI**, robotics, satellites and drone ecosystems is** essential to ensure that automated mobility and drone technologies are developed, deployed and governed **on European terms**, reinforcing safety, resilience, industrial competitiveness and societal value. The created methods and technology advances should be application-independent in principle (of course, capable of being tailored to specific applications). Collaboration with the AI and robotics community should be strengthened, e.g. with the AI Data Robotics Association (ADRA)[33] or the US National Robotics initiative[34].

[33] https://adr-association.eu

[34] https://hichristensen.com/post/roadmap-2024/

3.1.7.5 Major challenge 5: Edge-to-cloud mobility communication and applications

The rapid advancement of **Cloud–Edge–IoT** (**CEI**) technologies is driven by growing demand for **digital twins**, **satellite communication**, software-defined vehicles (**SDV**), and **secure mobile robotics**. These applications require ultra-low latency, real-time data processing, and distributed intelligence at the network edge. CEI technologies are therefore becoming a cornerstone of future digital infrastructures across multiple innovation domains, particularly transport and mobility.

Beyond technical performance, CEI solutions are essential enablers for addressing major societal challenges such as climate change, energy efficiency, and resilient mobility systems. Combining specialized hardware, AI-based optimization, and distributed computing with CEI architectures significantly improves energy and resource efficiency while enabling data-driven decision-making deep within complex systems of systems. In mobility, this results in powerful services distributed across cloud platforms, roadside infrastructure, and vehicle software, with cloud-native concepts increasingly extending into in-vehicle software architectures.

From a strategic perspective, CEI technologies create competitive advantages and open new business opportunities in a global market. Transport and mobility is one of the most relevant application domains, driven by the vision of **zero emissions, zero accidents, and zero friction between transport modes**, enabling sustainable, safe, and convenient mobility for passengers and freight. For Europe, CEI adoption represents an opportunity to strengthen domestic cloud and edge capabilities. However, the current dominance of international hyperscalers raises concerns regarding technological sovereignty, strategic autonomy, and long-term competitiveness of European actors.

Opportunities in Mobility and Transport

- **Edge-based processing** enables safety-critical, privacy-sensitive, and latency-critical data to be handled close to sensors and actuators with high reliability and security.
- **Centralized shared cloud capabilities** allow efficient handling of strategic transport functions such as planning, modelling, analytics, AI training, software engineering, lifecycle management, and software updates, including data valorisation.
- **New mobility services**, including shared mobility platforms, connected and automated driving, and integrated multimodal services, become feasible through CEI-enabled architectures.

Research topics

- **Data sovereignty and privacy concerns**, particularly in public transport, may limit acceptance of data processing on non-European or externally controlled cloud infrastructures.
- **Unclear data ownership models**, especially in the public sector, raise questions about governance, accountability, and long-term control of transport data.
- **Vendor lock-in risks** due to limited choice of cloud providers threaten competition and innovation in the European CEI ecosystem.
- **Growing cybersecurity risks**, as vehicles and infrastructure become increasingly connected to external networks and cloud services.
- **CEI Application Scope and Functional Layers**

Given the diversity of transport modes and services, CEI applications span traffic management systems, vehicles, mobility platforms, logistics, fleet management, planning tools, and data spaces. Efficient CEI deployment requires innovation across multiple functional layers:

Design Layer: Support for real-time processing of large, heterogeneous data streams (including vulnerable road users), combined with built-in privacy, security, and regulatory compliance.

Installation Layer: Scalable deployment of sensors and edge nodes, addressing power supply challenges (e.g. smart charging via lampposts), grid interaction, cost efficiency, and cross-departmental connectivity.

Operation Layer: Robust, AI-enhanced operation under varying conditions, enabling dynamic traffic control, seamless multimodal transfers, high data quality, and secure real-time access.

Value-Added Services: Two-way communication between vehicles and infrastructure, fast incident and weather detection, and content delivery for infotainment and user services.

Maintenance Layer: Lifecycle-aware maintenance strategies that bridge the mismatch between long-lived traffic control equipment and rapid IT innovation cycles.

Upgrade and Integration Layer: Phased integration of legacy systems and incremental upgrades to ensure continuity, scalability, and future readiness.

Key RDI Priorities

To realize CEI-based transport systems, research and innovation should focus on the following core building blocks:

- High-performance **edge computing platforms** capable of real-time processing for connected and automated driving (see also SRIA chapter 2.1).
- **Reliable, low-latency connectivity**, including V2V and V2I communication. Edge-to-cloud communication is no longer based solely on terrestrial infrastructure, but also on satellite communication. In this context, it is important for the European industry to develop solutions for safe and reliable communication between cars and satellites. Important items to consider are dedicated hardware solutions in the cars, specific antennas, interface solutions with different satellite systems and means to strengthen cybersecurity and resilience against failures (see also SRIA chapter 2.2).
- Secure and privacy-preserving **data management architectures** handling massive real-time data volumes.
- **Scalable and modular infrastructures** enabling gradual expansion and technology upgrades.
- **Intelligent sensor networks** robust against environmental stress.
- Deep integration of **AI and machine learning** for digital twins, predictive analytics, traffic optimization, and incident detection (see also SRIA chapter 2.3).
- Strong **interoperability standards** to avoid fragmentation.
- **Cybersecurity-by-design**, including encryption, secure updates, and continuous monitoring (see also SRIA chapter 2.4).
- **Energy-efficient system design**, including low-power devices and renewable energy integration.
- **Flexible maintenance and upgrade mechanisms** minimizing downtime and disruption.

Future CEI research in transport and mobility should emphasize large-scale pilots and cross-sector collaboration, particularly in SDV-related applications:

- **AI-driven traffic management** using real-time data from all road users.
- **Automated tolling systems** enabling seamless, Europe-wide payment without driver interaction.
- **Automated charging and billing**, including vehicle repositioning solutions to improve charging accessibility for users without private parking.
- **Automated parking fee payment** across public parking infrastructures.
- **Road weather information systems** supporting automated driving through shared vehicle, infrastructure, and forecast data.
- **Bidirectional (V2G) charging** to stabilize electrical grids using vehicle batteries.
- **Local traffic and pedestrian management** for real-time safety and efficiency.
- **SDV app ecosystems**, including vehicle app stores with OTA deployment.

These applications offer significant customer benefits and societal value but require **tight alignment between the automotive industry, infrastructure operators, energy providers, IT vendors, and regulators**. The automotive sector alone cannot deliver these solutions. Coordinated frameworks and regulatory support are often essential to accelerate deployment and adoption. European initiatives and associations such as **ECAVA, CCAM and 2Zero** play a critical role in aligning stakeholders across industries.

Cloud–Edge–IoT technologies are a foundational enabler for the digital transformation of transport and mobility. Their successful deployment requires not only technological innovation across compute, connectivity, data, and AI, but also strategic alignment across industries, governance models, and regulatory frameworks. CEI is therefore tightly interlinked with the broader ECS major challenges in transport and mobility and represents a key lever for achieving Europe's climate, safety, and competitiveness objectives.

3.1.7.6 Major Challenge 6: AI-enabled engineering toolchain: agile collaborative SDV SW development and SDV as well as ADAS/AD validation (see also SRIA chapter 2.3)

European automotive players face **intensified global competition**. Non-EU manufacturers and large technology companies have adopted software-centric strategies earlier and benefit from:

- Massive software investment budgets,
- Scalable cloud platforms and hyperscaler ecosystems,
- Indirect and data-driven business models,
- Strong state support in parts of East Asia.

To counteract this, Europe must establish **new cooperative development models, toolchains, and V&V concepts** that support fast, trustworthy, and collaborative SDV software development based on open ecosystems.

Next-Generation Toolchains for SDVs spanning the complete DevOps cycle

Modern SDV development requires **development pipelines** that go beyond traditional CI/CT/CD and DevOps pipelines and address the following challenges:

- Bringing AI-assisted automation to the complete DevOps cycle to significantly accelerate development
- Multi-party, collaborative SDV development (“Just-in-Time SDV integration”)
- End-to-end product lifecycle support, from requirement engineering to operation monitoring and very frequent OTA updates

This requires:

- Standardised artefact definitions and exchange formats
- Integration sandboxes for complete SDV stacks
- Domain-specific testing strategies and tools
- Technical and legal SDV guidelines (e.g. ADAS/AD, AI Act, Data Act, SOTIF, ISO standards)

Towards Fully Automated Software Development using Agentic AI-Based SDV Software Factories

To meet short development cycles and long operational lifetimes, SDV software engineering must move toward **full automation of the development lifecycle**. Generative AI and Agentic AI enable:

- Automated analysis of business epics into requirements and architectures,
- Automated code and test generation,
- Continuous quality analysis,
- Intelligent and optimized test-case and scenario selection from ODD, hazard, and scenario databases.

This results in an **AI.assisted SDV software factory**, combining speed, scalability, and safety. It will comprise several interacting pipelines, as indicated in *Figure* 3.1.6**.**

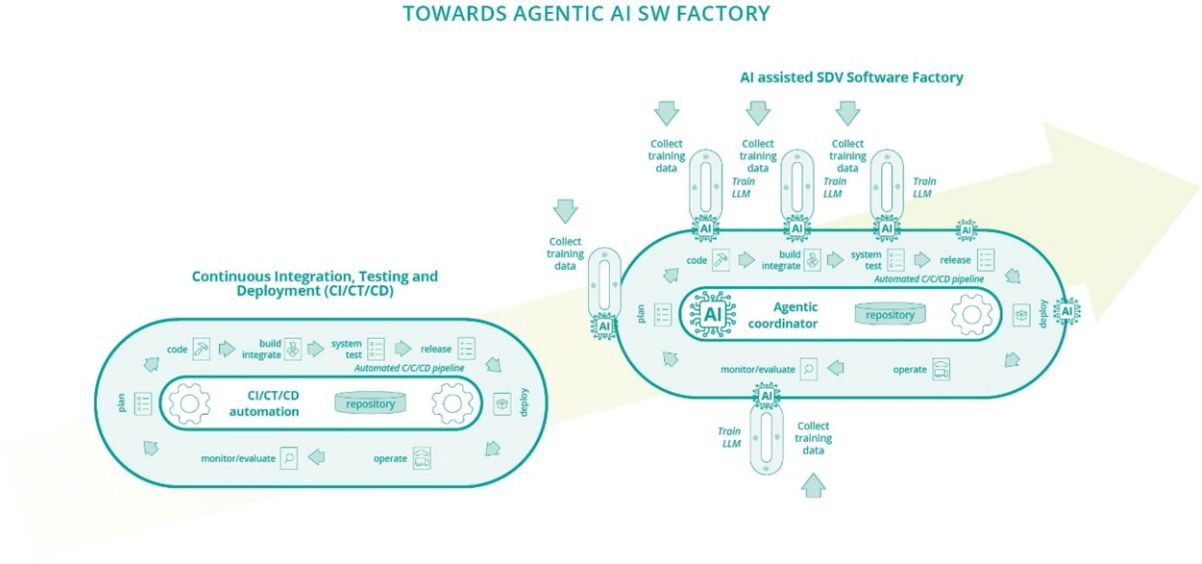

Figure 3.1.6: Towards Agentic AI SW factory

The yellow parts in the figure above indicate automated activities, which are mainly performed by development agents and coordinated by the agentic coordinator.

Integrated AI-Enhanced sub-pipelines of the SDV software factory

The automated SDV DevOps environment consists of four tightly coupled pipelines, interacting with human experts:

1. **Development Pipeline**
   Specification, architecture, coding, integration, and build (extended CI/CT/CD)
2. **System Test Pipeline**
   Automated, scenario-based testing across SDV domains
3. **DevOps Monitoring Pipeline**
   Continuous monitoring of field data, quality, and system behaviour
4. **AI Knowledge Enhancement Pipeline**
   Continuous improvement of AI models using development and field data

These sub-pipelines continuously improve their LLMs using the best practice data from within the companies or open source.

Multiparty Collaborative SDV Development

SDV software stacks are developed by **networks of OEMs, Tier-1 suppliers, SMEs, and open-source communities**. Today's fragmented CI/CD practices lead to long integration cycles—often several months—making rapid fixes for safety-critical issues impossible.

New **just-in-time collaboration models**, supported by shared toolchains and automated regression testing, aim to reduce the time from code change to vehicle-ready software to **days rather than months**, even for safety-critical ADAS/AD functions as depicted in Figure 3.1.7.

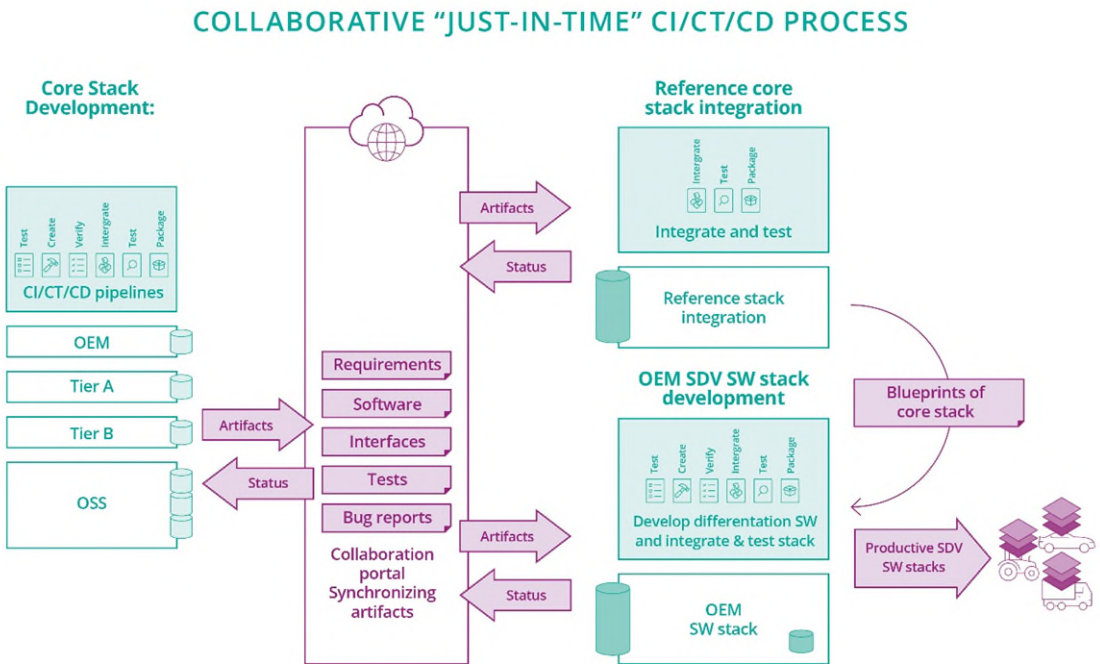

Figure 3.1.7 Collaborative "just-in-time" CI/CT/CD process (Source: Continental)

Continuous Validation/Homologation of ADAS and Automated Driving

Classical validation approaches are reaching their limits in SDV validation/homologation. Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) functions represent one of the most demanding domains for verification and validation (V&V) in cyber-physical systems. Traditional validation approaches based on extensive real-world driving are no longer viable. Studies estimate that several hundred million kilometres of road testing would be required to statistically demonstrate that an automated vehicle is at least as safe as a human-driven one. This makes certification based primarily on physical road testing impractical in terms of time, cost, and feasibility.

The challenge is amplified by:

- the highly dynamic and open operating environment of road traffic,
- the presence of rare but safety-critical edge cases,
- the increasing use of AI and machine-learning components,
- the frequent evolution of software through updates and feature extensions.

As automation levels increase, it is no longer sufficient to validate only nominal system behaviour. Instead, validation must address the full spectrum of possible operational scenarios, including degraded modes, corner cases, internal failures, and unexpected environmental interactions.

A defining characteristic of Software-Defined Vehicles is the ability—and necessity—to update software frequently via **over-the-air (OTA) updates**, including updates to safety-critical ADAS and AD functions. This fundamentally challenges the traditional one-time certification and homologation paradigm.

As a result, **continuous validation and continuous homologation** emerge as essential concepts.

- **Continuous validation** refers to the permanent, automated re-verification of system safety, performance, and compliance across the entire vehicle lifecycle. Every software change—whether functional, performance-related, or security-driven—must trigger targeted re-validation activities.
- **Continuous homologation** extends this concept to regulation and certification, enabling incremental approval of software changes rather than requiring full re-certification of the vehicle.

This approach requires:

- modular and traceable software architectures,
- precise impact analysis to identify affected functions, scenarios, and safety goals,
- automated regression testing focused on the modified components,
- digital artefacts that provide continuous evidence of compliance with regulatory and safety requirements.

Continuous validation and homologation are indispensable to enable **fast deployment of safety fixes**, secure updates, and feature evolution without compromising safety or regulatory acceptance.

Digital Twins and Scenario-Based Virtual Validation

To address these limitations, **Digital Twins and scenario-based virtual validation** have become central enablers for ADAS and AD V&V. Digital Twins enable a virtual representation of the vehicle, its software stack, sensors, actuators, and environment, allowing systematic exploration of scenarios that would be impractical or unsafe to test in the real world.

Scenario-based validation focuses on:

- representative and critical traffic situations,
- rare but safety-relevant events (e.g. sudden pedestrian crossings, extreme weather, sensor degradation),
- systematic variation of Operational Design Domains (ODDs),
- interaction with human road users and infrastructure.

Scenarios may be derived from safety analyses, naturalistic driving data, field operational data, or synthetically generated using optimisation and game-theoretic methods. Statistical safety evidence must be built from large-scale virtual testing combined with limited, targeted real-world validation.

Integration into CI/CT/CD Pipelines

Verification and validation must be fully integrated into **automated CI/CT/CD pipelines** for SDV software. This includes:

- automatic derivation of test plans from requirements, hazards, and change impact analyses,
- large-scale virtual testing using cloud-based MIL and SIL environments,
- selective use of HIL and VIL testing for safety-critical interfaces,
- automatic generation of safety arguments and validation reports,
- continuous monitoring of field data to detect emerging risks and unknown scenarios.

These pipelines must support rapid iteration while ensuring that any software deployed to vehicles in the field has passed a level of validation appropriate to its safety relevance.

OTA, Field Feedback, and Lifecycle Validation

Highly automated vehicles continue to evolve after deployment. New functions, performance improvements, and cybersecurity patches require safe and trustworthy OTA updates. This creates a closed-loop lifecycle where:

- operational field data is continuously collected,
- new or unexpected scenarios are identified,
- validation models, scenarios, and Digital Twins are updated,
- improved software versions are re-validated and redeployed.

This lifecycle-oriented approach ensures that safety, security, reliability, and user acceptance are maintained—or improved—throughout the vehicle's operational life.

Standards, Regulation, and Research Needs

Existing and emerging standards, such as ISO 26262, SOTIF (ISO 21448), UL 4600, cybersecurity standards, and UNECE regulations, provide a foundation for ADAS and AD validation. However, they are not yet fully aligned with:

- AI-based systems,
- continuous learning,
- frequent OTA updates,
- and continuous homologation concepts.

Consequently, close cooperation between **research consortia, industry, and standardisation bodies** is essential. Research is required to develop:

- scalable and accepted methods for continuous validation,
- digital compliance artefacts for homologation authorities,
- harmonised approaches across regions and domains.

Key RDI Topics

- Automated CI/CT/CD setup using open-source building blocks (“configuration as code”) (see also SRIA chapter 2.3)
- AI-supported, largely automated SDV development pipelines
- Bidirectional artefact synchronisation across partners
- Standardised artefact content and formats
- AI-based, adaptive test-plan generation
- Automated test-environment and stack generation

Key Focus Areas

- Integrated V&V toolchains for automated cyber-physical systems
- Scenario-based virtual validation and Digital Twins
- Open ecosystems for scenarios, metrics, and performance indicators
- Reliable sensor, vehicle, traffic, and environment models
- Secure, trustworthy OTA update and re-certification processes

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.

3.1.8 Timeline



Figure 3.1.8: Roadmap for electronics and software-based mobility applications

The roadmap for the key digital technologies in mobility is aligned with European roadmaps for terrestrial, maritime and aerospace transport:

- ECAVA roadmap
- 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)
- 2Zero SRIA.
- CCAM SRIA

3.2



ECS Key Application Areas

ENERGY

3.2 ENERGY

3.2.1 Scope: Change towards a carbon-neutral and resilient society and challenges for ECS

Energy systems *supplying affordable, clean and secure energy* are the focus of the *European Green Deal* and its successor, the *Clean Industrial Deal*[1]. To achieve this goal, the EU set targets for a renewable energy share of at least 42.5% (new binding target for 2030, but aiming for 45%)[2] and a greenhouse gas emission reduction of 55 percent by 2030. Renewable energies bring several benefits such as climate change mitigation, emission reductions as well as improvements in European energy security[3]. Although the EU even surpassed its 2020 target of 20 percent, sustained action at an accelerated pace is necessary to prepare the economy and society for the upcoming climate challenges and improve resilience, especially that of our power grids[4]. The power sector must be further transformed from fossil fuel-based to renewable generation and, at the same time, needs to grow to enable decarbonisation of mobility, industry, and thermal energy supply, and reach the climate targets. The change in the supply strategy in Europe towards independence from 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. Furthermore, there is a growing shortage of skilled workers, which needs to be compensated by fast technological progress and innovation. Therefore, smarter components are needed to compensate for 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, with regard to 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. This is also reflected in the European Commission's Strategic Roadmap on Digitalisation and AI in the Energy Sector[5], which underlines the need to accelerate digital and AI solutions for energy-system optimisation, while ensuring that fast-growing data centres are integrated into the energy system in a sustainable, transparent and grid-supportive manner. The IEA's Energy and AI report[6] further highlights this nexus by showing that AI will significantly increase electricity demand from data centres, while also offering major opportunities to optimise energy-system operation, security and innovation. At the same time, the rapid growth of AI-driven data centres creates new concentrated electricity demand, increasing pressure on already constrained grids, grid connection queues and the need for coordinated planning of generation, flexibility, storage and network infrastructure. The Energy

[1] https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en
[2] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en
[3] European Environment Agency (2022). Share of energy consumption from renewable sources in Europe. https://www.eea.europa.eu/ims/share-of-energy-consumption-from
[4] EU Action Plan for Grids / European Grids Package. https://energy.ec.europa.eu/topics/infrastructure/european-grids_en
[5] https://energy.ec.europa.eu/publications/strategic-roadmap-digitalisation-and-ai-energy-sector_en
[6] https://managenergy.ec.europa.eu/document/download/9a5aff7f-97ce-4d4f-ae88-b38070db98f8_en?filename=EnergyandAI%20%281%29.pdf

Chapter highlights the Major Challenges in the changing energy landscape associated with electrical energy generation, supply, conversion, and use. High efficiency and highly reliable, secure solutions are required to achieve the transition towards a climate-neutral continent by 2050.

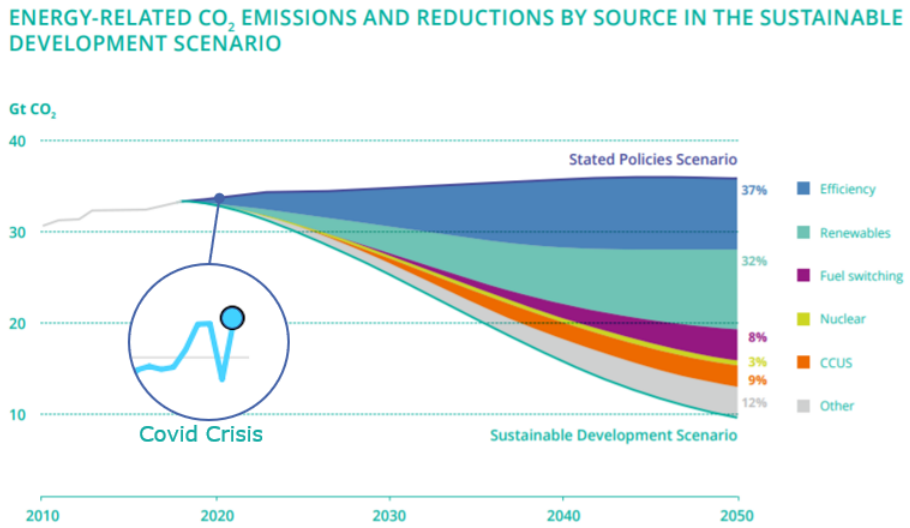

Figure 3.2.1 - Efficiency and renewables provide the most potential for CO_2 emissions reductions. Source: IEA World Energy Outlook 2019. In the graph the impact of Covid in 2020 & 2021 is indicated; the emission level is back on the levels from before the Covid crisis. Source: IEA Global Energy Review: CO_2 Emissions in 2021.

According to the IEA "CO_2 Emissions in 2023" report for the EU the trend is towards lower emissions; the main factors are an increased renewable electricity deployment and lower emissions in industry. The challenge is to accelerate that trend and manage the challenges of local use and balancing to integrate the decentralised, highly variable supply into the grid:

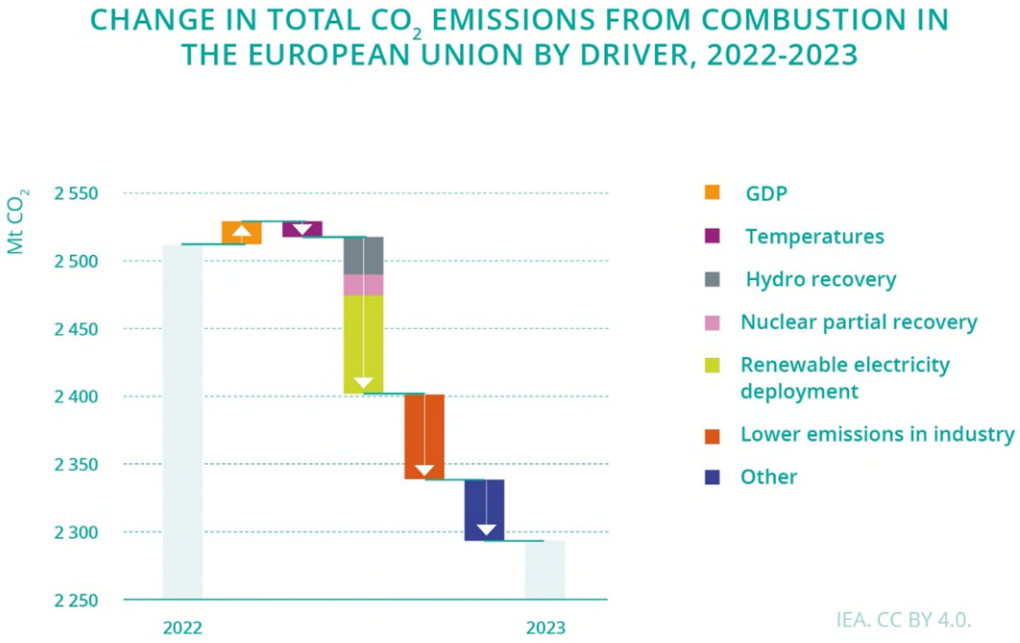

Figure 3.2.2 - Change in total CO_2 emissions from combustion in the EU – a clear trend towards lower emissions and the dominant factors relevant to lower emissions in the EU are visible. Source: IEA – CO_2 emissions in 2023: A new record high, but is there light at the end of the tunnel?

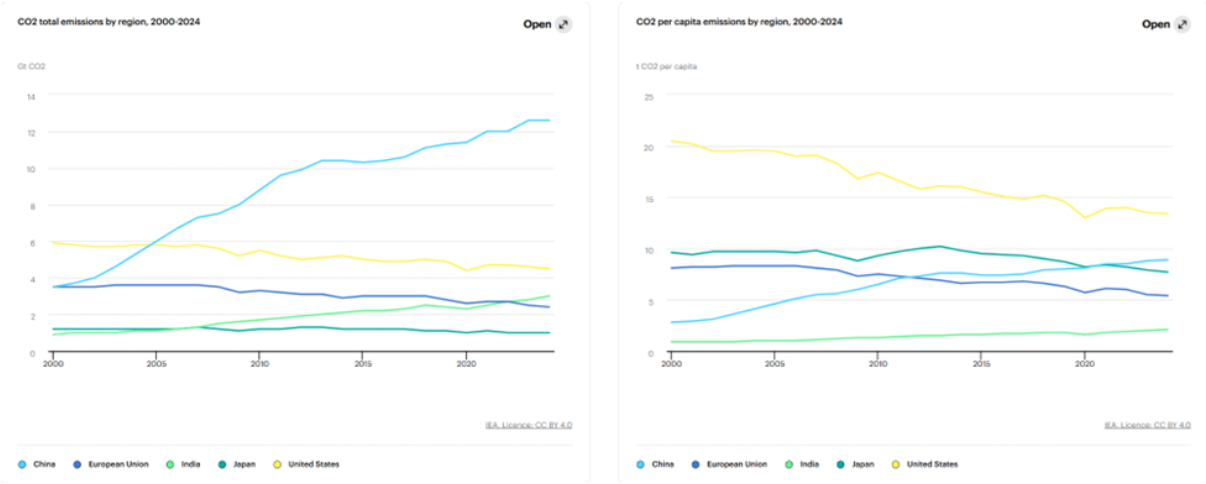

Figure 3.2.3 - Global CO_2 emissions – a clear trend towards lower emissions is visible, except in China and India. Source: IEA (2025), Global Energy Review 2025, IEA, Paris https://www.iea.org/reports/global-energy-review-2025, Licence: CC BY 4.0

3.2.2 Application trends and societal benefits

Application trends

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 10% in 2023. This increase is dominated by wind and solar energy, which are characterised by strongly intermittent, distributed generation. The share of wind and solar in Europe's electricity generation reached a record high of 26.6% (718 TWh) in 2023, almost twice the global share of 13.4% 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 levelized cost of electricity (LCOE) from photovoltaic (PV) sources dropped another 12% (global weighted average). 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, this enables the substitution of fossil fuel-based transportation, domestic heating, and commercial & industrial processes and helps 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 account for 30 % of CO_2 emission reductions by 2050 with current policy settings, while this share could increase to 40 % if worldwide announced climate pledges are met. Affordable and reliable energy supply to all sectors needs to match demand and availability as efficiently as possible (Figure 3.2.4).

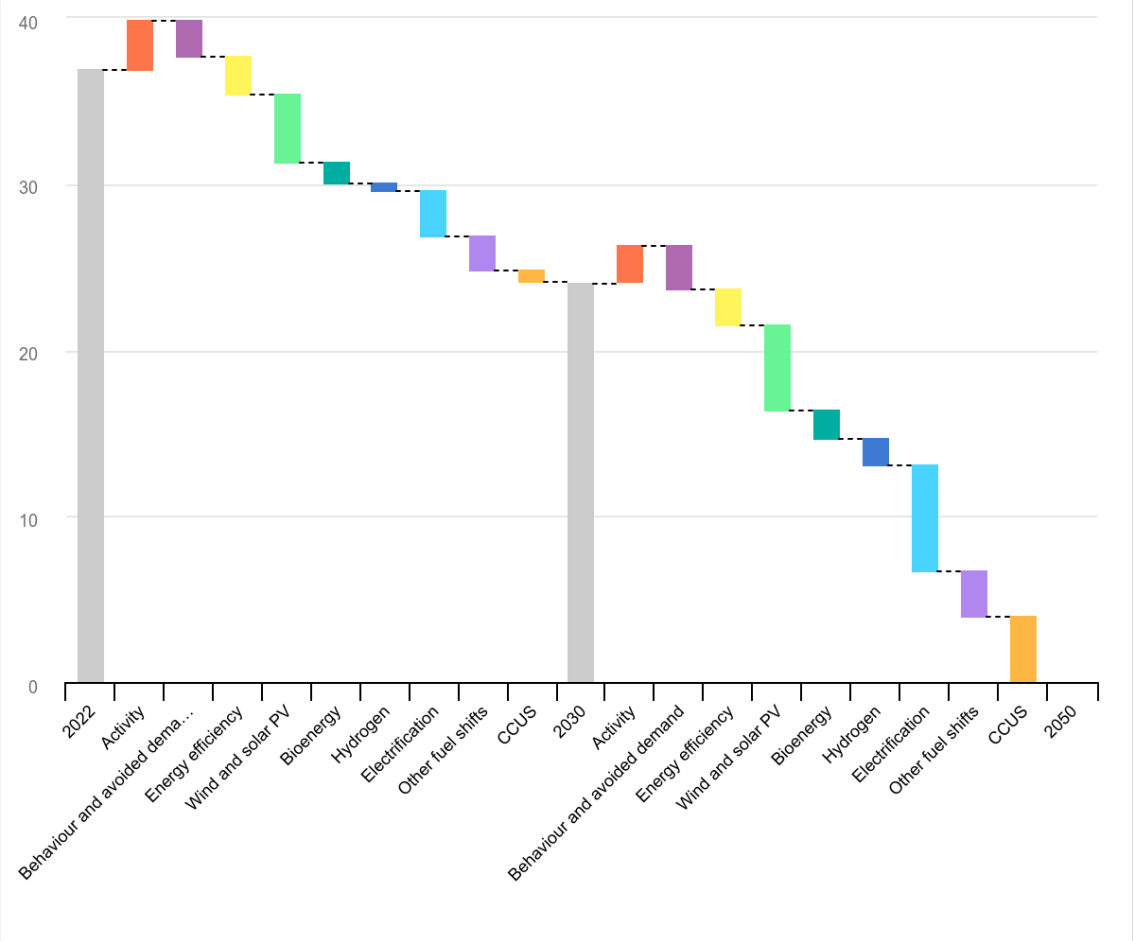

Figure 3.2.4 - Emission changes over time by mitigation measure in the Net Zero Scenario, 2022-2050. Source: IEA Net Zero Roadmap - 2023 Update.

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 3.2.5). 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 oriented towards demand, will turn into back-up power supply facilities.

The overall reduction of energy consumption in addition to efficiency measures will always be a target, since all energy usage that can be avoided also implies a reduction in emissions. This can be achieved by control elements for switching off energy use and providing zero-power standby functionality or by transitioning to new technologies, as the transition to LED illumination had a high impact over the last decade. Upcoming threats include energy-consuming ICT-related applications such as 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. According to a study by McKinsey[7], global demand for data centre capacity could rise from 60 GW in 2023 at an annual rate of between 19 and 22 percent to reach 171 to 219 GW by 2030. Quantum computing has, in general, the potential to decrease energy consumption for solving specific problems. Already within the design and development cycle, sustainability goals, energy efficiency and environmental legislation will need to be taken into account.

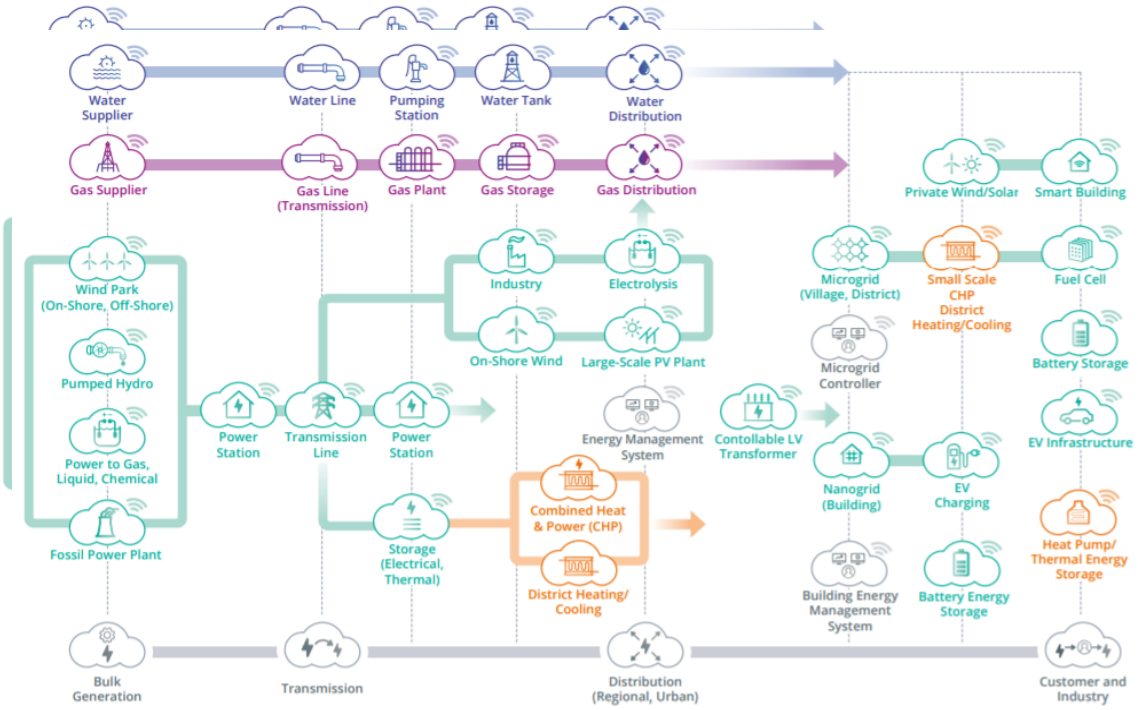

Figure 3.2.5- Interconnected Energy Infrastructure; Source: Siemens Corporate Technology

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 as well as in the event of any critical situation. The future grid operation requires a sophisticated information and communication infrastructure including cloud services, IT security, and AI technologies. Altogether, they will contribute to a significant reduction of energy consumption and, consequently, CO_2 emissions.

[7] https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/ai-power-expanding-data-center-capacity-to-meet-growing-demand

To achieve the targets of the Green Deal and to create 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 smart integration, at the system and power-electronics levels.

(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 life, 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, refurbishment, reuse and recycling capabilities, LCA of ECS and reduction of environmental impact

(12) Alignment 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.

(16) Design and development strategies of ECS that optimise the total environmental impact of energy solutions (e.g. trade-offs between environmental footprint and handprint, rebound effects)

(17) Innovation strategies for regulation-enabled energy markets and technologies.

External requirements and Societal Benefits

In alignment with the **Paris Agreement**, the EU committed to substantial reductions in CO_2 emissions. In particular, the EU aims to make Europe the first climate-neutral continent by 2050 (EU long-term strategy) while boosting the competitiveness of European industry. Carbon pricing throughout the EU economy will be implemented more strictly. Further climate laws will be introduced and continuing policies will be clarified by the European Commission in 2022. The **"Clean Energy for All Europeans" package** was completed by the EU in 2019 as a comprehensive update of its energy policy framework, which was updated with the "European Green Deal" in July 2021 and further enhanced with the "Clean Industrial Deal" in February 2025. 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 3.2.6 - 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 domains of ECS (energy, industry, mobility, communication, consumer goods, and cities), the energy domain with a targeted 40% share of renewables in the energy mix until 2030 is the foundation for all of them. Additional perspectives are provided by the United Nations' "**Roadmap 2050**", addressing sustainable development solutions and implementation pathways towards a carbon-neutral global population.



Figure 3.2.7 - Electrification of the transport sector.

All these factors are considered in the roadmaps for research, development, and innovation of ECS for 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 3.2.7), 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 3.2.8) and are essential for a highly developed energy landscape towards a fair, democratic, healthy and prosperous society.

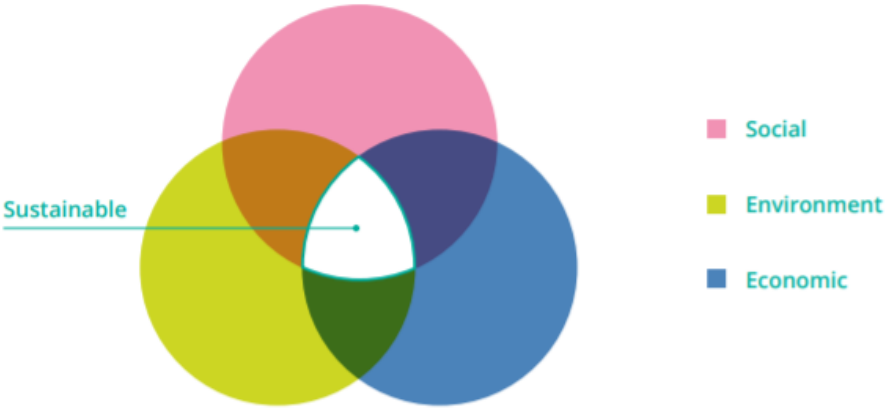

Figure 3.2.8- Three pillars of sustainability (Source: Purvis, Mao, Robinson 2018: Three pillars of sustainability: in search of conceptual origins).

Energy efficiency through ECS fosters economic development towards a circular economy and new employment opportunities. These developments will have a huge impact on job generation and education if they are based on the complete supply chain and fully developed in Europe. With more than 16 million jobs in the field of renewable energy[8] and indirectly related technologies, this is a visible and significant factor for economic and societal stability. The capability to maintain an understanding of complete systems as well as competence ranging from small-scale solutions up to balanced regional energy supply solutions are key to European competitiveness and success in the global market of energy solutions. Also, the consumer itself can contribute its share, thus consumer empowerment for energy savings and efficiency should be taken into account for the development of energy systems. Societal benefits include access to knowledge, development of modern lifestyles 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 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.

3.2.3.1 Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems

3.2.3.1.1 Status, vision and selected outcome

According to the IEA's Efficient World Strategy, digitalisation enhances energy efficiency gains in the transportation and industry sectors[9]. Smart and efficient energy systems are drivers of energy savings. Therefore, they are in full alignment with the Green Deal. Alternative forms of energy generation (hydro, photovoltaic, and wind) and the electrification of 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.

[8] IRENA (2024), Renewable Energy and Jobs – Annual Review.
[9] IEA (2019), Energy Efficiency.

Smart Energy Systems

To operate 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 increasing use of data, data management and AI control systems as well as the integration of sensors, connectivity and edge processing in supplementary/additional components will enable the creation of intelligent facilities by retrofitting. Application domains shall increasingly rely on energy-autonomous sensing systems with embedded intelligence, leveraging event-driven and neuromorphic processing to enable scalable, low-maintenance monitoring and decision-making. The creation of secure electronic control units requires the development of specific hardware and software. Scalable modular renewable energy supply with seamless installation capability enables renewables to be introduced or scaled up from single households to larger installations.

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 behaviour for evaluation of its health status.

For offshore energy generation, such as wind farms and tidal energy generators, fibre-optic sensors are an emerging technology that is beneficial for online monitoring of metal fatigue and excessive turbulence. This technology is currently being developed for such monitoring in aircraft wings and ship masts.

Conversion

Electrification and automation of industry and mobility are among the main measures 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 current CO_2-emitting solutions. In the case of Heating, Ventilation, and Air Conditioning (HVAC) systems, significant reductions in consumption can be obtained by optimising the system that handles all the processes of energy management or by changing the way Machine-to-Machine (M2M) technologies are used. For both strategies, efficient ECS are required to obtain optimal control functionality based on sensing, collecting, processing, and evaluating device-related data. DC power supplies based on advanced semiconductor power devices will provide lower power consumption and thus higher efficiency for the increasing ICT energy demand (i.e. through data centres, autonomous systems like cars, robots). Investments in the next-generation computing, storage, and heat removal technologies will be required to avoid a steep increase in energy demand 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 intermediate conversion to electronics. This will be highly efficient and save energy. The advanced features of 5G/6G will enable innovative uses of the technology (Figure 3.2.9), but as a consequence of larger data rates and throughputs, costs 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[10].

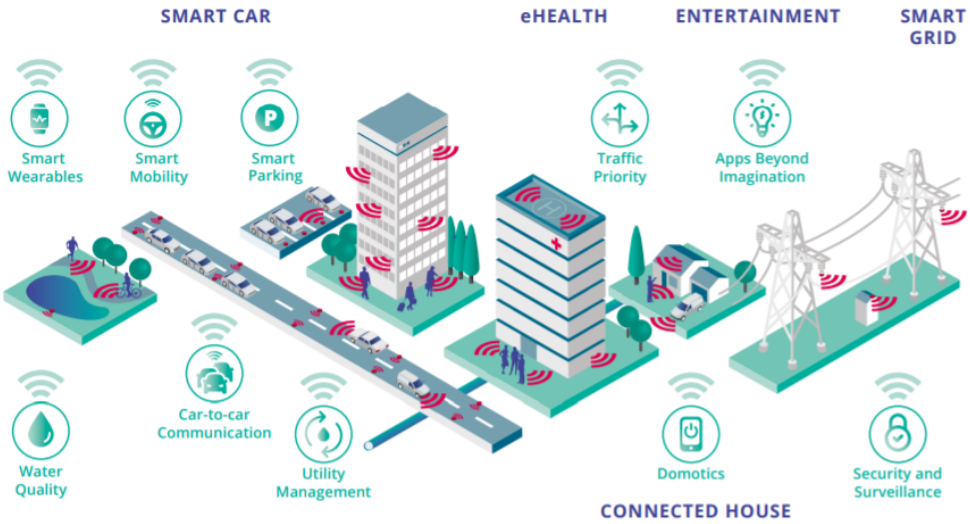

Figure 3.2.9 - 5G as enabler of an interconnected smart network. Source: European Commission, Towards 5G.

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. The integration of ultra-wideband gap (UWBG) semiconductors presents a transformative opportunity for power electronics. With thermal conductivities far surpassing those of traditional materials, UWBG semiconductors such as diamond offer unparalleled heat dissipation, enabling the creation of more compact, efficient, and high-performing power modules. Their capacity to handle extreme voltages further enhances device robustness and energy efficiency. As a strategic initiative, prioritizing research and development in UWBG materials could catalyze breakthroughs in power electronics, paving the way for advanced technological solutions that align with the goals of miniaturization, efficiency, and long-term reliability.

Due to this unstoppable trend, research on device reliability, packaging and assembly methods suitable for very high electric fields and high temperatures is strongly required. A focus also needs to be placed on the medium-voltage grid (< 45 kV), as the power rating of applications will increase beyond 1 MW (EV charging, BESS, hydrogen electrolyzers, etc.) and will preferably be connected directly to the medium-voltage grid. Here, solid-state transformers based on medium-frequency transformers will become a cost-effective alternative in the near future and consequently help to reduce material use for standard grid frequency transformers. As many concepts rely on a

[10] Tahir Abbas M. et al. (2024). Towards zero-energy: Navigating the future with 6G in Cellular Internet of Things, Journal of Network and Computer Applications, Volume 230, 2024, 103945, ISSN 1084-8045, https://doi.org/10.1016/j.jnca.2024.103945.

modular approach using power electronics building blocks (PEBB), aspects of coordinated system control and reliability based on redundancy also need to be investigated.

Storage

Energy storage deployment provides energy system flexibility. Considering further storage options, different options for different capabilities require further efficiency improvements. As an example, optimised converters, sensor solutions for monitoring, and battery management systems need to be developed for storage options, all of which include ECS. In power generation, hydrogen with its many uses (Figure 3.2.10) 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 clean-energy carrier since it allows electricity to be produced directly on board EVs or in areas that are cut off from the power grid. With declining costs for renewable electricity, interest is growing in electrolytic hydrogen. ECS will be employed in electronic systems for electrolyzers, fuel cells, as well as power management and health monitoring.

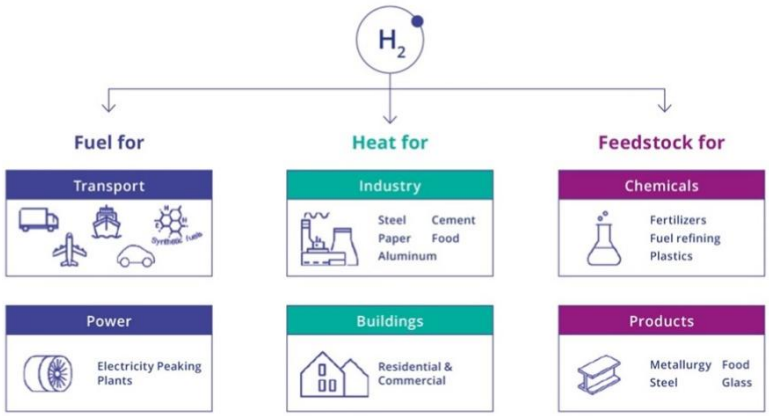

Figure 3.2.10 - The many uses of Hydrogen, source: Bloomberg NEF.

3.2.3.1.2 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.
    - Low-power control and edge-AI-based systems

- Residential, commercial, and industrial demand-side management (scheduling and load adaptation):
    - 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 the 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.
    - Fibre-optic 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 & industrial applications.
    - Industry 4.0 with a 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.

3.2.3.2 Major Challenge 2: Energy Management from On-Site to Distribution Systems

3.2.3.2.1 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 kinds of consumption.

Autonomous Control Systems

In the future distribution grid, generation and consumption by power-electronic systems will surpass the share of synchronous generation. This leads to potential grid instabilities due to a 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 storage systems 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 3.2.11). For larger power production facilities, hybrid generation and storage solutions are also discussed, which integrate the power production facilities with storage devices to optimise arbitrage costs. 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, they result in serious safety and cost issues for large industrial electrolyzers.

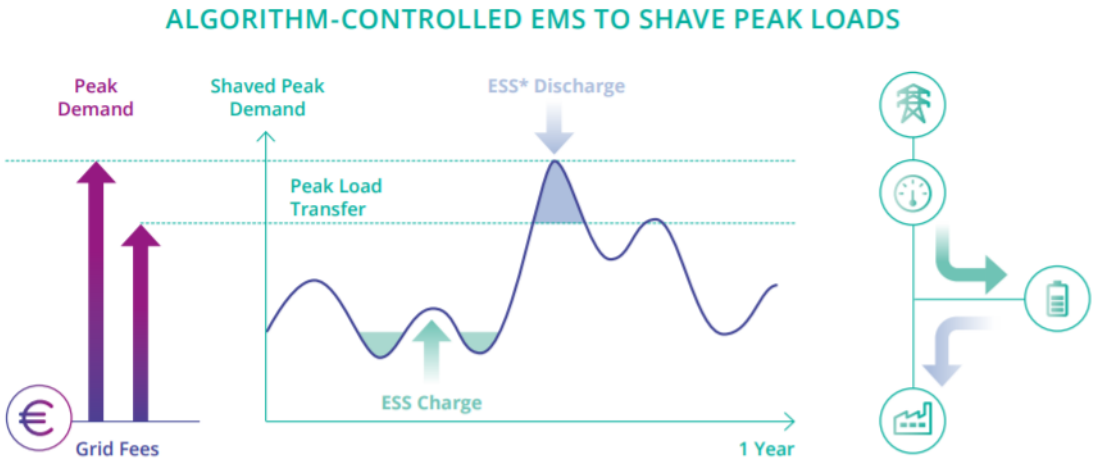

Figure 3.2.11: Visualisation of an algorithm-controlled energy management system to shave peak loads. An energy storage system predicts load peaks and charges/discharges a battery accordingly. Source: EDF Renewables.

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 set up, as well as support for self-learning to adapt to evolving needs.

Energy Management Systems for industrial and residential customers include an optimisation module, demand and generation forecasts, customer preferences, weather forecasts and price/tariff information/forecast. They require beyond-state-of-the-art techniques for scheduling controllable loads and generators and forecasting the weather to produce accurate generation profiles. Furthermore, the interface to the grid might be used for additional power quality services based on power electronic converter technologies beyond state-of-the-art reactive power compensation (e.g. virtual inertia and balancing).

3.2.3.2.2 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.
  - Trustworthy 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 perform health checks on grid assets to increase their 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 costs; maintaining the level of production according to the 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 electronic 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 setup 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 an increasing share of distributed generation.

3.2.3.3 Major Challenge 3: Future Transmission Grids

3.2.3.3.1 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 such as electricity, thermal energy, 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 consumption patterns 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 large amounts of electrical energy. New industries such as large-scale battery factories are planned in several places in Europe[11]. This, together with a massive expansion of supercharger stations for private passenger cars and heavy trucks with individual charging capacity of more than 1 MW, will pose severe challenges for grid capacity both in networking and in electronic components while maintaining the highest possible efficiency. Therefore, further ECS R&D needs to work towards improvements in grid capacity with the highest possible efficiency (Figure 3.2.12). Thus, continued development of components for HV transmission for 1.2 MV or even higher voltages is needed to enable efficient energy transmission across Europe. In addition, new business models must be developed for the electric energy market enabled by the smart-grid technology.

[11] Maisch, M. (2020). Europe's Gigafactory Boom in Full Swing with Another Plant Announcement. PV Magazine.

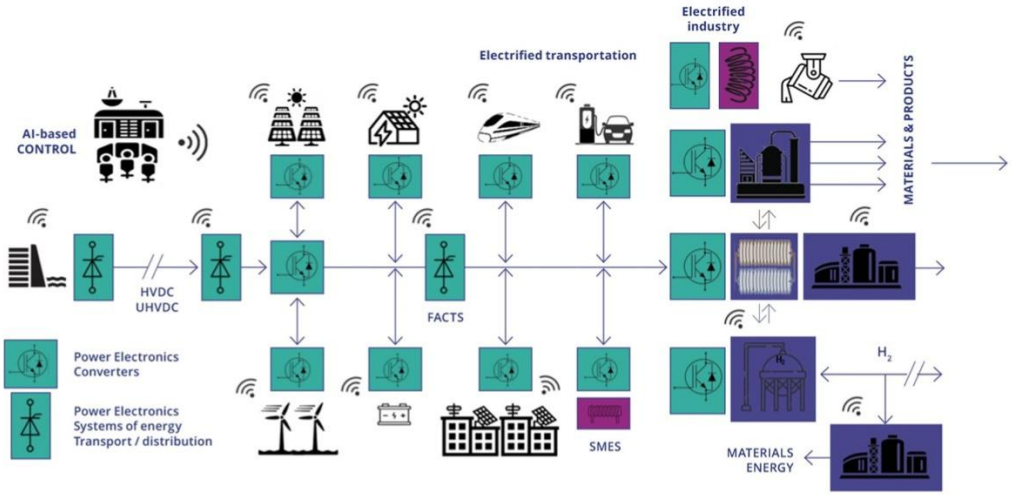

Figure 3.2.12: Power ECS at each point of the future transport and distribution grid. Source: CSIC Scientific Challenges: Towards 2030, Volume 8.

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 low tectonic activity in most parts of Europe, transmission grids could become much more resilient and lossless when buried in the ground. Thus, extra isolation technology needs to be considered and critical points should be equipped with smart ECS for monitoring, control, and prediction.

3.2.3.3.2 Key focus areas

- Grid stability during the industrial transition:
  - Efficiency increases.
  - Development of a 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 for ECS due to 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.

3.2.3.4 Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/Regional Energy Supply

3.2.3.4.1 Status, vision and expected outcome

A 40% renewable energy share in the electricity sector in Europe by 2030 requires additional decentralised, intermittent energy sources, a bi-directional grid and storage for energy supply in transport, industrial, and smart-city 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 storage systems 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 3.2.13). Integration with industry makes use of waste process energy using heat pumps to raise temperatures from low (40-50 deg) to high (80-90 deg) in the pipe. Electrolyzers add to the gas system or transport. Water treatment uses excess power from renewables adding further flexibility.

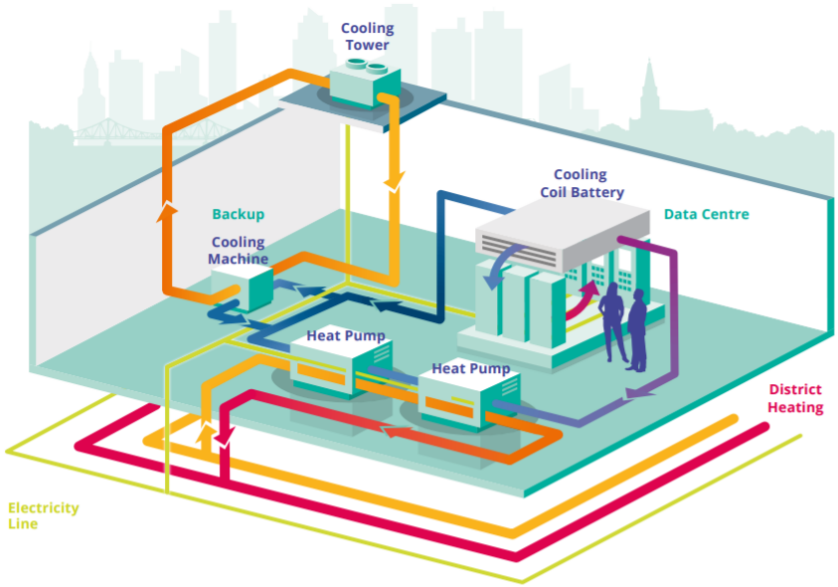

Figure 3.2.13: A Combination of heat pumps and district heating. Source: IEA HPT.

Local communities use MES concepts at regional level. Different local inputs are also aggregated for overall control of the larger regions. Autonomous controllers are used behind the meters to support overall control. A clear hierarchical setup, 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 obtain all data for control and optimisation. Risk and security analyses provide resilience and ensure stability of MES.

Urban Transformation

Emission-free cities use electrification and decentralised storage 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 former requires household and public charging, while the latter uses well-defined charging points on (bus) lines or at terminals. Power levels 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. Carbon capture technologies will add another dimension to the energy systems.

Storage Solutions

In households, battery energy storage devices can be 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 options (electrical, thermal, gas, water etc.) play an important role. V2X is used as a large distributed electrical energy storage resource. Systems with electrolyzers might use storage tanks for gas production. Thus, the development of grid-supporting control algorithms and support for regional energy management for communities (e.g. P2P trading via storage systems, self-consumption optimisation) are needed.

3.2.3.4.2 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 the 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 optimising the 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 energy demand for battery manufacturing and distribution logistics.

3.2.3.5 Major Challenge 5: Cross-Sectional Tasks for Energy System Management, Monitoring & Control

3.2.3.5.1 Status, vision and expected outcome

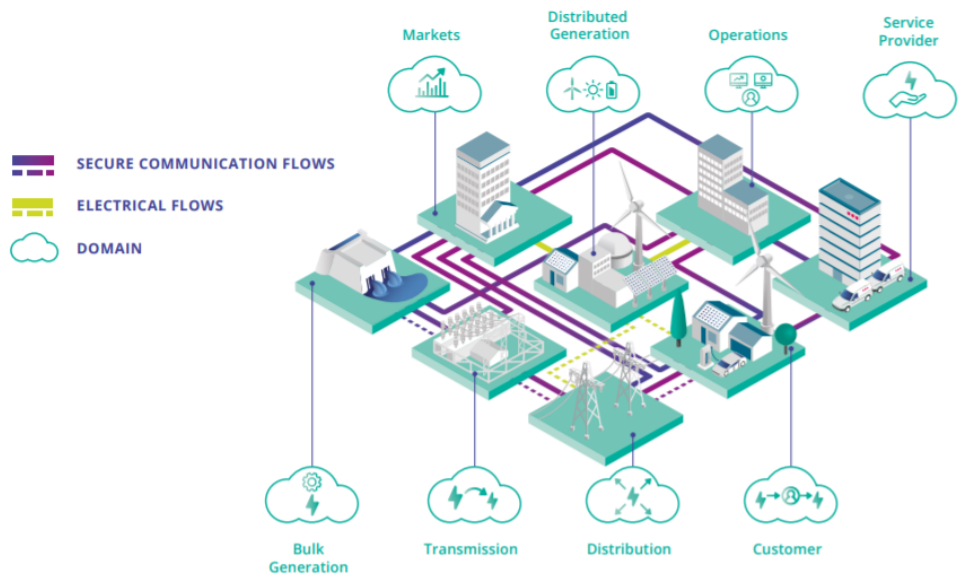

Figure 3.2.14: Interaction of actors in different Smart Grid Domains through secure communication flows and electrical flows. Source: NIST Framework and Roadmap for Smart Grid Interoperability Standards.

Current energy management platforms still have shortcomings in terms of automation, interaction and intelligence. Thus, as the traditional energy grid evolves into a smart grid, it needs to integrate ICT and power electronics on a large scale. ECS empower electrical utility providers

and consumers, improve efficiency and availability while constantly monitoring, controlling, and managing demand. The large, complex networks need cross-sectional approaches for monitoring and control to achieve efficiency, security and reliability of the communication and electrical flows (Figure 3.2.14) - all based on new ECS technologies.

Optimisation in Monitoring and Control

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 forecasts of expected production and consumption play an important role. This requires automation of the grids, the use of sensors at different levels, data storage, and AI and machine learning to operate the grids in an optimised way while at the same time complying with data security requirements and GDPR. Data collection within the grid needs to be limited to selected parameters to avoid unnecessary costs and complexity.

The application of IoT technology in the smart power grid can help to achieve sustainable energy, low latency, and reliability.[12] Machine learning used for forecasting energy demand in a smart-grid environment contributes to medium-term and long-term prediction of consumption and production and can address energy management issues through improved prediction accuracy[13]. It allows administrators to optimise and plan their resources and manage energy inconsistencies 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 level of security.[14]

Energy Management Platforms for integrated energy systems

The European electrical power system is undergoing a transformation process driven by targets for renewable energy sources. A challenge will be that all the different energy infrastructures (electric, thermal, molecules) will be interconnected at high, medium and low power/voltage scales, but they 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 addressed appropriately.[15] 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 long computation time is a significant weakness of current EMS. A possible solution could be heuristic algorithms. Furthermore, the study suggests that a stronger focus on high levels of uncertainty and robustness is needed in order to transfer EMS for operational management and scheduling into practice. The integration of forecasting methods also needs further attention. Regarding sector coupling (e.g. heat and electricity), major

[12] Laba Y. (2024). The Role of IoT in Smart Grid Technology, https://intelliarts.com/blog/smart-grid-iot/

[13] Ahmad, Chen 2018: Potential of three variant machine-learning models for forecasting district level medium-term and long-term energy demand in smart grid environment. https://www.sciencedirect.com/science/article/abs/pii/S0360544218313811

[14] Aloul, Al-Ali, Al-Dalky,Al-Mardini,El-Hajj 2012: Smart grid security: Threats, Vulnerabilities and Solutions.

[15] Camponesci et al. (2020). ENEL Energy Management Evolution in a growing complexity of the Italian market context. https://ieeexplore.ieee.org/document/9241132

challenges exist due to high complexity and uncertainties over longer optimisation horizons. Moreover, multi-level EMS in combination with cloud computing offer promising approaches for new research questions.[16]

Hardware

Electrical grids aim to become more distributed, smart, and flexible to meet the increasing electricity demand. For new grids, the trend is towards designing energy generation and consumption areas together in distributed form. Therefore, power electronic devices in particular play a crucial role in regulating distributed generation and dispersed energy-storage devices and integrating them into the grid. Future power converters also act as edge devices, actively contributing to a stable grid through grid-forming operation, virtual inertia and other functions. Hence, the intensive use of power electronic converters in the microgrid brings their control methods to the forefront; these should provide good dynamic response and high reference tracking characteristics[17]. Combining low-power and high-power components requires 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. For example, when sensors (e.g. for self-monitoring) are 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.

3.2.3.5.2 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 grids.
  - Fraud detection.
  - Design, development, and application of deep learning in smart grids.
  - 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 grids; 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.

[16] Schminke (2021). Overview of the current state of research on characteristics and algorithms of energy management systems in households and buildings. https://doi.org/10.1002/er.6738

[17] Bayhan, Abu-Rub (2020). Smart Energy Mangement System for Distributed Generations in AC Microgrid. Quatar Environment and Energy Research Institute, Hamad Bin Khalifa University; Texas A&M University at Qatar, Doha, Qatar.

  - 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 grids.
  - 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

- Technologies for an open distributed energy market

- 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 meters.

3.2.4 Timeline

The following timeline outlines the expected short-term, medium-term and long-term developments in the field of Energy.

MAJOR CHALLENGE	TOPIC	SHORT TERM 2027–2031	MEDIUM TERM 2032–2036	LONG TERM 2037 AND BEYOND
Major Challenge 1: 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 Solid State Transformers and Solid State Circuit Breakers	Further development of intelligent power devices and electronic control towards higher system energy efficiency, lower system costs and integration or use of newly developed device technologies - 55% GHG emissions	Getting closer to zero emissions (due in 2050)
	Topic 1.2: optimised storage options	Control interfaces to batteries, fuel cells, electrolysers; Optimised converters Sensor solutions for cell and module monitoring Battery management systems Self-powered electrochemical energy storage systems (SEESs) Grid Integration	Development of excellent storage options to balance energy generation volatility; efficient energy distribution and usage	Further development based on the needs and opportunities
	Topic 1.3: electric drives for domestic, commercial & industrial applications	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: 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 Secure gateways allowing energy trading, Coupling with energy trading systems (e.g. local energy market platforms) Renewable energy certification (labelling through ECS)	Integration of electricity, heating, cooling, and transport Virtual power plant functionality optimising the match between generation and demand;	Efficient energy distribution and usage; cost efficiency; high-level IT security

MAJOR CHALLENGE	TOPIC	SHORT TERM 2027–2031	MEDIUM TERM 2032–2036	LONG TERM 2037 AND BEYOND
	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 forecasting the weather to produce accurate generation profiles Data centre energy management with Solid State Transformers, DC grid and Solid State Circuit Breakers	Optimisation module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast; Demand side management for buildings Virtual Energy Market	Energy Management Systems optimising operation of components for lifetime & revenue
	Topic 2.3: autonomous control systems	Control of high-demand loads for efficient energy distribution Storage devices provide flexibility, stability and reliability in the grids	Price-control systems Minimise costs, provide peak-shaving; hybrid solutions; novel grid architectures for manufacturing to enable adaptive production optimization	Further development based on the needs and opportunities
Major Challenge 3: Future transmission grids	Topic 3.1: Grid stability during the industrial transition	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 protection	Further improvements on grid capacity with highest possible efficiency 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 Autonomous electricity generators based on fuel cells Modelling Intelligent power devices, systems, and switches	Modelling, weather forecasting, sensing data Digital twin ECS for multi-modal energy systems (cooling with excessive energy, use thermal capacities)	Multi-Modality across Europe

MAJOR CHALLENGE	TOPIC	SHORT TERM 2027–2031	MEDIUM TERM 2032–2036	LONG TERM 2037 AND BEYOND
Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply	Topic 4.1: Regional energy distribution infrastructure	Secure Cross-Regional Transmission Infra-structure 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 storage systems ensure the highest use of renewable energy while balancing fluctua-tions
	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 Reservation and optimisation services implemented with ICT solutions. Bi-directional charging and grid stabilisation solutions	Increase the 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 Sector coupling of large energy users (e.g. harbours, airfields) with urban users (electric cars, households, offices)	Emission-free cities with electrification and decentralised storage to improve efficiency and reliability
	Topic 4.3: Storage systems for urban communities	Development of grid-supporting/forming and peak-shaving control algorithms Battery energy/heat/cooling storage devices for households Integration of fuel cells and electrolyzers	Peer-to-peer trading by using storage systems; Self-consumption optimisation	Support for regional energy management for communities
Major Challenge 5: 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 grids; AI in advanced metering infrastructure; smart sensors with improved data processing; stream processing for real-time applications	Innovative approaches ensuring clean, secure and affordable energy for EU citizens; multiobjective optimisation algorithms in smart grids; optimal utilisation of storage systems; short-/long-term demand and generation forecast algorithms for different energy domains	Safe and interconnected smart grid network; 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 far as possible
	Topic 5.3: Hardware	Improvements in the robustness of HW de-vices 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

3.3



ECS Key Application Areas

DIGITAL INDUSTRY

3.3 DIGITAL INDUSTRY

The *Digital industry* chapter highlights the evolution of traditional industry through the introduction of advanced digital technologies in production, management, and distribution processes. These technologies include the Internet of Things (IoT), artificial intelligence (AI), data analytics, co-robotics, 3D printing, and other digital innovations that industry can adopt, including advances in sensing, power, communication, and computing.

Digital industry is characterised by the increasing integration of the physical world with the digital world through the use of data enabled by pervasive digitalisation. This digitalisation brings together heterogeneous topics across the product life cycle, from design to production efficiency and machinery maintenance. It involves all aspects of industrial and business activities, including workers and the working environment.

3.3.1 Scope

To manage machines, factories, and company networks, industry organises the required technologies into levels or technology stacks. In these levels, sensors and actuators are closest to material processing or item handling. Therefore, they are at the lowest level of the Edge-to-Cloud Continuum. Higher levels include supersets, systems of systems, and interconnected IoT devices, unit processes, production or manufacturing lines, operations control, and enterprise business processes. These levels also cover growing numbers of machines, lines, and company boundaries, as manufacturing becomes more networked, complex, dynamic, and global.

Industry 4.0 changes operating modes and strongly affects the management and operation of factories, supply chains, construction sites, and processes. Powerful networked digital tools are required to achieve the situational awareness and control needed for autonomous vehicles, robots, and processes at different autonomy levels. These capabilities support the increasingly pervasive Industry 5.0 approach. Technological tools linked to the decentralised Web 5.0 concept can encompass complex non-hierarchical environments and allow better control of user data.

The European Industry 4.0 and Industry 5.0 transition needs an open-source-based, stable, and extensible semantic internet to overcome user interface, networking, and communication challenges. An internet with smart agents is an overarching concept that includes multiple technologies, such as the industrial Internet of Things, artificial intelligence (AI), advanced data analytics, and augmented and virtual reality (AR/VR). The industrial metaverse, based on digital twins, can be seen as an expanding set of interconnected virtual and augmented worlds. It is accessible from AR/VR head-mounted displays, desktop computers, and mobile phones.

Digital twins created by formalised expert knowledge and the semantics of physics-informed processes allow accurate simulations of manufacturing processes for experimentation and optimisation. Neuromorphic processing is a new computing paradigm that can transform the industrial Internet of Things by replacing traditional power-hungry computing architectures with more energy-efficient brain-inspired systems. These approaches can improve the adoption of increasingly autonomous and environment-aware robotic solutions by generating and fine-tuning synthetic data to explore application scenarios. Entities in the industrial metaverse can include people, devices, and autonomous physical or virtual machines, such as digital twins and AI agents.

The digital transformation of manufacturing processes, software tool creation, data-driven and AI-supported decision-making, and the harmonisation of human-technology relationships enable the next stage of human-robot coworking for Industry 5.0.

This SRIA addresses the digitalisation of major European industrial sectors and promotes European sovereignty within the internal manufacturing ecosystem, together with sustainability and greener industrial processes and artefacts. These sectors include discrete manufacturing, for example automobiles, trains, airplanes, satellites, white goods, furniture, toys, and smartphones. They also include process industries, for example chemical, petrochemical, food, pharmaceutical, pulp and paper, and steel, as well as provisioning, production services, machinery, connected machines, UAVs, and robots. This chapter also emphasises factories, production plants, operating sites, value chains, supply chains, product life cycles, and new materials for structures and electronic components.

Digitalisation is a key enabler for the future success of European industry. This chapter addresses the development potential of responsive, smart, and sustainable production, AI in digital industry, industrial services, digital twins, and autonomous systems. As discussed later in this chapter, nearly all topics in the technology chapters of the SRIA are vital for industrial applications. These topics include standardisation, engineering tools, cybersecurity, and digital platforms. To digitalise European industry and expand and embed the related supply chains, Europe must use potentially all enabling technologies to achieve the required competitive edge. A focus on digital industry also requires the effective use of enabling technologies in industrial applications.

Today, the digital landscape remains fragmented, with significant challenges in standardisation, interoperability, and translation of research into commercial impact. Europe must address these challenges effectively to build a strong, greener, resilient, and responsive economy. Sustainable and human-centric solutions can help Europe achieve strategic autonomy in the future, as outlined in the Draghi Report[1] "*EU competitiveness: Looking ahead*" and in the more sector-specific WMF Report 2024 "*New Perspectives for the Future of Manufacturing: Outlook 2030*"[2].

3.3.2 Application trends and societal benefits

The recent "*2030 Digital Decade*"[3] initiative under *Shaping Europe's Digital Future*[4] highlights the urgent need for the EU to prioritise action in areas that foster innovation and growth, improve productivity, and mitigate disruptions, particularly in digital technologies and digital skills.

Europe needs industry to become greener, more circular, and more digital while remaining competitive globally. The ecological and digital transitions affect every part of the economy, society, and industry. They require new technologies, supported by investment and innovation. They create new products, services, markets, and business models. They also create new job profiles that require skills that are not yet widely available. In addition, they drive the shift from linear production to a circular economy.

The digital sector also contributes to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint. Scalability is essential in a digitalised economy. Therefore, strengthening the digital single market supports Europe's transition. Europe must also

[1] https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en
[2] https://www.effra.eu/news/wmf-report-2024-new-perspectives-for-the-future-of-manufacturing-outlook-2030
[3] https://digital-strategy.ec.europa.eu/en/policies/europes-digital-decade
[4] https://commission.europa.eu/system/files/2020-02/communication-shaping-europes-digital-future-feb2020_en_4.pdf

accelerate research investment and technology deployment in AI, 5G/6G, and data and metadata management. Private 5G/6G networks are expected to expand in industry, while hybrid clouds enable seamless sharing of content and resources across networks. Web 4.0 smart services and smart things require this evolution through goal-oriented intelligent connection of semantic resources. Connectivity will increasingly link systems and people. Personnel at plant level will become more aware of their operations, and cloud-based artificial knowledge will move closer to devices, sensors, processes, and people. Accuracy can be improved, for example, through hardware-level support for precision time protocol (PTP) in industrial devices. This support can improve indoor localisation through better communication capabilities, such as Bluetooth® Low Energy and ultra-wideband, together with advances in sensors and algorithmic approaches such as time of flight and electrochemical impedance spectroscopy (EIS) for innovative applications.

European factories and machines already have a high level of automation and digitalisation. Many leading end-user companies are based in Europe. Europe also has major system builders, machine builders, engineering companies, and contractors with a competitive edge in automation and digitalisation. However, the business environment is changing. Through specialisation in new or niche end products, production is becoming more demand-driven and agile. At the same time, production is becoming more geographically distributed, which expands supply chains. In addition, the outsourcing of auxiliary business functions such as condition monitoring and maintenance is becoming more common, which leads to highly networked businesses. Industry has many opportunities for optimisation of energy, waste, water, material use, and recycling across value chains and company boundaries. These advantages require a significant increase in digitalisation and the embedding of functions and intelligence in the physical production layer.

This transition should also include applications that do not need to remain internal or confidential. Web-based and cloud-based solutions can support such applications and make them easier for non-AI professionals to use. These solutions can also support offline development of advanced models and inference engines by specialised centres.

The use of AI for core business functions often requires a full redesign of data management, data use, and data tracking across the supply chain. A system-of-systems (SoS) framework can enable effective data capitalisation through suitable actions, especially where conventional analysis and analytical tools reach their limits. Interaction between systems will become more direct. This trend requires more standardised interfaces that enable adaptive connectivity with secure access rights, while some information remains hidden.

The industrial metaverse, based on digital twins, can accelerate employee training and help build the trust required to use intelligent agents. It can enable virtual simulations before construction of physical systems and can speed up research and innovation cycles. It can also support field workers through AR/VR. In addition, it can make worldwide product design collaboration possible. Virtual designs can support physical product creation, and physical items can feed digital assets into digital environments.

Much of the value chain will come from existing installations, because completely new factories are not often built. New fast and secure communication protocols can provide easier connectivity and interoperability across systems and support extensive integration. Secure access to internal networks can provide users with information at any time and from any location within the plant. In addition, cloud-based or edge-based computing systems can provide new features. However, these capabilities require additional hardware infrastructure and greater processing power to handle larger data volumes.

Digital infrastructure and microservices can help evolve business models towards selling added value as a service. Investment in projects can create networks among vendors and providers. In modern business-to-business (B2B) relationships, ongoing R&D and industrial pilots aim to deliver a range of after-sales services to end customers. These services typically include condition monitoring, operation support, spare parts and maintenance services, help desk functions, troubleshooting, operator guidance, performance reporting, 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 continues to grow. The share of services is generally higher in high-income countries than in low-income countries. Service businesses are important because they enable sustained revenue after traditional product sales. In many cases, they are also more profitable than the original product sale.

3.3.3 Major Challenges

Each major challenge (MC) focuses on a specific topic. However, all digital industry major challenges interact extensively. Improvements in one MC can support progress in another. Artificial intelligence, robotics, digital twins, and augmented reality often appear together as connected tools that improve industry across many domains.

Six major challenges have been identified for digital industry:

- **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, collaborative robotics.

3.3.3.1 *Major Challenge 1: Responsive and smart production*

3.3.3.1.1 Status, vision and selected outcome

Responsiveness, flexibility, and smartness are still largely addressed in the European production landscape through pre-Industry 4.0 automation technology. At the same time, European industry must become much more responsive to change, not only from a scientific and technological perspective, but also in response to critical situations.

Today’s automation solutions are not inherently flexible by design. Industry must apply adaptive and self-learning system principles to automation solutions to improve flexibility, responsiveness, and smartness. Relevant examples include AMR fleets, fleet orchestration, brownfield integration, subscription models, over-the-air management, and secure fleet operations.

Many European initiatives and reports address this topic, including EFFRA[5] publications, SMART EUREKA[6] mission statements, and ManuFuture[7] reports. These initiatives emphasise resilient and adaptive European manufacturing systems that can cope with rapid change, overcome disruptions, and respond to new market needs.

The main benefits of more responsive and resilient production are:

- Ability to forecast demand, supply, and the evolution of the competitive ecosystem
- Capability to change production and provisioning quickly
- Efficiency in high-mix, low-volume production
- Capacity to continue operation with reduced operational capability
- Ability to support rapid innovation through integration, product evolution, redesign, and process re-engineering
- Ability to limit performance, reliability, maintainability, and interoperability degradation when disturbances affect plants.

Chips JU can play a leading role in this evolution towards more responsive, robust, and resilient factories. Responsive and resilient manufacturing has long been a key challenge, from integrated sensors in wearables and prosthetics to systems of systems that enable self-healing and self-reconfiguration.

AI also plays a key role in increasing the flexibility of manufacturing systems. For example, AI applied to real-time scheduling allows production to adapt to rush orders and disturbances in production lines or supply chains. However, the current focus on deep learning should be complemented by other AI approaches that are more explainable and more aware of the environment and the task.

The continuing effects of COVID-19 and current global instability have highlighted why flexible factories must adapt better in times of change. A flexible factory can better support the European response to crises by:

- Modifying production according to medical needs and exogenous inputs
- Scheduling production with fewer human resources and with social distancing constraints
- Enabling agile work and telepresence
- Adapting to supply chain changes and promoting European independence through differentiation and more resilient supply chains
- Developing local or shorter supply chain capacity for components that normally come from global markets
- Developing redesign and re-engineering capacity when raw materials or electronic components are unavailable

Although automation and digitalisation are essential building blocks for a flexible and resilient manufacturing industry, a well-trained and agile workforce remains critical. Workforce agility and flexibility, achieved for example through cross-skilling and empowered by smart technologies such as AR/VR or assistive chatbots, make people indispensable in production processes.

[5] https://www.effra.eu
[6] https://www.smarteureka.com/about-us/mission-vision/
[7] http://www.manufuture.org/wp-content/uploads/Manufuture-Vision-2030_DIGITAL.pdf

Standardisation is also essential. Modern industrial digitalisation depends on standards because interoperability would not be possible without them. Standards support quality, safety, and reliability in large industrial projects. Many engineering methods are standardised and provide consistency across professional engineering practices. However, these standards must also be supported by appropriate engineering tools for design, development, and operation.

3.3.3.1.2 Key focus areas

- **Robust and optimal production, scalable first-time-right production**: Future manufacturing plants should become more robust and continue production when disturbances occur. This evolution requires advances in self-healing and redundant automation systems, first-time-right and zero-defect manufacturing, and predictive maintenance that supports adaptable production.

- **Mass customisation and personalised manufacturing, customer-driven manufacturing**: Progress towards lot-size-one manufacturing and personalised product design is expected to continue. IoT sensors can self-correct disturbances, real-time warehouse connectivity can optimise the shop floor, and edge devices can run predictive analytics. These advances support greater flexibility.

- **Resilient and adaptive production, including shorter supply chains and modular and flexible factories:** Resilience is a critical property of systems that absorb internal or external stress and adjust their organisation and performance to maintain necessary operations, even with reduced productivity.

- **Cognitive production:** This area combines natural and artificial cognition with IoT devices and data analytics to enable new analytics and learning, event-driven processing, AI processing, in-memory compute evolution, and neuromorphic approaches. These capabilities can support responsive, sustainable and adaptable production.

- **Manufacturing as a service:** Technological advances can expand the geographical distribution of manufacturing and support manufacturing as a service (MaaS). Examples include 3D printing, outsourced production chain elements, and moveable factories. These solutions can support decentralised manufacturing in construction projects or temporary production locations.

- **Embedded, edge, and cloud architectures:** System architectures now commonly include embedded computing near machinery or processes, edge computers or local servers, and cloud computing. 5G technology strengthens edge-to-cloud and edge-to-edge communication and moves workload and services closer to production.

- **Standardisation:** Because of the many existing standards and their installed base, the focus should be on bridging systems across standards. Semantic technologies, software, platforms, digital testing, development environments, and licensing approaches are required to support high-level connectivity and broad acceptance.

3.3.3.2 Major Challenge 2: Sustainable production

3.3.3.2.1 Status, vision and expected outcome

This major challenge focuses on how Industry 4.0 should address future regulations and market requirements linked to the European Green Deal and to zero-carbon or below-carbon-neutral operations.

Nearly 200 countries have committed to the Paris Agreement on climate change, aiming to limit global warming to below 2ºC. Rapid transformation is therefore required across all sectors. Many European countries have set even more ambitious targets. Chips JU can strongly reduce environmental impact through sustainable manufacturing, including energy efficiency, resource efficiency, and circular economy strategies such as eco-design, repair, reuse, refurbishment, remanufacture, recycling, and waste prevention

Some rare earth materials must be preserved, and careless material use can be both uneconomical and harmful to the environment. The vision of Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) translates high-level objectives into practical actions, including more efficient use of energy and resources, waste reduction, reuse of waste streams and energy across sectors, replacement of current feedstock with renewable alternatives, and reinvention of materials and products to improve efficiency across the value chain.

3.3.3.2.2 Key focus areas

- **Monitoring flows of energy, materials, waste and life cycle assessment**: Many industry sectors already require full traceability of material and energy streams. As more products and raw materials become critical, this strategy must expand. Sustainable manufacturing requires comprehensive environmental data and other measurements. IoT sensors, software sensors, virtual sensors, and life cycle assessment (LCA) methods are important tools for this purpose.

- **Virtual AI assistants**: Discharges or losses often occur when production does not proceed as planned because of mistakes, poor machinery condition, or insufficient operator skills. AI-supported assistants can help operators by providing advice, preventing suboptimal changes, and addressing production dynamics.

- **Human–machine interfaces and machine-to-machine communications**: Augmented reality and virtual reality can support many tasks. Improved data visualisation and analytics presentation are required to support decision-making.

- **Human operators in more autonomous plants and in remote operations**: The relationship between machines and people must be reconsidered. This includes touch displays, wearable devices, augmented reality, and retention of the central role of people in new production contexts. Skills 4.0 are required for data administration, privacy, cybersecurity, and more.

- **Human safety**: With localisation of personnel, machines, and vehicles, situation-aware safety becomes increasingly important. Relevant capabilities include safety sensing, proximity detection, online human risk evaluation, and map generation.

- **Competence and quality of work in 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. Workers in production and maintenance may require higher levels of formal training, while specialisation continues to increase company-specific training needs.

- **European Green Deal alignment:** All industries must focus on high efficiency, low energy use, carbon neutrality or zero carbon, and zero waste in water, soil, and air. These targets must be measured, calculated, or estimated at product, factory, global and life cycle levels. Industry must also develop new materials while prioritising recycling, reuse, demanufacturing, and remanufacturing.

Many of these advances require development in engineering, business, and social domains beyond the scope of Chips JU. However, electronics and software technologies remain essential to their implementation.

3.3.3.3 Major Challenge 3: Artificial Intelligence in digital industry

3.3.3.3.1 Status, vision and expected outcome

Major Challenge 3 focuses on connected and smarter cyber-physical systems (CPS), industrial internet, big data, machine learning, optimisation, and other AI-based methods. Local edge-based intelligence is a major opportunity for Europe. AI-optimised and open hardware is becoming increasingly important to support the European AI framework.

This major challenge extends towards AI-enabled adaptable and resilient factories, including people as part of a sociotechnical system. AI methods can enhance modern industrial systems, such as predictive condition monitoring, maintenance, scheduling, planning, and quality control. These methods can support reconfigurable first time-right and zero-defect manufacturing, while also supporting human decision-making under uncertainty.

AI-enhanced systems can enable resilient manufacturing ecosystems based on new business models. They can also increase safety and security in working environments, improve productivity, and shorten the return on investment period. Explainable AI (XAI) is an emerging field that supports better understanding of decision-making and therefore improves human trust and system robustness.

Condition monitoring techniques can be applied to many types of industrial components and systems. Their business value often depends on increased equipment availability, better maintenance planning, lower cost, improved on-time delivery, greater safety, and better dimensioning of spare parts and maintenance staff. As a result, condition monitoring can help avoid serious breakdowns and unplanned interruptions.

Another important AI subfield is generative artificial intelligence (GenAI), which uses generative models to produce text, images, video, and other types of data. GenAI is changing digital transformation by changing how companies create, innovate, and interact internally and with customers. It supports generation of personalised marketing content, product descriptions, maintenance documentation, social media content, source code, virtual prototypes, and new digital products and services.

AI affects several main areas relevant to digital industry:

- Productivity, by exploiting AI in the design, manufacturing, production and deployment processes through the automation of routine tasks and data-driven analysis.
- Flexibility, through AI across the value stream from supply to delivery .
- Customer experience, through faster and better-quality products and more efficient services.
- Assistance to human operators, through support for decision-making in increasingly complex environments.
- Radical innovation, through new products and productivity gains beyond support for existing solutions

These fundamental impacts will be experienced in all areas of every market sector. In manufacturing and production, AI will deliver productivity gains through more efficient resources, energy and material use, better design and manufacturing processes, and in products and services, enhancing their operation with more refined contextual knowledge.

The AI Continent Action Plan[8] from April 2025 aims to make the EU a global AI hub and to ensure that AI remains human-centric and trustworthy. The AI Continent Action Plan aims to bring the benefits of AI to various sectors highlighting five strategic areas: *(1) computing infrastructure*, including AI Factories, AI Gigafactories, Cloud and AI development Act, *(2) the Data Union Strategy*, improving data access and interoperability, *(3) skills* or AI talent, by boosting specific education programmes in EU universities, *(4) development of algorithms and their adaptation* in strategic sectors, and *(5) simplifying rules* to facilitate the implementation of the AI Act[9].

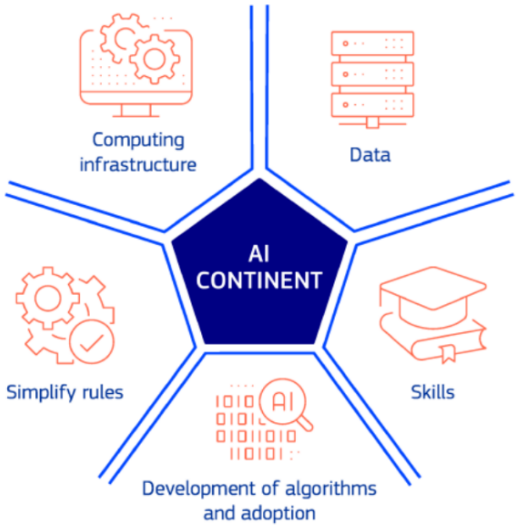

Figure 3.3.1 Five strategic areas of the AI Continent Action Plan
[Source: https://digital-strategy.ec.europa.eu/en/factpages/ai-continent-action-plan]

[8] https://digital-strategy.ec.europa.eu/en/factpages/ai-continent-action-plan
[9] https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

3.3.3.3.2 Key focus areas

a) European AI framework

Figure 3.3.2 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: the legal and societal fabric that underpins the impact of AI on stakeholders and users; AI innovation ecosystem enablers: essential ingredients for effective innovation and deployment; and cross-sectoral AI technology enablers: the core technical competencies essential for the development of AI systems.

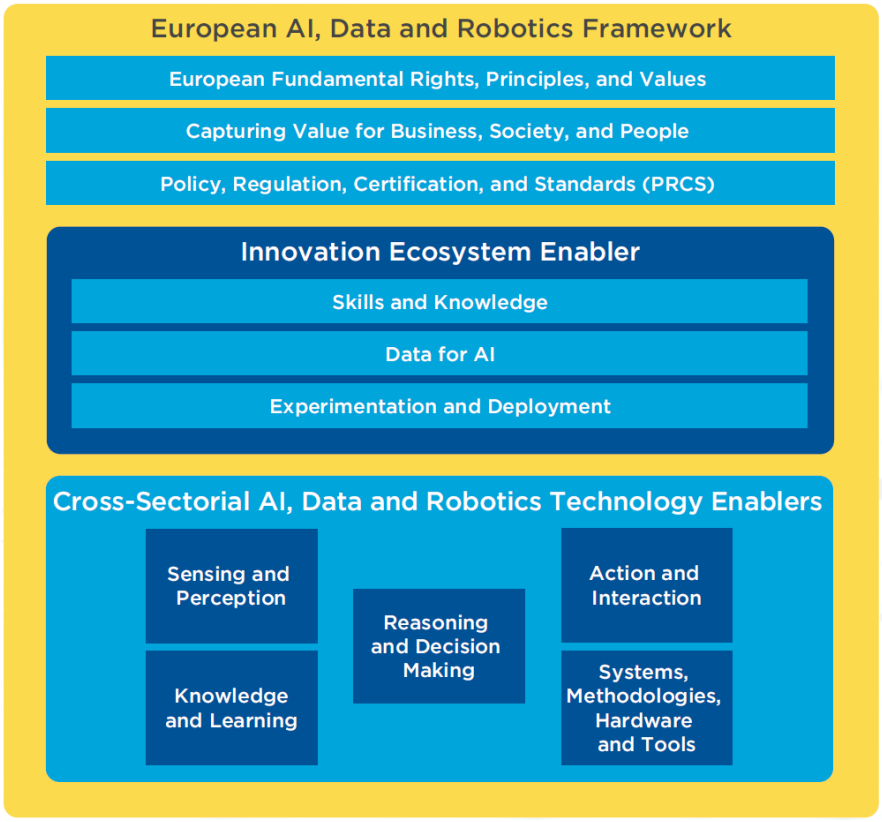

Figure 3.3.2 European AI framework and enablers – SRIDA on AI, Data and Robotics Partnership[10]

b) AI in manufacturing

- AI for dynamic production planning and management: This involves making real-time decisions to optimise factory operations by quickly modifying the production schedule based on the current state of the shop floor, predicted sales orders, and unexpected events, such as machine breakdowns or changes in job priorities.
- Virtual models spanning factory operations and the life cycle: A holistic and coherent virtual model of the factory and its production machinery results from integrating modelling, simulation, and forecasting methods and tools that strategically support manufacturing activities.

[10] https://bdva.eu/download/92/publications/3122/ai-data-and-robotics-sirda-joint-version-rel3-1.pdf

- AI for green/sustainable manufacturing**:** The development of software-based decision-support systems, as well as energy and resource management, monitoring, and planning systems, leads to reduced overall energy consumption, more efficient use, and optimised energy sourcing**.**
- AI in supply chain management**:** Planning and managing logistics for real-time operations, collaborative demand and supply planning, traceability, execution, global state detection, time-to-event transformation, and discrete or continuous query processing are therefore challenging because of the distributed nature of these elements.
- AI for advanced manufacturing processes**:** The ability to design functionality using 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 approaches (additive manufacturing, laser or other jet technologies, 3D printing, micromachining or photon-based technologies, physical vapor deposition, PVD) or chemical approaches (chemical vapor 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

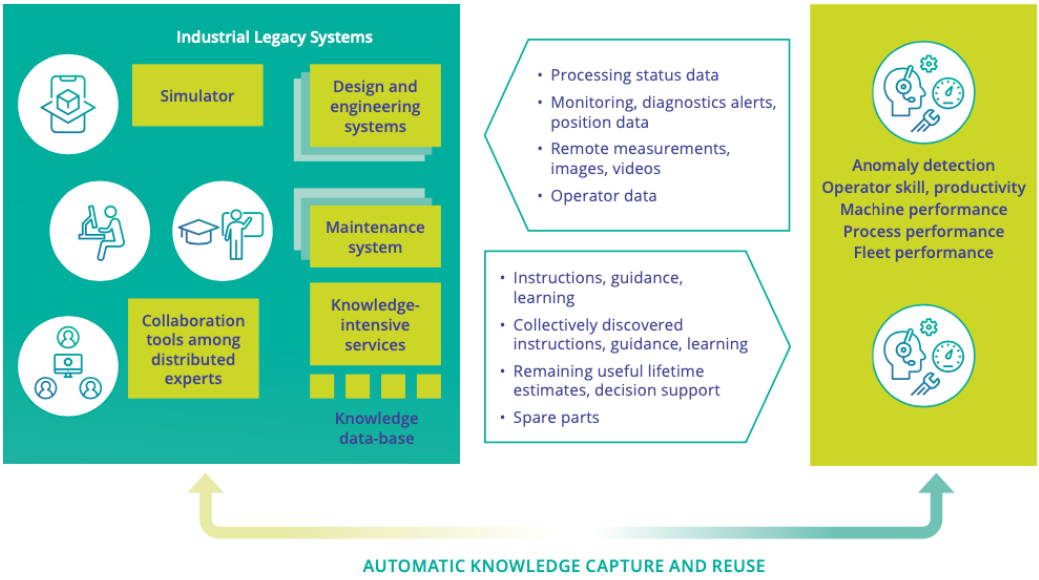

Figure 3.3.3 - Industrial service business between a machine or system vendor or service provider and an end-customer. Services or lifecycle businesses deal with, for example, anomaly detection or condition management, operator skills development, productivity issues, machine or system performances, and fleet performances.

c) AI for decision-making

Decision-making is at the heart of AI. Furthermore, Explainable AI will increase "human-centric" approaches in autonomous industry.

- AI supports complex decision-making processes or helps develop hybrid decision-making technologies.
- Human, machine, mixed decision-making and decision support.
- Sliding or variable decision-making, dealing with uncertainty.
- AI for human interaction with machines.

d) AI for monitoring and control

- AI for control technologies.
- AI for monitoring services.
- AI for maintenance systems that increase reliability.
- AI services for continuous evaluation and mitigation of manufacturing risks.
- AI for quality inspection.

3.3.3.4 Major Challenge 4: Industrial service business, lifecycles, remote operations and teleoperation

3.3.3.4.1 Status, vision and expected outcome

The volume and value of industrial services are increasing by 5% to 10% each year. For many machine, systems, and service vendors, the share of services already exceeds the share of machinery sales. This trend affects final assembly factories and supply chain companies alike.

Companies increasingly aim to take larger shares of customer business, starting with spare parts and extending to remote condition monitoring and additional tasks once considered part of the customer core business. From the customer's perspective, this trend is a form of outsourcing.

Industry as a service changes production by outsourcing local tasks to specialised providers. This approach increases flexibility, resilience, and adaptability in production. It also redefines the supply chain by embedding all production phases, from procurement of raw materials and semifinished products to customer services and product or part design.

While many businesses have become global, some services are still provided locally, close to customers' locations, while other services are provided centrally by the original vendor or companies specialised in such services. The industrial era is increasingly becoming a service era, enabled by advanced Chips JU technologies. This distributed model fits well with the edge-to-cloud continuum, supported by computing infrastructures for emulation, training, machine learning, and real-time communication.

Service businesses are important because they generate revenue beyond product sales and are typically more profitable than the original product sales. Europe can differentiate in the global service business market through its skilled workforce, deep technology knowledge, and strong ICT capabilities. To succeed, however, Europe needs continued innovation and industrial transformation.

3.3.3.4.2 Key focus areas

- **Remote operations, teleoperation**
  - Remote engineering, telepresence, and remote operation support
  - Distributed service applications on edge-cloud systems
  - Use of low-latency 5G for remote operation

- **AI services for monitoring and collaboration**
  - Collaborative product-service engineering and life cycle engineering
  - Training and simulation
  - Condition monitoring, condition-based maintenance, anomaly detection, performance monitoring, prediction, and management
  - Strategic partnerships and data capitalisation, with data as currency, for new service business models

- **Fleet management, edge and local/global decision-making**
  - Decision and operation support through diagnostics, engineering, and knowledge management
  - Fleet management based on experience from similar components and machines in different conditions

- **Business services integration**
  - Local and global services: Organizing services locally close to customers and centrally at vendors' sites.
  - Full life cycle tutoring, from operation through end of life, including waste handling, recycling, and redesigning for the next product generation

3.3.3.5 Major Challenge 5: Digital twins, mixed or augmented reality, telepresence

3.3.3.5.1 Status, vision and expected outcome

A digital twin is a dynamic digital representation of an industrial asset that helps companies understand and predict machine behaviour and performance and identify new revenue streams. Cloud connectivity now enables large-scale deployment of digital twin technology across industries. A physical asset can have a virtual copy running in the digital twin environment and can increase value through continuous operational data. Several plants can also operate in the same virtual environment by sharing data and supporting remote automated decision-making.

Digital twins at factory or plant level are becoming increasingly autonomous and intelligent and can adapt through online learning. If needed, they can interact with cloud-level systems to evaluate models and optimise parameters through transfer learning.

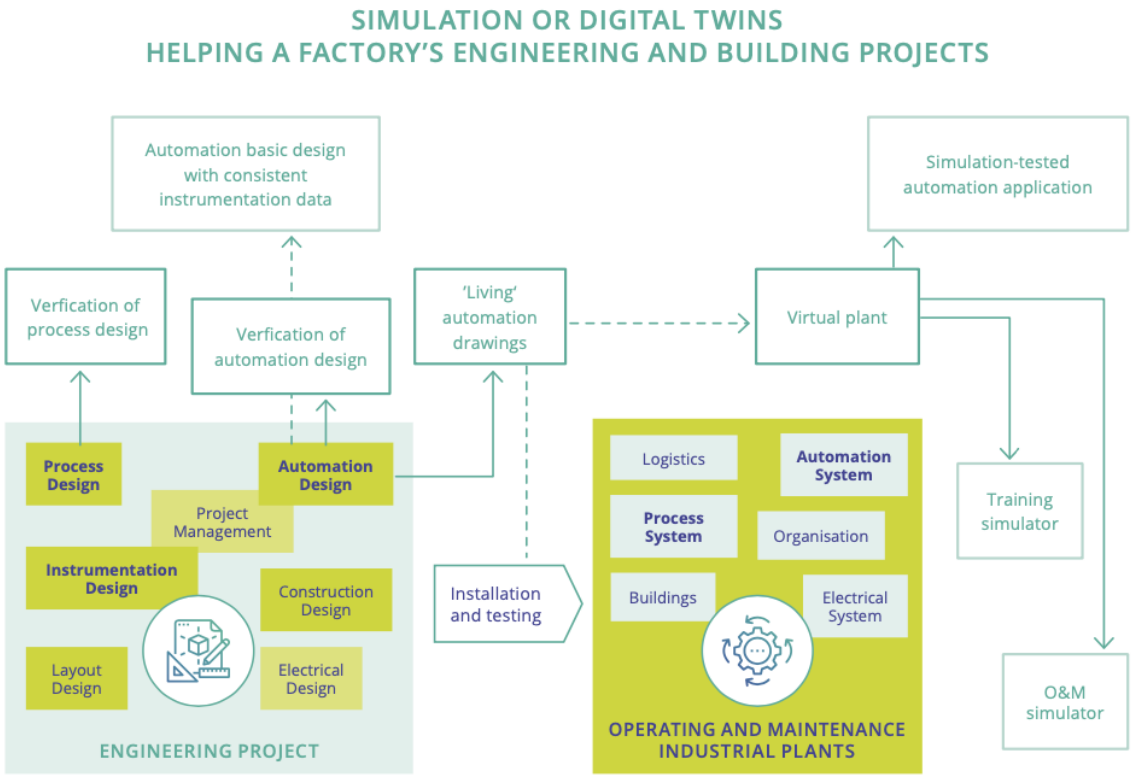

Figure 3.3.4 - Simulation or digital twins helping a factory's engineering and building projects

Simulation capability is already a key element in the competitiveness of the European machine tool industry. In the Industry 4.0 paradigm, modelling plays a central role in managing technological complexity. A holistic engineering approach is required to span disciplines and provide end-to-end engineering across the entire value chain. Modelling and simulation can also address many digitalisation challenges. They can visualise real-world phenomena, support design optimisation and safety analysis, assess changes in advance in virtual domains, support training with synthetic data, and shift digitalisation focus from computer-aided design to simulation-based design.

In addition to virtual commissioning, modelling and simulation can offer versatile environments for training operators and users, capable of generating the synthetic data necessary for the development of increasingly sophisticated robotic implementations, such as the adoption of autonomous (humanoid) robots in unstructured environments within production areas.

Simulators can be used online and in parallel with real systems to predict behaviour, provide early warnings, and outline decision scenarios. Although simulator technology has long research roots, current simulators still need co-design and further improvement, including use of recent European investments in computing infrastructure (e.g. HPC EU families, EPI initiative), with a special focus on the industrial context.

Telepresence technologies can also be considered predecessors of extended reality (XR) presence. The combination of XR, AIoT, edge computing, high-performance computing (HPC), 5G, and open integration platforms offers major innovation potential for European digital industry.

As an example, XR is a combination of virtual and augmented reality, and XR presence is a continuum between a physical reality presence and a virtual reality presence. 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. Smart glasses and related platforms can support industrial use cases and can connect to services such as digital twins and condition monitoring systems. These services can optimise operations and provide critical information to field workers. Longer-term integration of human actions and data can also support knowledge graphs that help other users work with expert-level knowledge.

The EC "Data Act" initiative[11] promotes reliable and secure access to data within the European data economy and supports the digital transformation and data sharing and exchange. In industrial applications and in interoperability across different legal entities, data ownership and use must be managed properly.

3.3.3.5.2 Key focus areas

- **Digital Twin: Design process digitalisation, telepresence**
  - Interoperability across heterogeneous systems
  - Immersive telepresence for industrial robotics
  - Digital twins for sustainability and circular economy analysis
- **Virtual commissioning, interoperability:**
  - Virtual commissioning across different domains of engineering (mechanic, electronic, automation) in the same environment.
  - Adequate interoperability must ensure the use of applications across different platforms.
- **Simulators: tracking and simulator-based design**
  - Tracking mode simulation: Model adaptation based on measurements. Automatically generating simulators from other design documentation and measurementss, etc.
  - Simulator-based design: 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).
  - New methods to generate large 3D scenes, for example, on NeRF (Near Radial Field) and/or the Gaussian Splats.

[11] https://digital-strategy.ec.europa.eu/en/policies/data-act

- **Human and 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 to provide the Situational Awareness for an industrial process as a whole.
    - Live 3D Digital Twins: to provide the state awareness (animation, colour, etc.) in AR/VR/XR.

3.3.3.6 Major Challenge 6: Autonomous systems, robotics

3.3.3.6.1 Status, vision and expected outcome

Machines are typically more precise and efficient than people in repeatable tasks. Therefore, replacing or supporting work processes that are prone to human error, quality defects, or safety issues can improve quality and reduce waste. AI in robotics, and robotics without AI, expands the opportunities for automation of manual tasks and can increase sustainability, safety, security, and support for the green transition. This evolution can reduce environmental impact, reduce waste efficiently, optimise product quality towards zero defects, and improve processes and workforce support. It can also create safer and more secure work areas for human-machine and machine-machine coworking. Progress in physical AI and robot foundation models allows robots to understand their surroundings and autonomously perform and learn complex physical tasks through natural language.

Autonomous systems, robots, and working machines cover many domains, including industrial machines and robots, consumer robots, healthcare and medical robots, moving machines, transport systems, and utilities and critical infrastructures.

The main goals and trends for robots and autonomous systems in digital industry are:

- Production efficiency, speed and reduced costs,
- Higher precision and quality, safety in working conditions,
- Scaling up “smart and high-end manufacturing”.

These goals highlight the strategic need for complete general-purpose industrial robot platforms and for a transition of advanced and anthropomorphic robot solutions from research laboratories to serial production and integration in production plants. Strategic sovereignty in AI robotics must grow with advances across the full robot stack, including actuators, hands, sensors, batteries, safety controllers, communication, AI, middleware, and production scaling.

Robots, machines, and autonomous systems are relevant across all application chapters of this SRIA, not only digital industry. They also affect digital society, health and well-being, mobility, energy, and agrifood and natural resources, and they benefit from advances in foundational and cross-sectorial technologies.

There is a clear move towards higher automation and digitalisation in industry, including robotic solutions with anthropomorphic and humanoid forms based on advanced AI cognitive platforms. In these solutions, mechanics, sensor advances, tactile skin, multimodal end effectors, compliant actuation, manipulation benchmarks, and AI work together to support multimodal perception,

learning from experience, real-time prediction, and adaptive decision-making beyond traditional solutions.

However, between fully manual and fully autonomous manufacturing, there will always be a wide range of semiautonomous equipment, machines, vehicles, lines, factories, and sites. In many cases, it remains beneficial to stay below full autonomy or full digitalisation because full autonomy can be technically very difficult, very expensive, overly complex, brittle, or unsafe. A semiautomatic solution can often be easier to implement at a satisfactory level.

When automation and digitalisation increase gradually and professionally, they can provide major competitive advantages and savings. Because the degree of automation often remains well below 100%, negative employment effects can remain negligible or absent. On the contrary, broader adoption of robotics and autonomous systems can strengthen company market positions and increase demand for people in related businesses. Work organisation and leadership may need to evolve to unlock the full potential of digital industry.

3.3.3.6.2 Key focus areas

a) Autonomous functions of systems:

Advances in AI simplify the development of autonomous systems that automate work tasks in many domains, reduce the need for human intervention, and enable innovative new functions. Autonomous robotics is a key enabling technology for autonomously operating shop floors. This includes humanoid and anthropomorphic robots, robotic arms and end effectors, and autonomous mobile robots. Benefits include additional safety, increased productivity, improved accessibility, higher efficiency, and positive environmental impact. The following figure provides a generalised view of technologies and functionalities used in autonomous systems developed in the automotive domain. Nevertheless, this schematic representation of required building blocks can be generalised to many other types of autonomous systems.

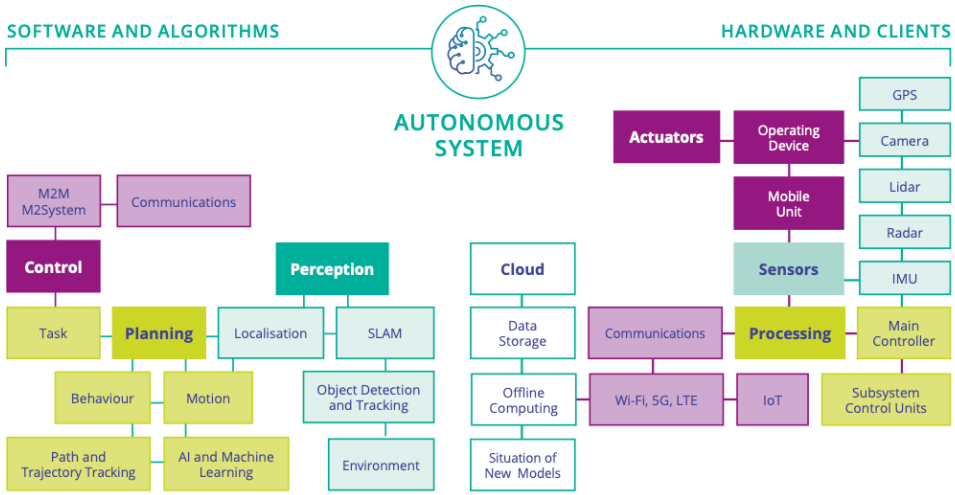

Figure 3.3.5 - A generalised overview of autonomous system (AS) technologies and functionalities. Adapted from Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). "Perception, Planning, Control, and Coordination for Autonomous Vehicles". Machines 5(1), p. 6.

The following figure shows how the ISA95 standard, which defines control and other enterprise functions, maps onto the building blocks of autonomous systems. Autonomy is expected to increase at Levels 2 and 3 of ANSI/ISA95[12].

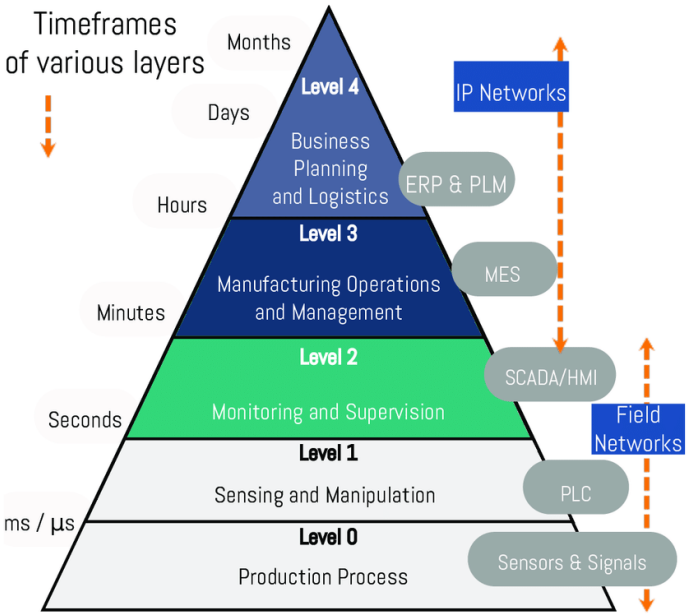

Figure 3.3.6 - ISA95 Hierarchy Model with building blocks of Autonomous Systems according to the 5 levels of the conventional automation pyramid[13]

b) Safety and security in autonomous systems:

Current safety approaches for autonomous machines include:

- On-board sensors and safety systems for machines that operate near people and other machines in indoor environments
- Isolated autonomous machines that work in separate areas, mostly in intensive outdoor environments where other machines or humans are monitored.
- Machine perception and prediction of expected and/or unexpected human activities to assist people, preserve health and safety, and protect machinery.
- Operator responsibility transfer, with sufficient warning time, for reacting to a hazardous situation encountered by an autonomous machine.

Advanced robot integration in industry also requires new focus on robot data, simulation-to-real methods, and certification of learned robot behaviour, including dataset handling, test environments, field data augmentation, robot policy validation, and failure mode discovery.

12 https://www.isa.org/standards-and-publications/isa-standards/isa-standards-committees/isa95
13 https://www.researchgate.net/figure/The-conventional-automation-pyramid-according-to-the-ANSI-ISA-95-model-The-five_fig1_343473533

c) Requirements management and conceptual modelling of autonomous systems:

Increasing autonomous functionality makes traditional safety-critical software development methods less adequate. Autonomous systems must operate in complex real-world environments and react correctly to a nearly endless variety of scenarios. Their design must consider expectations from various stakeholders such as the internal engineering teams, people involved in the autonomous systems management (e.g. passengers, drivers, workers, e-Health patients), regulatory authorities, and commercial autonomous vehicle/robot fleet operators.

d) Human–machine interaction in autonomous systems:

Advances in sensing, actuation control, industrial IoT, and SoS distributed capability are key enablers 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, autonomous system oversight and tactical awareness.
- Autonomy that enhances human capabilities.
- Natural human interaction with autonomous systems.
- Assisted, safety-oriented and proactive robot interaction with people.

e) Digital design practices including digital verification and validation (V&V):

- Automatic or semi-automatic Verification & Validation.
- Digital design environment, digital twins and physical mock-ups.
- Sub-task automation development, generation of training data and testing solutions and field data augmentation.
- Machine state estimation based on system measurements.

f) Simulators and autonomous systems:

- Process-model-based and product-3D-model-based approaches,
- Environment and object models.
- Early design phase simulators.
- Robotic test environments.
- Empirical and semi-empirical simulators based on real and simulated data.
- Off-road environments.

g) Autonomous capabilities development in a digital environment

- Autonomous decision-making.
- Self-evolving capabilities.
- Use of knowledge for cognitive flexibility and adaptive reactions.
- Edge AI in robotics with applications focused on manufacturing and automation

3.3.4 Requirement Overview

The most obvious requirement for digital industry is the availability of the technologies, components, and systems described in other parts of this document, both as foundational technologies and as cross-sectorial areas that enable the European digital industry mission.

It is also extremely important to meet several societal and policy needs, particularly the following aspects of EU legislation related to working environments:

- Adoption of trustworthy, responsible AI, extended reality and robotics.
- Preparation for the use of next-generation hardware architectures and new chip design, for example RISC-V.
- Adoption of technologies that safeguard worker safety and security.

The following policy aspects must also be considered to promote:

- **Resilience** of EU production capabilities and supply chains for industrial sovereignty.
- **Sustainability** of EU manufacturing renovation and evolution towards a greener and safer EU.
- **Digitalisation** of EU Industry towards faster Innovation vocation, cost-efficient production, lower energy consumption and improved ability to forecast market and societal needs.

3.3.5 Timeline

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
Major challenge 1: Responsive and smart production	**Topic 1.1:** Robust and optimal production, scalable first-time-right production	Disturbance-tolerant production demonstrated with fault detection, safe degraded operation and measured quality/yield.	Reconfigurable lines qualified against representative failures with verified recovery and controlled quality feedback.	Cross-site production adaptation qualified under supply disruption with independent quality and continuity evidence.
	Topic 1.2: Mass customisation and personalised manufacturing, customer-driven manufacturing	Lot-size-one production workflows demonstrated with traceable configuration, setup time and quality evidence.	Mass-customisation platforms qualified across product variants with coordinated planning and validated changeovers.	Distributed personalised production qualified across suppliers with maintained configuration and product-quality assurance.
	Topic 1.3: Resilient and adaptive production, including the shortening of supply chains and modular and flexible factories	Brownfield AMR fleets and modular production cells demonstrated with secure orchestration, OTA updates and recovery.	Reconfigurable factory modules qualified across suppliers and changing production tasks.	Cross-site modular manufacturing qualified under component shortages with traceable substitution and continuity.
	Topic 1.4: Cognitive production	Cognitive production pilots demonstrate AI-assisted planning and operator decisions with measured benefits and bounded actions.	Closed-loop cognitive production qualified for selected processes with monitored drift and safe fallback.	Federated cognitive operations qualified across plants with controlled adaptation and independent performance evidence.
	Topic 1.5: Manufacturing as a service	Manufacturing-service platforms demonstrated with secure capacity discovery, order traceability and measured service performance.	Distributed production services qualified across suppliers with verified quality, scheduling and data rights.	Reconfigurable service ecosystems qualified under cross-border disruptions with controlled process transfer and recovery.
	Topic 1.6: Embedded/Edge/Cloud architectures	Private-5G industrial edge/cloud platforms demonstrated with bounded latency, local fallback and secure workload placement.	Interoperable edge-cloud orchestration qualified for critical production; 6G adoption conditional on products and allocations.	Cross-operator workload migration qualified under changing networks with maintained real-time, safety and security evidence.
	Topic 1.7: Standardisation	Conformance-tested OPC UA, Asset Administration Shell (AAS) submodels and fleet-interface profiles demonstrated in heterogeneous brownfield plants, with manufacturing-data-space exchange.	Cross-standard semantic and data-space integration qualified with versioned models, governed cross-company exchange, conformance tests and controlled migration.	Lifecycle interoperability qualified across successive standards and independently maintained production systems.
Major challenge 2: Sustainable production	**Topic 2.1:** Monitoring flows of energy, materials, waste and life cycle assessment	Operational energy/material monitoring demonstrated with calibrated sensors, Digital Product Passport-ready identifiers, traceable product data and auditable lifecycle calculations.	Cross-site resource optimisation qualified with verified data provenance, interoperable environmental reporting and measured reductions.	Value-chain resource orchestration qualified with independent lifecycle benefit and circularity evidence.
	Topic 2.2: Virtual AI assistants	Industrial AI assistants demonstrated on operator tasks with verified answers, protected data and human approval.	Context-aware assistants qualified across sites with measured error reduction and controlled tool access.	Lifecycle support agents qualified under changing products and procedures with auditable knowledge and maintained operator authority.
	Topic 2.3: Human–machine interfaces and machine-to-machine communications	Multimodal HMI and machine interfaces demonstrated with measured usability, workload and accessible alternatives.	Interoperable XR decision support qualified for real production tasks with validated information and user control.	Adaptive interfaces qualified across changing roles and abilities with sustained task-performance and safety evidence.

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
	Topic 2.4: Human operators in more autonomous plants and in remote operations	Teleoperation and assistive robotics demonstrated with tested handover, cyber protection and operator workload limits.	Human-robot workspaces qualified for selected collaborative tasks with validated safety and responsibility allocation.	Adaptive human-robot teams qualified across changing tasks with verified intervention and lifecycle safety evidence.
	Topic 2.5: Human safety	Personnel/vehicle localisation and proximity safety demonstrated with measured coverage, confidence and fail-safe behaviour.	Context-aware protective functions qualified against occlusion, localisation faults and foreseeable human behaviour.	Coordinated workspace protection qualified under changing layouts with independently assessed residual risk.
	Topic 2.6: Competence and quality of work in human-centred manufacturing	XR/AI-supported industrial training demonstrated with measured competence transfer, accessibility and worker participation.	Reusable training and task-support systems qualified across sites with sustained skills and workload evidence.	Lifecycle competence-support platforms qualified under changing automation with independent evidence of work quality and effective oversight.
	Topic 2.7: Green Deal	Resource-efficient production and circularity workflows demonstrated with auditable energy, material and emissions baselines.	Repair, remanufacturing and recovery systems qualified with traceable product data and measured lifecycle benefits.	Cross-value-chain circular production qualified with independently assessed resource savings; climate policy targets remain external constraints.
Major challenge 3: Artificial Intelligence in digital industry	**Topic 3.1:** European AI framework	European industrial-AI deployment toolchains demonstrated with reproducible evaluation, representative data and traceable governance.	Reusable AI qualification workflows validated across industrial domains with monitored operating assumptions.	Sustained cross-sector AI ecosystems qualified through transferable evidence and controlled lifecycle change.
	Topic 3.2: AI in manufacturing	AI planning, inspection and maintenance integrated in operational pilots with measured production, quality and resource benefits.	Vertical and horizontal AI workflows qualified across business and shop-floor systems with bounded closed-loop actions.	Adaptive production coordination qualified across suppliers with verified stability, resilience and human authority.
	Topic 3.3: AI for decision-making	Explainable decision support validated against operator tasks with confidence information and explicit escalation.	Mixed human/AI decision workflows qualified under uncertainty with auditable allocation of authority.	Adaptive decision coordination qualified across sites with sustained oversight and independently assessed operational outcomes.
	Topic 3.4: AI for monitoring and control	AI monitoring/control demonstrated with measured false alarms, drift detection and safe fallback, including GNSS-denied environments.	Adaptive control qualified for selected industrial processes with physical validation and monitored model limits.	Cross-process autonomous optimisation qualified with bounded control authority and independent stability/recovery evidence.
Major challenge 4: Industrial service business, lifecycles, remote operations, and teleoperation.	**Topic 4.1:** Remote operations, teleoperation	Secure remote operation demonstrated with verified latency, operator handover and safe response to communication loss.	Distributed remote services qualified across sites with measured availability, access control and recovery.	Cross-operator remote operations qualified for selected tasks with sustained safety and accountability evidence.
	Topic 4.2: AI services for monitoring and collaboration	AI-based monitoring and collaborative services demonstrated with validated diagnostics and governed lifecycle data exchange.	Cross-site maintenance services qualified with uncertainty-aware forecasts and measured availability benefits.	Federated lifecycle services qualified across suppliers with transferable models and independently verified service performance.

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
	Topic 4.3: Fleet management, edge and local/global decision-making	Mixed AMR fleet orchestration demonstrated using VDA 5050 profiles, conformance tests and local collision protection.	Cross-vendor fleet management qualified under congestion, network failure and changing production routes.	Multi-site fleet coordination qualified with governed local/global decisions and independently tested recovery.
	Topic 4.4: Business services integration	Production/business service integration demonstrated with versioned interfaces, data-space identity and usage control, and measurable customer outcomes.	Lifecycle service orchestration qualified across vendor and customer systems with traceable knowledge updates.	Cross-organisational product-service ecosystems qualified through successive product generations and controlled evidence exchange.
Major challenge 5: Digital twins, mixed or augmented reality, telepresence	**Topic 5.1:** Digital Twin: Design process digitalisation, telepresence	Operational digital twins and telepresence demonstrated with verified interfaces, model fidelity and measured task benefits.	Interoperable twins qualified across production and lifecycle services with validated circularity and telepresence use cases.	Federated twins qualified across suppliers with synchronisation, uncertainty and controlled lifecycle evolution.
	Topic 5.2: Virtual commissioning, interoperability	Virtual commissioning demonstrated across mechanical, electrical and automation models with physical correlation.	Cross-platform commissioning qualified through conformance tests and controlled model/interface versions.	Reusable commissioning ecosystems qualified across successive production generations with independent evidence continuity.
	Topic 5.3: Simulators: tracking and simulator-based design	Measurement-calibrated simulators demonstrated for design changes with quantified fidelity and uncertainty.	Simulator-assisted plant reconfiguration qualified with verified interfaces and retained physical acceptance tests.	Lifecycle simulator generation qualified across changing plants with monitored validity and independent calibration.
	Topic 5.4: Digital twins combined with data-driven models (knowledge and data fusion)	Hybrid physics/data twins demonstrated with traceable training data and measured predictive validity.	Hybrid twins qualified for selected processes with drift monitoring and verified synthetic-scene transfer.	Adaptive hybrid-twin federation qualified across sites with bounded uncertainty and maintained physical evidence.
	Topic 5.5: Human and knowledge integration	Human-in-the-loop XR/twin workflows demonstrated with validated task performance, workload and safe collaboration.	Collaborative knowledge/twin services qualified across sites with provenance and effective operator control.	Adaptive shared workspaces qualified over lifecycle changes with sustained competence and human-safety evidence.
Major challenge 6: Autonomous systems, collaborative robotics	**Topic 6.1:** Autonomous functions of systems	Task-bounded autonomous robots, including humanoid pilots, demonstrated with measured reliability, energy use and safe intervention.	Multi-task robot cells qualified within defined operating envelopes with tested failure handling.	Adaptive robot teams qualified across changing production tasks with independent safety, uptime and lifecycle evidence.
	Topic 6.2: Safety and security in autonomous systems	Robot perception and protective functions demonstrated with measured coverage, fault handling and safe human interaction.	Collaborative robot applications qualified under defined hazards, cyber threats and supervision arrangements, including post-update safety and cybersecurity reassessment.	Evolving robot workspaces qualified with compositional safety/security evidence and controlled behavioural updates.
	Topic 6.3: Requirements management and conceptual modelling of autonomous systems	Stakeholder requirements and operating envelopes translated into traceable autonomous-system models and scenario tests.	Requirements/toolchains qualified for controlled changes with explicit scenario-coverage and residual-risk evidence.	Lifecycle requirements assurance qualified across changing compositions without claims of exhaustive real-world scenario coverage.

Major challenge	Topic	Short term (2027–2031)	Medium term (2032–2036)	Long term (2037 and beyond)
	Topic 6.4: Human–machine interaction in autonomous systems	Natural-language/gesture robot programming and haptic teleoperation demonstrated with verified commands and safe fallback.	Multimodal robot interaction qualified across representative users and production tasks with measured intervention performance.	Adaptive human-robot cooperation qualified under changing tasks with sustained usability, authority and safety evidence.
	Topic 6.5: Digital design practices including digital verification and validation (V&V)	Digital V&V pipelines demonstrated using traceable scenarios, synthetic/field data and physically correlated twins.	Simulation-led robot qualification validated for selected tasks with coverage metrics and retained physical tests.	Continuous robot V&V qualified for restricted updates with independently assessed behavioural change and evidence continuity.
	Topic 6.6: Simulators and autonomous systems	Robot simulators demonstrated with representative environments and measured simulation-to-real transfer.	Reusable test environments qualified across robot types with calibrated physics and validated synthetic data.	Adaptive simulation ecosystems qualified through sustained field feedback and independently quantified model limits.
	Topic 6.7: Autonomous capabilities development in a digital environment	Digital robot-policy development demonstrated with reproducible training, safe deployment gates and bounded edge execution.	Adaptive robot skills qualified within monitored envelopes with rollback and verified policy transfer.	Controlled skill adaptation qualified across robot generations with independent assurance and sustained field reliability.

3.4



ECS Key Application Areas

HEALTH AND WELLBEING

3.4 HEALTH AND WELLBEING

3.4.1 Scope

Technological effervescence

In the field of Digital Health, a significant discrepancy can be observed. There are thousands of digital health solutions available on the market, and thousands more are being developed, mostly by tech companies (including start-ups) that are entering the sector for the first time, rather than traditional healthcare companies.

Many of these companies have high expectations, but they are learning that success depends on demonstrating a clear clinical need, fitting into real care pathways, involving clinicians early, and navigating a complex and highly regulated sector.

As a result, only a small fraction of digital health innovations succeeds in the market. Certain aspects of the healthcare industry may also hinder market entry, including inconsistent regulatory interpretation across countries and concerns regarding the reimbursement of medical technologies.



Figure 3.4.1 - Harvard Business Review: "Why innovation in healthcare is so hard?"

Another issue lies in the conventional practices regarding the manufacture of medical devices and equipment, as many such devices and items of equipment will, for the most part, continue to be developed as dedicated instruments for specific clinical applications, and rightly so given the regulatory and clinical adoption constraints involved. This inevitably constrains the return on investment that can be expected from any single design, and more critically limits the volume effects on which the semiconductor industry depends — with healthcare today representing barely 1% of the total addressable market for semiconductors. The opportunity for the ECS community does not lie in pursuing multi-application devices, but one level below, at the level of architectures: reusable platforms and reference designs that can be embedded, with minimal adaptation, across a family of distinct, clinically validated devices, allowing volume to be aggregated across applications without requiring any single device to be multi-purpose. The objective of the Chapter is to highlight the business opportunity that the current acceleration of Digital Health Transformation should bring for the ECS community, especially through this logic of architecture reuse rather than device reuse.

Healthcare systems sustainability

Current megatrends highlight the ubiquity of healthcare in our society. Both urbanisation and rural depopulation create healthcare delivery challenges: dense urban settings amplify population-related health issues, while remote and underserved areas face reduced access to care, especially for elderly populations. The ageing population means more health issues, such as chronic diseases. The COVID-19 pandemic has shown that major health crises have a global impact and require preparedness: in addition to their catastrophic effects on population health, they may disrupt access to health services worldwide, even where access already needs improvement for certain population groups.

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 explicit national strategies to manage costs, by using more effective treatments along with Digital Health strategies associated with roadmaps to deploy solutions. Technology adoption, through the healthcare digital transformation, is considered a pivotal element in securing the sustainability of health systems worldwide.

By adopting a prevention-first, participatory model—co-designed with patients and caregivers—we aim to improve care pathways and transparently report outcomes such as time-to-diagnosis, 30-day readmissions[1], nurse time allocation, and service utilisation, ensuring accountability and continuous improvement.

Opportunity for the European Electronic Components and Systems 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), life sciences, the pharmaceutical industry and the 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, life sciences 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 (including patient diagnostic and monitoring equipment, laboratory instruments, etc.), advanced electronic sensors and photonics, microelectromechanical systems (MEMS), and the production capabilities of the ECS industry: small to large volumes, high quality and competitive cost.

[1] a patient's return to a hospital for any reason within 30 days of being discharged from a previous hospital stay

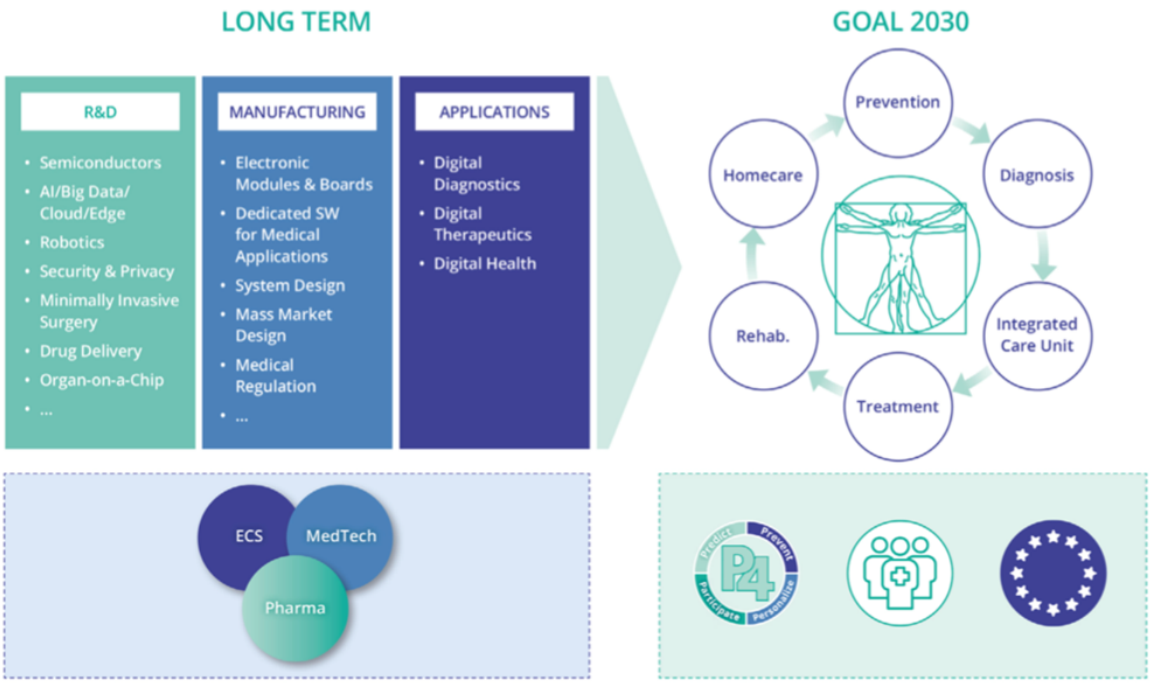

Figure 3.4.2 ECS Industry impact in Healthcare Digital Transformation

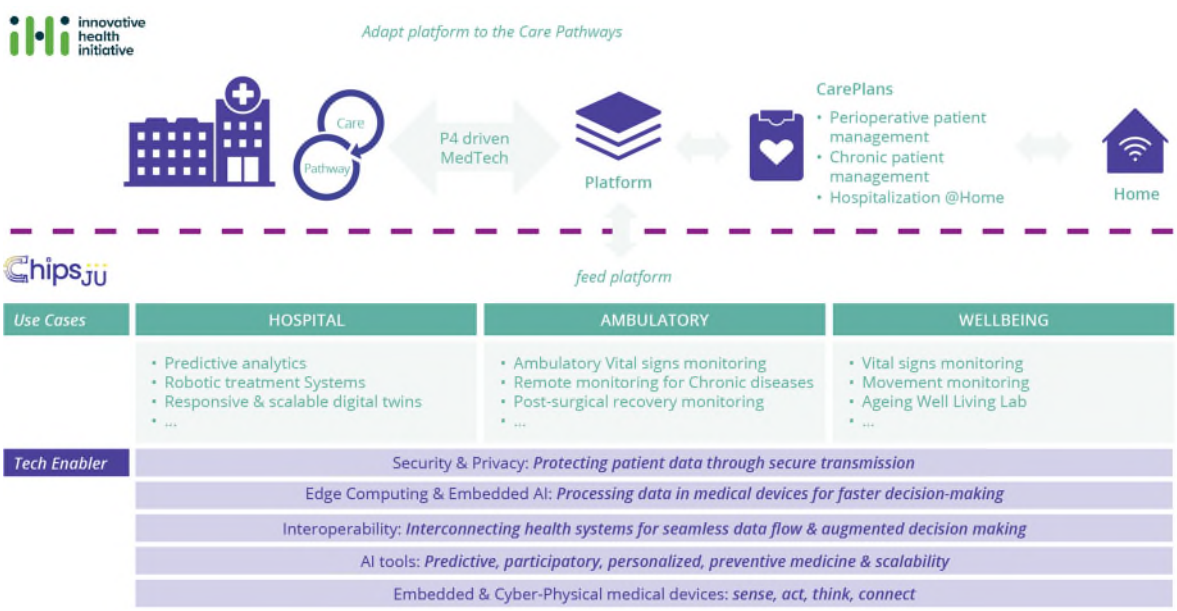

*Figure 3.4.3 Complementary efforts of **ChipsJU** and the **Innovative Health Initiative (IHI)***

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. It is based on aspects like wearable devices, remote patient monitoring, prevention, ageing well and P4 medicine, which together 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. Technical solutions shall also cover the full health value chain, from research and prevention to diagnosis, acute treatment and rehabilitation.

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 healthcare due to differing regulations, ethical considerations and infrastructure requirements.

“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 and towards “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 across different pathologies and use cases and offers broader opportunities for manufacturers than a dedicated medical device for a specific pathology. Another related and important aspect amplifies this “platform effect”. The boundaries between Pharma, MedTech and electronics companies are blurring due to the digitisation of healthcare, e.g., “Healthcare 4.0”. MedTech companies are focusing on the development of advanced wearable devices, implantable sensors, research and diagnostic tools, and connected healthcare solutions to improve patient monitoring, research, 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. In addition, researchers, diagnostic experts and clinicians in academia, hospitals, and pharma are using ECS-based advanced research instruments and data analysis to improve understanding of the scientific causes of illnesses, including at the molecular scale. This is resulting in more effective treatments, from both clinical and cost perspectives, better prevention strategies and, eventually, truly personalised medicine at the physiological level.

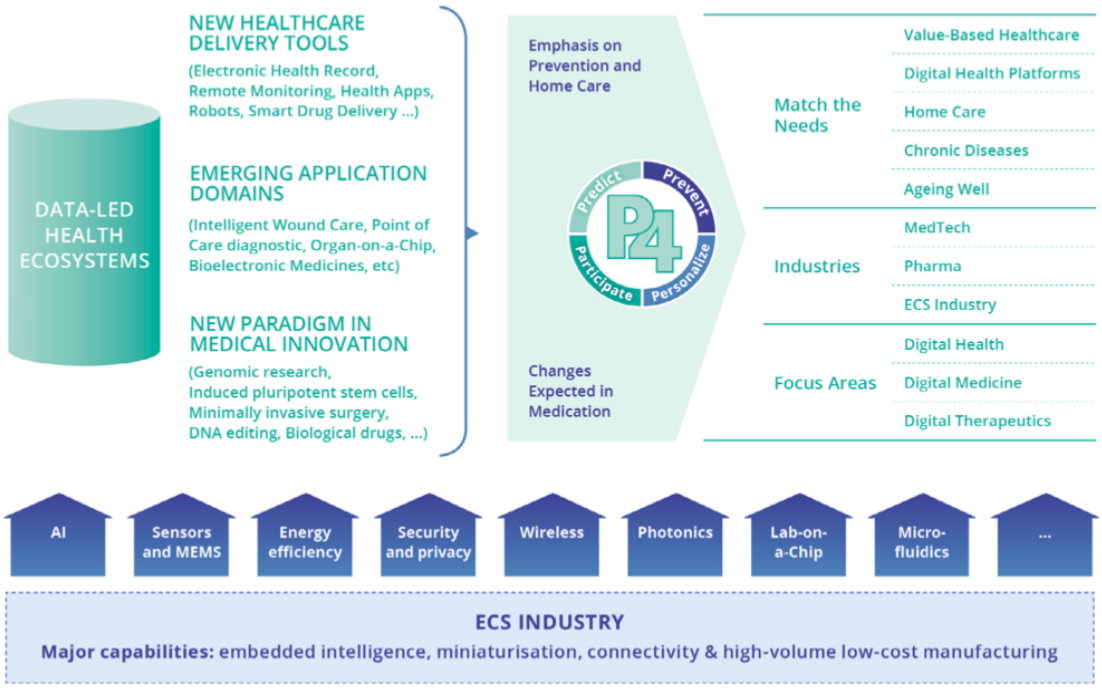

Figure 3.4.4 - Synergies in Data-Powered Health: Unveiling P4 Medicine & Future Use Cases through Industry Convergence (Source: STMicroelectronics)

Second, the consumerisation of medical devices leads to an increased demand for, and wider use of, microelectronic components and systems. The consumerisation of day-to-day health is driven by technology, including the growing involvement of “Big Tech” (Apple, Google, Amazon...), and is most clearly illustrated by wearables (watches, hearables, rings, glasses, …) and consumer apps. This is changing the way “Health Consumers” or even “Patients” expect to interact with healthcare.



Figure 3.4.5 - Healthcare consumerisation: GAFAM's Preponderant Role in Reshaping the Future of Health Tech

Consumerisation is essential for the sustainability of healthcare systems, 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 lagging far behind the consumer domain and needs reinforcement due to its 'under-the-hood' nature and high complexity and specific requirements, further complicated by typically small product volumes. Consequently, many benefits familiar from the consumer domain are missing from healthcare systems.

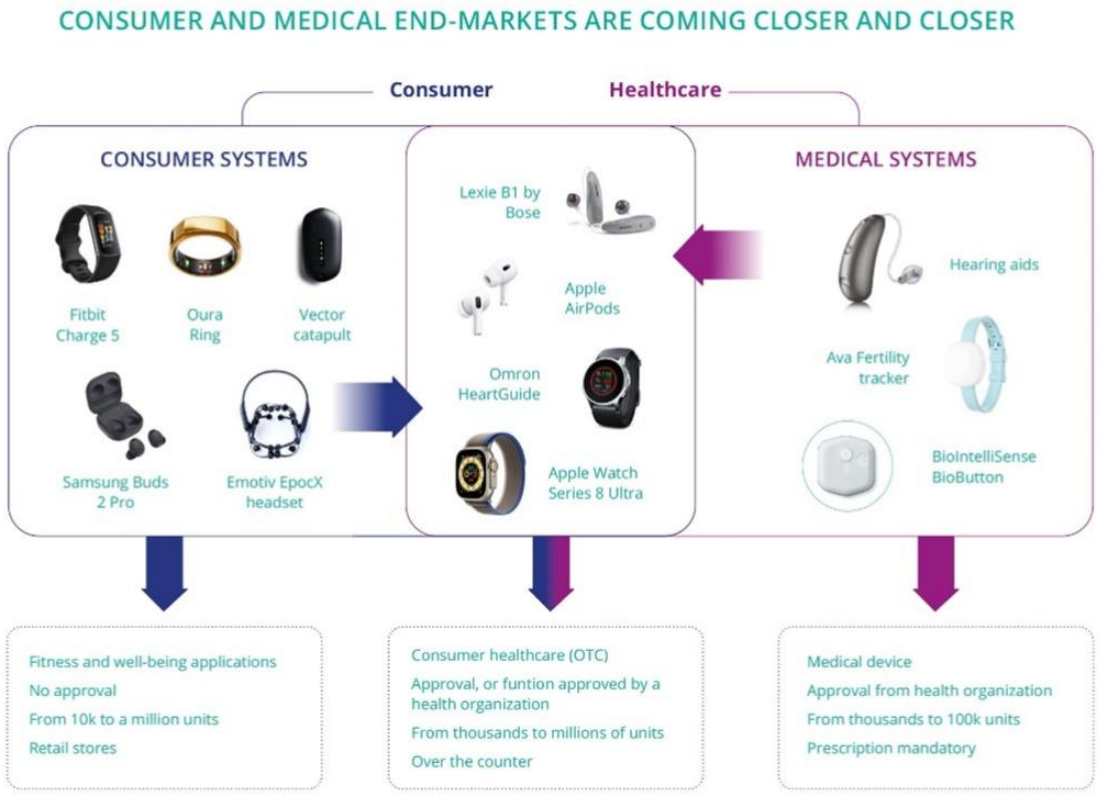

Figure 3.4.6 - The Merging Paths of Consumer and Medical domains (source: Yole Group)

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 (watches, hearables, rings, glasses, …) 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.

Societal trend: The shortage of staff in hospitals, coupled with increasing workflow burdens, poses significant challenges to healthcare delivery and operational efficiency. As hospitals try to deal with this issue, the remaining healthcare professionals find themselves dealing with increased workloads, which often lead to fatigue and burnout. This scenario can compromise the quality of patient care, as clinical staff may struggle to provide adequate attention to each patient, potentially impacting diagnostic accuracy and treatment effectiveness. Moreover, the constant pressure to manage high caseloads contributes to heightened stress levels, adversely affecting the mental health and job satisfaction of healthcare providers. Burnout emerges as a critical concern, leading to high turnover rates that further exacerbate staffing shortages.

These staffing constraints can reduce access to healthcare services, forcing hospitals to limit patient admissions and the scope of services offered. In addition, the burden limits opportunities for staff training and development, diminishing readiness to embrace new practices and technologies. Operational inefficiencies arise as workflow bottlenecks caused by understaffing hamper hospital processes, with delays often stemming from inadequate use of technology or inefficient processes.

Healthcare technology trend: Another important trend in hospital healthcare is the increasing adoption and development of minimally invasive treatment techniques and technologies. This trend is driven by advancements in medical technology, including imaging, robotic-assisted surgery and interventional radiology. These techniques allow surgeons to perform complex procedures through smaller incisions or natural orifices, using specialised instruments and cameras to guide the operation. The following aspects are needed for this:

1. Technological Advancements:
   - Development of imaging systems that enhance visualisation for physicians
   - Introduction of assistive SW/HW tools to ease or automate parts of the clinical procedure workflow
   - Increased use of robotic systems that provide greater precision and control.
   - Utilisation of smart instrumentation and enhanced navigation systems.

2. Broadening Applications:
   - Expansion of minimally invasive procedures into more complex surgeries, including cardiovascular, orthopaedic, neurosurgical, and bariatric procedures.

3. Patient-Centric Focus:
   - Shift towards improving patient outcomes and experiences by reducing recovery times and minimising complications.

Climate change: Electronic devices and digitalisation approaches, which could be deployed in low- and middle-income countries, could contribute to the fight against endemic infectious diseases. Climate change is having a clear negative effect, facilitating the rapid spread of these diseases. Digital solutions that aid in the early and rapid detection of infectious outbreaks and that could be cost-effective and easily mass-produced could help stop the spread of such diseases. Examples of diseases where digital solutions could play an important role include tuberculosis and malaria.

3.4.2.2 Societal benefits

Companies in the MedTech and Pharma industries are transitioning from focusing on individual therapies to providing all-inclusive healthcare solutions and developing 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. For conditions such as dementia, hearing impairment and vision impairment, stigmatisation and isolation can be mitigated, allowing patients to participate more actively in social life.

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 help 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 and appropriate, redesigned payment schemes are currently being addressed to allow the EU to gain a strategic advantage in the digital transformation of healthcare.

Reduced Recovery Time: Patients typically experience shorter hospital stays and faster recovery periods due to less trauma to the body.

Decreased Pain and Scarring: Smaller incisions often result in less postoperative pain and fewer visible scars, improving patient comfort and satisfaction.

Cost-Effectiveness: While the initial setup for minimally invasive technologies can be costly, the overall reduction in hospital stays and complications can reduce healthcare costs over time.

Higher Patient Turnover: Shorter recovery times can lead to increased patient throughput and more efficient use of hospital resources.

Improved Access to Treatment and Healthcare: As technologies become more widespread and affordable, a greater number of patients can benefit from minimally invasive procedures. Also, these technologies improve the efficiency of hospital staff workflows, thereby reducing staffing constraints. This will increase access to healthcare.

Overall, these advancements contribute to improved quality of care and greater efficiency in healthcare delivery, reflecting a positive impact on both individual patient outcomes and societal healthcare resources.

3.4.3 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 P4 healthcare 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.

A multi-stakeholder coalition—bringing together ECS actors, MedTech and Pharma companies, healthcare providers, industry associations, and patient groups—can steer interoperability, evidence generation, and adoption of trusted digital health solutions across Europe.

3.4.3.1 Major Challenge 1: Enable digital health platforms based upon P4 healthcare

3.4.3.1.1 Status

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 technologies, such as the Internet of Medical Things (IoMT), minimally invasive implants, energy-efficient devices, advanced analytics, cognitive computing for advanced clinical decision support, cybersecurity and 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.

3.4.3.1.2 Vision and expected outcome

The P4 healthcare vision is not only about placing doctors and other health professionals at the centre of the care process, but also about including everyone relevant to the health consumer. Although the healthcare ecosystem operates 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 improve quality of life. The MedTech industry is not alone on this journey. New pharmaceuticals and treatments will be developed for personalised medicine settings through the use of advanced research techniques and equipment, embedding connected devices and exploiting the potential of the IoT and AI.

The future of personalised medicine lies at the intersection of biology, engineering, and artificial intelligence. Advanced in vitro platforms—such as Organ-on-a-Chip (OOC) systems and 3D tissue models—are enabling the generation of highly specific, human-relevant biological data. These models replicate patient physiology more accurately than traditional methods, offering a powerful foundation for individualised insights. Layered on top of this, AI-driven multiomics analysis integrates genomic, proteomic, and metabolic data to decode the complex molecular signatures of health and disease. This allows for the identification of precise biomarkers and tailored therapeutic strategies. Looking ahead, predictive disease modelling will transform care from reactive to proactive. By simulating disease progression and treatment outcomes, these models will enable early intervention and long-term health planning. Together, these innovations are not just enhancing diagnostics and treatment—they are redefining medicine as a deeply personal, data-driven discipline.

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.

The P4 healthcare model—predictive, preventive, personalised, and participatory—integrates seamlessly with image-based diagnosis and treatment, enhancing its effectiveness and impact across the healthcare continuum. Here is how each component contributes to image-based medical practices:

Predictive:

- Advanced Imaging Techniques: Predictive healthcare leverages advanced imaging technologies such as MRI, CT scans, and PET scans to identify potential health issues before clinical symptoms arise. These imaging modalities can detect early markers of diseases like cancer or cardiovascular issues, providing crucial information for risk assessment and early intervention.
- AI and Machine Learning Algorithms: Predictive analysis uses AI and machine learning to evaluate imaging data, identifying patterns and forecasting disease progression or treatment outcomes. This approach assists in refining diagnosis accuracy and improving prognostic capabilities.

Preventive:

- Routine Screening and Monitoring: Image-based tools are vital in preventive healthcare, enabling regular screenings to detect abnormalities early. Techniques like mammography and low-dose CT for lung cancer screening exemplify preventive applications, reducing the prevalence of advanced-stage diseases through early detection.
- Integration with Lifestyle and Health Monitoring: Imaging can be combined with data from wearable devices and other health monitoring systems to provide comprehensive assessments, facilitating interventions aimed at disease prevention and health maintenance.

Personalized:

- Tailored Imaging Protocols: Personalised healthcare ensures that imaging protocols are adapted to the individual's specific health risks and needs. This personalisation enhances diagnostic precision and helps devise customised treatment plans that reflect the patient's unique biological makeup.
- Quantitative Imaging: Techniques like radiomics extract large volumes of quantitative data from imaging that can inform personalised treatment plans, such as tailoring radiation therapy doses based on tumour characteristics.

Participatory:

- Patient Engagement through Imaging Data: Participatory healthcare encourages patient involvement in their treatment process, facilitated by easy access to imaging results and reports. Patients can engage more actively in their healthcare decisions when they understand the visual evidence of their health status and disease progression.
- Collaborative Decision-Making: Imaging data fosters a collaborative environment among healthcare providers and patients, allowing for better-informed decisions regarding diagnostic and therapeutic options. Patients can discuss imagery with clinicians, ask questions, and make choices aligned with their preferences and values.

Overall Contribution

By incorporating the paradigms of P4 healthcare, image-based diagnosis and treatment become more effective and patient-centric. Predictive imaging aids early detection and informs preventive strategies, while personalised imaging enhances diagnostic accuracy and treatment customisation. Participatory aspects empower patients to engage with their healthcare journey, leading to improved outcomes and satisfaction. This integration ultimately advances the goal of delivering more precise, proactive, and personalised healthcare services.

3.4.3.1.3 Key focus areas

The addition of AI capabilities – person-centred AI-based consumer devices/embedded AI-based medical devices and systems – to electronic components and systems 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 sensing and action.

This distributed approach significantly reduces both the bandwidth required for data transfer and the processing demands on 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 multilevel 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 – higher-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 network performance and to offer sophisticated and advanced services to the users, due to edge computing and metadata, for instance.

With the growing number of wearables and other battery-operated devices with small form factors, very low power consumption is a major technology challenge for product designers, increasingly complemented by battery-free operation concepts and wireless power transfer.

The transition from a linear to a 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 technologies – through local data processing 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 advanced research, early diagnostics, personalised medicine and potential curative technologies (e.g., regenerative medicine, immunotherapy for cancer). This will increasingly combine imaging, electrophysiology, biochemical sensing, multiomics, including single-cell and spatial omics, and physics- and physiology-informed models to build more robust and clinically relevant digital twins and decision-support systems. In addition to these higher-level capabilities, specific ECS building blocks are increasingly decisive for breakthrough health applications. These include microelectrode arrays (MEAs) and analogue front ends (AFEs) for high-fidelity biosignal acquisition, nanopore sensing and single-molecule electrical biosensing for next-generation molecular analysis, as well as TEER and impedance-on-chip approaches for barrier-function assessment and organ-on-chip monitoring. Together, these components strengthen Europe's position in electrophysiology, bioelectronics, precision diagnostics and translational life-science platforms.

A healthcare edge-to-cloud reference architecture leveraging open APIs to ensure interoperability must embed security- and privacy-by-design principles, while aligning with EU guardrails such as GDPR, the Data Governance Act (DGA), the AI Act, and the Cybersecurity Act to ensure trusted, compliant, and resilient digital health services. For AI-enabled medical devices, this must be complemented by total product lifecycle management, drift monitoring, update governance, and predetermined change control plans.

Home and community care should prioritise sensor-rich, low-power devices with embedded edge machine learning to enable early detection, on-site triage, and safe actuation. Examples include multimodal wearables, continuous glucose monitors, smart inhalers, fall sensors, and closed-loop drug-delivery patches—all designed to operate autonomously and contextually. Edge inference reduces latency, preserves privacy and battery life, and streams standardised events into human digital twins and care-pathway engines for real-time, personalised intervention. Emerging ECS-enabled Bio-IT technologies should also be considered, including speech brain-computer interfaces translating neural activity into intelligible speech, DNA and mRNA writing on-chip with massively parallel synthesis, engineered biological components and living sensors enabled by synthetic biology, and electronic stents integrating sensing, actuation and long-term monitoring. These directions are still emerging, but they illustrate how ECS can move from supporting digital health to actively shaping new therapeutic, diagnostic and bio-manufacturing paradigms.

3.4.3.2 Major Challenge 2: Enable the shift to value-based healthcare, enhancing access to P4 healthcare technologies

3.4.3.2.1 Status

A major trend in healthcare is the transformation of large healthcare systems to an optimised hospital workflow: a shift from general hospitals treating any disease towards integrated practice units that specialise in specific 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.

3.4.3.2.2 Vision and expected outcome

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, caregivers 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 after care is completed. This first involves assessing health status, relying, for instance, on EHRs that support precise communication between different caregivers, PoC diagnostic systems and AI-based clinical decision support. Early diagnosis is key for the successful treatment of both minor and serious medical conditions.

Health outcomes are also related to recovery and the sustainability of health. Readmission rates, levels of discomfort during care, and return to normal activities should be taken into account for both providers and patients. Humanoid robots interpreting human body language and emotions in care delivery, sensors, and companion devices that anticipate and contextualise acute or chronic conditions in EHRs, supported by health models describing patient outcomes in both the short and long term, will have a 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.

3.4.3.2.3 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, minimally invasively inside the body, at the general practitioner's practice or at home – will support the integration of specialised care units. A diverse set of information, including images, patient monitoring and lab results will be combined with other sensor data and biomedical models to obtain precise, quantified information about the person's health condition, providing, for instance, preventive insights and 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 throughout the whole care cycle, from the research phase to post-treatment. Precise quantified and annotated imaging and reconstruction 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, organs, cells and pathways will enable clinical trials and individualised computer simulations used in the research, 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. Full electronic medical records will also enable optimised hospital workflows that increase efficiency and therefore reduce the burden on medical practitioners.

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. Image analysis and semi-automated decision-making, including applications like digital pathology will significantly benefit from underlying AI-based methods.

Magnetic resonance imaging should more explicitly evolve toward a patient-centred imaging service that integrates smoothly with optimised care pathways. From that perspective, the MRI examination should be conceived as a guided interaction rather than a purely technician-led procedure, where cameras and other ambient sensing modalities provide contextual awareness for unobtrusive patient guidance, continuous safety monitoring, and near-real-time adaptation of scan execution. By treating MRI as a workflow-aware and contextually guided service, new MR concepts can better serve integrated practice units and value-based care models while reducing logistical overhead and lifecycle environmental impact.

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, magnetic 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 reduce 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 have a critical impact by shrinking devices and reducing costs, allowing devices to be used in wider fields beyond ophthalmology.
- AI-enabled image analysis: AI algorithms can be employed to analyse medical images, such as X-ray, MRI and CT scans to identify anomalies and patterns with high precision and speed. These AI systems assist radiologists in detecting early signs of diseases like cancer, reducing diagnostic errors, and streamlining the workflow by prioritising cases requiring immediate attention.

- Automatic image segmentation: AI algorithms can automatically delineate structures and regions of interest in medical imaging, significantly reducing time and effort compared to manual segmentation. This enhances the accuracy of measurements and diagnostics in fields such as oncology, where precise tumour boundary identification is crucial for treatment planning.
- Data- and AI-driven applications provide situational awareness during clinical procedures in operating rooms and imaging labs. Such applications are able to understand how a procedure is progressing, recognise key events and anomalies, and anticipate the next steps to be carried out.

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 an emerging and continuously expanding 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 self-monitoring of glucose levels or pregnancy to testing for 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 need for molecular biology expertise to perform a real-time reverse transcription polymerase chain reaction (RT-PCR) test, enabling innovative in vitro diagnostic (IVD) platforms and making decentralisation possible from highly specialised clinical laboratories to any hospital lab and near-patient sites, with dedicated sample prep cartridges, more efficient prevention (referring to the recent Covid-19 pandemic) and prompt personalised diagnosis.

Complementing the strength of Europe in diagnostic imaging, interventional imaging and surgery, and patient monitoring, Europe has a leading ecosystem of research, development and manufacturing of healthcare and life sciences analytical equipment solutions, which depend on underlying ECS hardware and software technologies. These analytical solutions are applied not only in e.g., the hospital or clinical laboratory, but also during academic, clinical and pharmaceutical research to understand the fundamental scientific causes of disease and develop more effective, potentially personalized, treatments.

Healthcare and life sciences analytical solutions are used in workflows spanning sample preparation, physical or chemical analysis, data acquisition and processing, leading to results and analytical or clinical conclusions, including scientific understanding or diagnosis. Accuracy, quality, robustness and speed of workflows are paramount to reduce time to reliable results, enabling quicker, more efficient and cost-effective research and development, or prescription of the most beneficial treatments. Examples include, amongst others, the swift and accurate diagnosis of a disease and prescription of drug therapy (e.g., cancer), or the analysis of a virus and development of vaccines as the virus evolves (e.g. COVID-19).

Healthcare and life sciences analytical solutions utilise a broad range of underlying techniques, including: chromatography, spectroscopy, sequencing, micro-arrays, electron and optical microscopies, multiplex/high-throughput ELISA, bioinformatics, with photonics-based spectroscopic methods such as Raman and infrared spectroscopy deserving explicit attention as key enablers of molecular-level sensing.

When combined with imaging, electrophysiology and biochemical sensing, these spectroscopic approaches can provide the physically grounded observables needed to make digital twins more causally consistent, interpretable and clinically relevant, rather than predominantly statistical constructs.

A stronger multi-scale framing is also warranted, spanning molecular, tissue, organ and whole-body levels. In that perspective, spectroscopy can anchor the molecular layer, while spectroscopic imaging bridges toward tissue and organ scales, and hybrid AI models constrained by optical, spectroscopic and physiological principles can improve robustness, validation and regulatory acceptance of digital twin systems.

In the life-science and research domain, genomics research and DNA writing increasingly depend on genomic-scale infrastructures combining high-throughput sequencing, data acquisition, storage, AI accelerators, high-bandwidth data movement, cloud/HPC/edge computing architectures and specialised bioinformatic pipelines. These infrastructures will also support genomic foundation models and sequence-to-function approaches that are becoming strategic for next-generation personalised medicine and bioengineering.

In addition, digital supply chains, automation, robotics, and next-generation interoperability can drive operations management and back-office efficiencies. Using robotics to automate ancillary hospital

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 can also be used for certain hospital revenue cycle and accounting/finance functions, such as scheduling and claims processing.

This complexity also motivates more autonomous, workflow-aware imaging services, including MRI systems that can support guided, context-aware and patient-centered examination workflows.

Such factors add to the cognitive load of physicians, and case complexity can lead to inefficiencies, increased risk of errors, and challenges in maintaining high-quality patient care. As healthcare demands grow, data and artificial intelligence (AI) emerge as valuable tools to help manage these workflows. By harnessing vast amounts of patient data, AI can offer predictive insights that assist healthcare professionals in making more informed clinical decisions, ensuring that patient care is thorough and timely. AI-driven clinical procedure automation can streamline tasks such as diagnostics, treatment planning and treatment delivery, and reduce the administrative burden on physicians, enabling them to focus more on direct patient care.

3.4.3.3 Major Challenge 3: Support the development of the home as the central location of the patient, building a more integrated care delivery system

3.4.3.3.1 Status

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 diagnosis and treatment in integrated practice units, while supporting recovery and health sustainability at home.

3.4.3.3.2 Vision and expected outcome

The transition to healthcare delivered outside conventional hospitals requires 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, wearables, biosensors, monitoring implants, remote sensing, etc.), also including AI-enabled devices for remote rehabilitation assistance. 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 drug reconstitution process 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 patient groups and for populations, taking heterogeneous data involving history, context, or population information into account.

3.4.3.3.3 Key focus areas

Supporting prevention, diagnosis, aftercare, and rehabilitation with sensors and actuators to ensure efficient medical decision-making, 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 then be 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 (remote and on-body) 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 for both wearables and biosensors.
- Printed electronics technologies 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 (micro-)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-based 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 further developments.

Among the emerging applications of advanced MedTech, “smart wound care” – i.e., the merger of highly miniaturised electronic, magnetic, optical and communications technologies with conventional wound dressing materials – will allow the treatment of chronic wounds of patients in their home without daily nursing intervention and/or constant monitoring of the wound’s status. 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.

3.4.3.4 Major Challenge 4: Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases

3.4.3.4.1 Status

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. The overall demographic change especially in Western and some Asian (Japan) countries will significantly increase the number of patients who suffer from those diseases. It will become impossible to treat all affected people within a hospital environment, simply because of costs and the lack of the required workforce.

3.4.3.4.2 Vision and expected outcome

One of the crucial means of coping with the prevalence of 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 valuable means of engaging patients with chronic diseases 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, IoT, edge AI, etc.) is 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 hold 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.

Personalized regenerative medicine is transforming chronic disease care—from managing symptoms to restoring function. Cell therapies, tissue engineering, and organ regeneration offer tailored healing using a patient's own biology. Patients actively participate in their treatment journey, shaping therapies around their needs and data. In the future, lab-grown organs may replace damaged ones entirely, redefining what recovery means.

3.4.3.4.3 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 systems relies on sensors integrated into beds or chairs. Optical sensing techniques, for instance for remote reflective photoplethysmography, as well as capacitive and radar sensing support this approach. This will be multimodal, with data fusion techniques and smart analytics to combine the data into usable information. The strength of remote sensing relies not only on the quality of the acquired signals, but also on 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. Since Magnetic Resonance Imaging is the gold standard for brain imaging, these new implants are faced with the fact that they need to be MR-conditional. The increasing prevalence and number of implants also has a negative

effect on MR image quality and/or throughput time, hence innovations are required in the power, RF and software/AI domains to mitigate these effects.
- Organ-on-a-chip (OOC) platforms, which lie at the intersection of biology and microfabrication for personalised and safer medicines, are another treatment approach, addressing, for instance, pathologies currently without effective treatment (rare diseases). Rare diseases are often 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.
- New pharmaceuticals are emerging for the treatment of chronic diseases and may have side effects that require regular hospital-based diagnostic imaging. Innovations are needed to optimise the workflow for “companion diagnostics”.
- In the long run, tools for regenerative medicine will enable cell therapies, tissue engineering, organ regeneration and replacement.

For chronic disease diagnosis, 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.

3.4.3.5 Major Challenge 5: Ensure more healthy life years for an ageing population

3.4.3.5.1 Status

In the last two decades, effort has been made to enhance two important objectives of smart living environments for ageing well: on the one hand, avoiding or postponing hospitalisation by optimising patient follow-up at home; on the other hand, enabling a better and faster return home when hospitalisation does occur. The demographic change already introduced in the previous challenge has two effects. Firstly, it increases the number of patients who suffer from age-related diseases, such as dementia as well as hearing & vision impairment. Secondly, it reduces the overall size of the workforce in European countries which brings healthcare systems in their current form close to failure. ECS shall help to overcome this dilemma.

3.4.3.5.2 Vision and expected outcome

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, pulse meter, oximeter, thermometer, weight scales, expanding to sensor hubs for vital signs enabling applications like Electroencephalography (EEG), Electromyography (EMG), Electrooculography (EOG), Electrocardiogram (ECG), galvanic skin response (GSR), blood volume pulse (BVP).
- Proactive speech-centric HMI approaches to enable interactive operation of healthcare-related devices.
- Hospital software interface, the patient’s file, the patient's risk alarm centre with automatic call to healthcare practitioners.

- Audio and 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 the consent of the patient or the patient's family.
- Teleconsultation for nights and weekends at the bedside in a 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 and encourage and enable active participation in social life.
- 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: supporting patients in adopting 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, like speech recognition and synthesis, human-computer interaction is becoming increasingly natural. Consequently, 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 programmes, 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.

In the ageing well domain, exoskeletons and soft exosuits should be addressed more explicitly as a distinct class of assistive and rehabilitative technologies. Coupled with intention recognition, multimodal sensing, embedded AI and adaptive actuation, these systems can support mobility, reduce caregiver burden, improve rehabilitation outcomes and extend independent living for older adults and frail patients.

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%.

3.4.3.5.3 Key focus areas

The ECS industry can significantly scale up 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 the ECS industry’s role in ageing well, taking into account that ageing well is very much related to “ageing in place”:

- Low-power technology for sensors and actuators, microprocessors, data storage and wireless communication modules, etc.
- Miniaturisation technology for sensors and actuators, 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.
- Robotic systems enabling patients to overcome loneliness or mental healthcare issues, complemented with cognitive stimulation by AI-based speech recognition and synthesis enabling augmented HMI for social robots.

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 developed 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; guidance for dialogue between the parties involved in interface specification; minimisation of different interfaces; and minimisation of expenses for interface implementation.

3.4.4 Timeline

The following table illustrates the roadmaps for Health and Wellbeing.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 1: Enable digital health platforms based upon P4 healthcare	Topic 1: establish Europe as a global leader in personalised medicine deployment	Reusable low-power IoMT architectures and edge-AI devices demonstrated with calibrated multimodal sensing, secure updates and clinically evaluated outputs. Standardised OOC/advanced in-vitro readouts and multiomics pipelines validated for defined research questions.	Interoperable disease-specific platforms qualified across sites with prospective clinical evidence, drift monitoring, controlled AI updates and measured energy benefits. Hybrid physiological/multiomics models validated within defined populations and uses.	Federated precision-medicine services qualified across care pathways with maintained evidence, model uncertainty and patient participation; predictive twins remain bounded to validated indications.
Major Challenge 2: Enable the shift to value-based healthcare, enhancing access to P4 healthcare technologies	Topic 2: enable the shift to value-based healthcare	Integrated EHR, imaging, laboratory and PoC workflows demonstrated with interoperable data, clinically validated biomarkers and measured time-to-result. AI-guided imaging and smart minimally invasive instruments evaluated for defined procedures with clinician control.	Cross-provider outcome measurement and decision support qualified for selected care pathways. Workflow-aware imaging, optical/ultrasound guidance and robotic assistance validated for safety, dose/image quality, procedural benefit and staff workload.	Multi-condition care platforms qualified through longitudinal outcomes, resource use and equitable access. Advanced image-guided instruments and hybrid patient models support validated personalised interventions; physical and clinical evidence remain necessary.
Major Challenge 3: Support the development of the home as the central location of the patient, building a more integrated care delivery system	Topic 3: build an integrated care delivery system	Home monitoring and decentralised-trial platforms demonstrated with interoperable PGHD, validated alerts and care-team escalation. Existing drug-delivery devices integrated securely; smart wound/rehabilitation prototypes assessed for clinical benefit, usability and waste.	Cooperative on-body sensing and selected patch/microneedle delivery platforms clinically qualified for defined drugs, doses and users. Remote sensing and rehabilitation integrated with care workflows, tested fallback and long-term signal quality.	Cross-provider home-care ecosystems qualified for selected multi-morbidity pathways with longitudinal outcome evidence, maintained device support and patient/caregiver control; no assumption of autonomous management of every condition.
Major Challenge 4: Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases	Topic 4: enhance access to personalised and participative treatments for chronic and lifestyle-related diseases	Chronic-disease monitoring, adherence and existing implant therapies integrated in validated pathways. OOC and electronic biosensing platforms qualified for defined disease-modelling or drug-response assays, including repeatability and physiological relevance.	Selected miniaturised/wirelessly powered neuromodulators qualified with biocompatibility, power, longevity and MR-conditional evidence. ECS-enabled cell/tissue manufacturing and monitoring platforms validated for specified regenerative-therapy development workflows.	Indication-specific closed-loop implants and patient-derived model services qualified through long-term safety and benefit evidence. ECS supports validated regenerative-treatment production and monitoring; general organ replacement is not assigned a maturity date.
Major Challenge 5: Ensure more healthy life years for an ageing population	Topic 5: ensure more healthy life years for an ageing population	Accessible home-support systems demonstrated with validated fall/health alerts, semantic device interoperability and effective escalation. Rehabilitation robots, soft exosuits and assistive interfaces evaluated with representative older users and caregivers.	Integrated ageing-in-place services and task-specific assistive robots/exosuits clinically qualified with measured independence, workload, safety and sustained usability. Multimodal/neurological interfaces validated for defined assistive purposes rather than general emotion inference.	Longitudinally validated assistive ecosystems adapt to changing abilities across home and care settings with patient control, maintained security and evidence of healthy-life and caregiver benefits.

3.5



ECS Key Application Areas

AGRIFOOD AND NATURAL RESOURCES

3.5 AGRIFOOD AND NATURAL RESOURCES

3.5.1 Scope

Climate change is already affecting ecosystems, societies, and food systems worldwide. Rising temperatures, shifting precipitation patterns, and more frequent extreme events - such as droughts, floods, wildfires, and sea-level rise - are increasingly disrupting agricultural production and natural ecosystems. Impacts vary widely across regions, climates, and farming systems. Climate change is also altering species distributions, including the poleward shift of warm-adapted species and the decline of those dependent on cooler conditions, thereby disrupting ecological interactions, biodiversity, and ecosystem functioning in both terrestrial and marine environments.

Agriculture is both highly vulnerable to climate change and a significant contributor to it. Changes in temperature, rainfall, water availability, and extreme events directly affect crop yields, soil health, livestock productivity, pest and disease dynamics, and overall system stability. At the same time, agriculture is a major source of greenhouse gas (GHG) emissions, including methane (CH_4) from livestock, nitrous oxide (N_2O) from fertiliser and manure management, and carbon dioxide (CO_2) from land-use change and deforestation.

This dual role underscores the need to transform food production systems to be more productive, resilient, and environmentally sustainable. Climate-Smart Agriculture (CSA) offers a framework for this transition by improving productivity and resilience while reducing emissions and enhancing carbon sequestration. Agroforestry and other ecosystem-based approaches complement technological solutions by improving soil structure, supporting biodiversity, enhancing water retention, and increasing carbon storage.

Climate change is only one of several pressures on agriculture and food systems. Population growth, dietary shifts, competition for land and water, biodiversity loss, resource scarcity, geopolitical instability, market volatility, and health risks all add further strain. Food systems must therefore evolve towards a better balance of productivity, quality, resilience, and environmental sustainability. This requires action across the entire value chain - from production to processing, distribution, and consumption - including reducing food loss and waste, improving resource efficiency, and shifting consumption patterns.

Digitalisation can play a central role in this transformation, but agriculture poses specific challenges. Farming systems are highly heterogeneous and dynamic, with strong spatial and temporal variation in climate, soils, crops, livestock, and management practices. Digital solutions must therefore be adaptable, accessible, and usable across diverse contexts and skill levels. Adequate infrastructure, connectivity, training, technical support, and maintenance are essential to ensure that digital tools deliver value rather than added complexity.

Smart Internet of Things (IoT) systems enable continuous reliable monitoring of agricultural and environmental conditions, including soil, crops, weather, water, livestock, fisheries, aquaculture, forests, and air quality. Integrated with automation and intelligent control, IoT can improve the efficiency of water, fertiliser, feed, energy, and other inputs; enable earlier detection of pests, diseases, and environmental risks; strengthen traceability and supply-chain management; and improve greenhouse gas (GHG) monitoring and reporting. These systems can support higher productivity, resource efficiency, resilience, and sustainability across agriculture, livestock, aquaculture, fisheries, and forestry.

Artificial Intelligence (AI), particularly Machine Learning (ML), enables the transformation of large datasets into actionable insights. AI can identify patterns and anomalies, forecast risks and outcomes, optimise operations, and provide location- and context-specific recommendations. Foundation models and Large Language Models (LLMs) can expand access to agricultural knowledge, decision support, and advisory services, provided they are grounded in accurate, timely, and locally relevant data. AI should augment, not replace, human decision-making, and humans must remain accountable for those decisions.

Physical AI and embodied AI extend these capabilities into the physical environment. They enable robots, autonomous machines, drones, and other cyber-physical systems to perceive conditions, make decisions, learn, and act.

Geospatial Artificial Intelligence (GeoAI) integrates AI with Geographic Information Systems (GIS) and Earth observation. This combination is especially relevant for agriculture due to its strong spatial and temporal dynamics.

GeoAI fuses data from satellites, drones, GNSS/GPS, weather stations, and field sensors to enable high-resolution monitoring and decision-making. Applications include crop health assessment, irrigation and fertiliser optimisation, pest and disease detection, yield prediction, land-use monitoring, and harvest planning. Multispectral Earth observation data further enhance precision agriculture by providing timely information on vegetation and crop conditions.

The integration of IoT, AI, and GeoAI enables a new generation of adaptive agricultural systems. Instead of relying on static datasets or fixed recommendations, these systems continuously integrate multi-source data and adjust guidance to evolving conditions. This improves input efficiency, reduces environmental impacts, and strengthens resilience.

Digital technologies also support broader food systems goals. Traceability and data sharing improve transparency and supply-chain coordination, while concepts such as the Digital Product Passport enable circular-economy approaches. Robotics and drones further enhance precision operations, monitoring, and targeted interventions, reducing chemical use and improving efficiency.

Five Major Challenges are identified in this Chapter. The first challenge concerns livestock and crop health, particularly early detection and management of pests, diseases, and other threats. IoT, sensors, AI, robotics, and drones enable early warning, targeted interventions, and reduced reliance on pesticides and veterinary medicines. The second challenge concerns farming systems and supply-chain assurance. Smart systems improve traceability, logistics, and resource management across the food chain. Secure, reliable data infrastructures are essential to support trust and collaboration among stakeholders. The third challenge concerns soil health, air quality, and environmental protection. Integrated monitoring supports continuous assessment of soil and environmental conditions and more efficient resource use. Reducing reliance on synthetic fertilisers is a key priority, as excessive use contributes to soil degradation, water pollution, and GHG emissions. Precision application and data-driven management help optimise nutrient use and reduce impacts. The fourth challenge concerns water management and access to clean water. Agriculture is a major freshwater user and increasingly affected by scarcity and variability. Smart systems support efficient irrigation, water-quality monitoring, and the reuse of wastewater, rainwater, and other sources, contributing to more circular and resilient water management. The fifth challenge concerns biodiversity and ecosystem resilience. Agricultural, aquaculture, fisheries, and forestry systems depend on healthy ecosystems. Digital monitoring supports assessment of habitat and species changes and informs conservation and

restoration efforts. Electronic components and systems (ECS) enable distributed sensing, remote monitoring, and intelligent management to support ecosystem preservation.

All five Major Challenges in this Chapter align with key Horizon Europe missions, as well as the European Green Deal and Digital Europe. However, Europe faces a growing challenge as immediate priorities such as defence, energy security, and supply chain resilience increasingly compete with the urgent need to address climate change and environmental degradation.

To efficiently address these challenges, Europe needs a new generation of electronic components and systems that prioritises sustainability and resilience, supported by advances across sensing, electronics, photonics, communications, materials, manufacturing, AI, robotics, energy systems, Earth observation and geospatial technologies. These must be supported by infrastructure, interoperability, cybersecurity, skills, and user-centred design to ensure effective adoption. This vision calls for widespread adoption of ultra-efficient Edge AI, advanced chiplet-based architectures, low-power computing, and local decision-making systems that minimise energy consumption and reduce reliance on cloud infrastructure. Data should be processed locally, translated into immediate actions, and discarded when no longer needed, creating a more resource-efficient digital ecosystem. Achieving this transformation will require updated safety standards, stronger collaboration across industries, and policy measures that stimulate demand for sustainable technologies. By aligning technological innovation with environmental objectives, Europe can strengthen its sovereignty while safeguarding the natural systems on which society and economic prosperity depend.

The Electronic Components and Systems (ECS) community plays a key role in this transition. Advances in sensing, connectivity, edge computing, AI, robotics, drones, photonics, energy-efficient electronics, and geospatial technologies provide the foundation for next-generation smart agriculture. Their integration enables more precise, productive, resilient, and low-carbon food systems while protecting natural resources and biodiversity. Table 5.3.1 presents the ECS crosscutting technologies used in the five Challenges mentioned above.

Table 3.5.1: ECS crosscutting technologies vs Application across Challenges

ECS Technology Layer	Application Across Challenges
Advanced sensing	Soil, water, air, crops, livestock, food, biodiversity
Photonics & hyperspectral sensing	Crop/food/environmental monitoring
Quantum sensing	Soil, water, GHG and environmental measurements
IoT/IIoT	Distributed monitoring and control
Edge AI	Real-time local decision-making
Cloud/HPC AI	Large scale modelling and optimisation
Foundation models / GenAI	Advisory, knowledge access, decision support
GeoAI	Satellite/drone/field-data fusion
Digital Twins	Farms, crops, livestock, food chains, water and ecosystems
Robotics / Physical AI	Agriculture, food processing, forestry, aquaculture
Autonomous systems	Monitoring, intervention and logistics
Connectivity	Rural IoT, satellite, 5G/6G, NTN
Cybersecurity	Connected farm/food/environment infrastructure
Interoperability	Data spaces and cross-vendor systems
Energy harvesting	Autonomous remote sensors
Sustainable electronics	Biodegradable/low-impact field sensors
Data governance	Data spaces, sovereignty, sharing and reuse
MRV (Measurement, Reporting and Verification) technologies	Carbon, biodiversity, water and environmental compliance

3.5.2 Application trends and societal benefits

External requirements

According to the UN[1,2], if the global population reaches an expected 9.8 billion by 2050, the equivalent of almost three Earths 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 increasingly demanding and sophisticated diets, while net-zero emissions are simultaneously required. At the same time, productivity is being severely affected by climate change, particularly in regions where food scarcity and inefficient resource management are most prevalent. The necessary acceleration in productivity growth is being hampered by the degradation of natural resources and soil, the decline of biodiversity, and the spread of transboundary pests and diseases of plants and animals, some of which are already becoming resistant to antimicrobials[3].

Investments in changing agricultural practices and incorporating technological innovation have contributed to increased productivity, but yield growth is far from sufficient. A more holistic and innovative approach is therefore needed to reduce pressure on natural resources and improve their quality, while simultaneously increasing food productivity. At the same time, food losses and waste account for a significant proportion of agricultural output, while inadequate management of bio-waste and packaging contributes to environmental pollution.

Addressing key challenges related to food security and sustainable production would reduce the need for further production increases while improving the natural resource base. For instance, reducing greenhouse gas (GHG) emissions is a priority because of their significant contribution to climate change. Three major sources (land-use change, enteric fermentation and energy use together) account for almost 74% of total GHG emissions. Other priorities include mitigating the effects of natural and human-induced pressures on water bodies by reducing pollution from plastic contamination, eutrophication, acidification, and warming as much as possible.

Less than 2.5% of the world's water is fresh[4], and water pollution in rivers and lakes is occurring faster than natural systems can recycle and purify water. Currently, more than 2 billion people live with the risk of reduced access to freshwater resources[5], and by 2050 at least one in four people is likely to live in a country affected by chronic or recurring freshwater shortages. Today, 2.6 billion people are economically dependent on agriculture[6] 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 due to increasing concentrations of particulate matter and the release of GHGs, all of which have detrimental effects on human health[7] and climate.

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[1] Microsoft Word - Key Findings WPP 2017_Final EMBARGOED (un.org), https://population.un.org/wpp/
[2] FAO GLOBEFISH 2025
Claude E. Boyd, What is biodiversity and its relevance to aquaculture certification?
https://www.aquaculturealliance.org/advocate/biodiversity-relevance-aquaculture-certification/
[3] 2017 FAO. 2017. The future of food and agriculture – Trends and challenges. Rome
[4] All about water, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull53-1/53105911720.pdf
[5] UN 2019 The Sustainable Development Goals Report 2019: Goal 6: Clean water and sanitation / https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf
[6] ibid: Goal 15
[7] https://www.eea.europa.eu/themes/air/health-impacts-of-air-pollution

Today, farmers still apply more fertiliser than is required on their fields. Consequently, excess nutrients such as nitrates and phosphates accumulate in the soil and leach into groundwater with significant impacts on the environment and public health. There is therefore increasing pressure on the agriculture sector to find decarbonised and sustainable solutions to reduce environmental pollution associated with fertilisation, pesticides, livestock, and energy use.

Smart production processes and intelligent logistics systems across the entire supply chain are among the solutions that can optimise resource use and reduce emissions while increasing productivity and ensuring safe food production. This is particularly important given that almost one in ten people falls ill every year due to food-borne diseases.

The COVID-19 pandemic demonstrated the vulnerability of the overall agri-food supply chain when disrupted by employee illness or travel restrictions imposed during lockdowns. While these circumstances were unprecedented in scale, they highlight vulnerabilities that are relevant to any future pandemic that could emerge globally, cross international borders and affect large populations.

New epidemiological methods that utilise dynamic network analysis[8] to identify and analyse the key drivers of emerging pathogen transmission and movement are therefore needed. In the agrifood sector, this is particularly important because its different elements are closely interconnected. From seeds and plants to livestock management and crop production, and through to post-harvest processing and transportation, each stage of the value chain can represent a potential point of risk for the introduction and spread of pathogens and mycotoxins, including during food storage.

Effective surveillance strategies are essential to support agrifood health programmes, prevent and manage crises, strengthen biosecurity, and contribute to the decarbonisation of agriculture. Here also, ECS technologies and solutions can make an important contribution by enabling improved monitoring, sensing, data collection, connectivity, and decision-making across the agri-food value chain.

Figure 3.5.1 establishes the strategic logic: Global pressures → ECS-enabled transformation → system outcomes & societal benefits. It brings together climate change, resource/water scarcity, biodiversity and soil degradation, pests/diseases, and food loss/waste on the left, then shows the principal ECS capabilities in the centre: Sensing & monitoring, Connectivity & IoT, AI, data analytics & digital, Automation & robotics, Traceability & decision support and finally the desired outcomes on the right.



Figure 3.5.1 - From global pressures to resilient and sustainable agrifood systems. Image generated by ChatGPT on request.

[8] The persistent threat of emerging plant disease pandemics to global food security at https://doi.org/10.1073/pnas.2022239118

Figure 3.5.2 shows ECS-enabled agrifood and natural resources value-chain: Seeds/inputs → production → forestry/aquaculture/fisheries → harvesting/processing → logistics/storage → food/water/resource use → waste/recovery/circularity with the ECS capability layer cutting across the entire chain.



*Figure 3.5.2 - **ECS-enabled agrifood and nature-resource value chain. Image generated by ChatGPT on request.***

Societal Benefits

In response to the growing range of challenges facing the world, the UN defined 17 Sustainable Development Goals (SDGs) as a blueprint for achieving a better and more sustainable future for all. The implementation of the SDGs (particularly SDGs 2, 6, 12 and 15) is highly relevant to addressing global challenges related to food security, the protection of biodiversity and natural resources and action on climate change. The SDGs also address socioeconomic challenges, including the elimination of poverty and hunger, the reduction of inequality, and the promotion of responsible consumption and production, sustainable prosperity, peace and justice.

In Europe, national and EU policies including "**From Farm to Fork"**[9] and "Biodiversity Strategy 2030" reflect and reinforce these underlying SDG objectives through a range of measures, from regulatory frameworks to incentives and investments supporting research, development, and deployment. These policies promote holistic and innovative approaches based on circular economy, agroecology, agroforestry, climate-smart and sustainable agriculture, the bioeconomy, and the Blue Economy.

3.5.3 Major Challenges

The agrifood and natural resources sector is undergoing a profound transformation driven by climate change, resource constraints, biodiversity loss, evolving food-safety risks, digitalisation, artificial intelligence, automation and increasing expectations for resilient, sustainable and trusted food systems.

The European research and innovation landscape is also moving towards a more integrated approach linking agriculture, food, water, biodiversity, climate, circularity and health. The European

[9] https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf

Commission's 2026 strategic approach through AgRI 2040[10] and Food 2040[11] brings together soils and agri-ecosystems, cropping and livestock systems, bioeconomy, multifunctional forests, agri-food value chains, digitalisation, artificial intelligence and robotics, while also addressing food safety, resource efficiency, resilience and aquatic food systems.

The following five Major Challenges of the existing SRIA remain relevant. Their scope and associated technical topics are updated below to reflect current European research and innovation priorities and the increasing need to integrate sensing, artificial intelligence, digital twins, robotics, autonomous systems, cybersecurity, interoperability and *Measurement, Reporting and Verification* (MRV).

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 and Resilient Food Production Systems.
- **Major Challenge 2**: Food Safety, One Health and Trusted Food Chains.
- **Major Challenge 3**: Climate-Smart, Nature-Positive and Circular Production.
- **Major Challenge 4**: Water Resilience, Quality, and Circular Management.
- **Major Challenge 5**: Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems.

[10] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN
[11] AgRI 2040 – Strategic approach - Agriculture and rural development at https://agriculture.ec.europe.eu

3.5.3.1 Major Challenge 1: Food Security and Resilient Food Production Systems

Food security[12] and food safety[13] are two complementary and mutually reinforcing dimensions of sustainable agrifood systems. Food security refers to the physical, social, and economic access to sufficient, safe, and nutritious food, while food safety concerns the prevention and control of biological, chemical and physical hazards that may compromise food quality and human health.

Figure 3.5.3[14] illustrates the interrelationship between food security and food safety and highlights their principal constituent elements. From an ECS perspective, ensuring both food security and food safety is essential for achieving resilient, sustainable and trustworthy food systems capable of addressing current and future societal challenges.



Figure 3.5.3 - interrelationship between food security and food safety

Food security increasingly depends not only on production capacity, but also on resilience, adaptability, and resource efficiency. Climate variability, extreme weather, soil degradation, water scarcity, changing pest and disease pressures, labour constraints and supply-chain volatility require production systems capable of adapting dynamically to changing conditions.

[12] Food 2040 – Research and innovation -European Commission at https://research-and-innovation.ec.europe.eu

[13] Food security has been defined by the FAO as "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life"

[14] Food safety is an umbrella term that encompasses many facets of handling, preparation, and storage of food to prevent illness and injury. Included under the umbrella are chemical, microphysical, and microbiological aspects of food safety

3.5.3.1.1 Status, vision and selected outcome

Consolidated advances in Industrial Internet of Things (IIoT) and Artificial Intelligence (AI) have already begun to shape smart manufacturing in the food and beverage[15] industries. Access to relevant and role-based information, in real-time or near real-time, is key to ensuring efficient AI/ML (Machine Learning) data storage and processing and the appropriate use of these data for optimised decision-making at all levels of next-generation automation and robotic systems, such as cyber-physical systems (CPS). Therefore, sustainable production, safety and quality depend not only on the product itself, but also on the respective processes and their control, through the collection and monitoring of key data, smart autonomous sensing, data analysis based on AI/ML models to perform diagnostics and predictive maintenance, and their use in 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, ensuring 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 core element of quality assurance in the agrifood sector.

3.5.3.1.2 Key focus areas

In particular, smart sensing has recently benefited from the emergence of low-cost, low-power, self-powered solutions, making it possible not only to remotely monitor crops (satellites, drones, robots using multi-spectral cameras), but also to install sensors, including quantum sensors and advanced photonics, within crops and plants, to receive the data needed directly from the site to understand the health status of plants and soil. A LinkedIn post from World Economic Forum identified Plant Wearable Sensors as one of the five technologies about to change the world[16], and as one of the key solutions to increase food production by 70% by 2050 to feed the world population.

Following the trend in manufacturing industries, AI and digital twins[17] are the next steps for the food industry and farming systems. In short, AI plays a growing role in the production of food and beverages. For instance, in some key applications[18], [19], [20]: Optimisation of production processes, Quality control, Demand Forecasting, Food safety, and Product personalisation. These technologies help to make the production chain more sustainable, efficient, and responsive to market needs. Digital twins allow digital/virtual representations (models) of physical objects and processes, coupled with behaviour models that enable simulation and prediction of changes to variables associated with the objects or the surrounding conditions. Digital twins are remotely connected in real time 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 pest infestation to simulate the effects 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 determine

[15] Adapted from FAO definitions of food security and food safety.
[16] Beverage will be considered as food in the rest of the document.
[17] https://www.linkedin.com/posts/world-economic-forum_wef24-ugcPost-7149142642344296448-lxGR/?utm_source=share&utm_medium=member_ios
[18] https://www.sciencedirect.com/science/article/pii/S0308521X20309070
[19] McKinsey & Company: « Artificial Intelligence: The next Frontier for Food and Beverage Industry ». (2021)
[20] Trends in Food Science & Technology: « Applications of Artificial Intelligence in Food Processing and Quality Control ». (2020)

the optimal treatment (and timely application) against the infestation in order to minimise both the impact on productivity and the environmental footprint of the treatment. Essentially, digital twins will become the ultimate decision-making optimisation tools by integrating production process variables and market and consumer 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.

These technologies contribute to sustainability by enhancing resource management, environmental protection, and food security.

3.5.3.1.3 Intelligent, adaptive and autonomous food production

Key technology requirements include:

- In-line inspection and automation: Networked packaging, robotics, and smart workflow systems to monitor and optimise all processes
- Quality control: AI-driven computer vision and smart sensors to detect defects and enable predictive maintenance, reducing costly downtime.
- Food safety: Smart bio-sensing and AI monitoring to reduce water and chemical use and prevent contamination.
- Production optimisation: AI/ML and big data models for smarter decision-making, waste reduction, and edge AI deployment for energy efficiency.
- Demand forecasting: AI analysis of past sales and market trends to reduce waste.
- Product personalisation: IIoT and digital twins tailor products to evolving consumer diets.
- Smart expert systems: Integration of IIoT with Large Language Models for next-generation advisory tools.
- AI-based monitoring: For prediction and decision support for crops and livestock.
- Multimodal sensing combining environmental, biological, imaging, and operational data.
- Edge AI and distributed intelligence for real-time agricultural applications.
- Predictive modelling of crop growth, yield, pests, diseases, and resource requirements.
- Digital twins of farms, production units, and agricultural processes.
- Integration of satellite, drone, proximal, and in-situ sensing.
- Trustworthy and explainable AI for agricultural decision support.
- AI-enabled optimisation of water, nutrients, energy and other inputs.
- Continuous MRV of production, environmental performance, and resource use.

3.5.3.1.4 Re-designing Farming Systems

Autonomous and robotic farming systems

Advanced machines, collaborative robots, and edge AI platforms are essential for cost-effective land and livestock management:

- Autonomous agricultural vehicles and machinery.
- Autonomous navigation, localisation and safe operation in changing outdoor environments.
- Energy-efficient autonomous systems and low-power sensing.
- ***Robotic systems****:* Autonomous or swarm robotics and coordinated fleets for harvesting, weeding, spraying, pest inspection and control, crop monitoring and pruning, replacing declining manual labour with adaptive, multifunctional, edge-AI systems through Physical AI and AI-enabled robotic decision-making. Collaborative robots and human–robot interaction.
- ***Drones:*** UAVs for large-area monitoring using intelligent computer vision and precision application of phytosanitary products.
- ***Satellites:*** Field-level data with improved resolution; small satellites can extend IoT connectivity in areas lacking internet coverage.
- ***Wearable technologies:*** Smartwatches, smart glasses, sensor vests, and GPS devices to improve operator safety, productivity, and communication.
- ***Real-time edge AI platforms:*** Multi-sensor architectures measuring soil pH, salinity, moisture, and nutrient levels, combined with machine vision and hyperspectral imaging for crop health monitoring and automated interventions.
- ***Augmented Reality (AR):*** Applications for crop monitoring, farmer training, equipment maintenance, and precision agriculture.
- ***Cybersecurity:*** Strong encryption, multi-factor authentication, IDS/IPS systems, GDPR compliance, and staff training to protect ECS infrastructure and sensitive agricultural data.
- **F*arming as a Service (FaaS):*** Digital solutions delivered via cooperatives or specialist providers, enabling small and medium farms (the majority in Europe) to access precision agriculture tools, sensors, drones, and AI advisory services affordably.
- ***Interoperability is critical****:* standards such as AgMES, ISO 15926, SO 10303 (STEP), DEMETER, AIM model, IEEE 1451 must be adopted to ensure consistent data exchange across devices and systems.

Digital agricultural infrastructure and inclusive adoption

Novel and well-adapted agricultural infrastructures are essential to support the ECS technologies. These infrastructures should consider the following aspects:

- Interoperable agricultural data spaces and platforms.
- Secure sharing and use of data generated by agricultural machinery, sensors and IoT devices.
- Connectivity for rural and remote environments.
- Edge/cloud computing architectures.
- Standardised data models and semantic interoperability.
- Cybersecurity and resilience of connected agricultural systems.
- Affordable, modular, and energy-efficient technologies.
- Human-centred interfaces and technology adoption.

Combining the technologies cited above with these data sources can enrich knowledge and help address other field issues.

3.5.3.1.5 Climate-resilient and resource-efficient production

Considering climate change and its substantial impact on agriculture, the following considerations should be taken into account to ensure a more climate-resilient agricultural system and more resource-efficient production practices:

- Precision management of water, nutrients, energy, and agricultural inputs.
- Early warning and adaptation to drought, heat, floods, and extreme weather.
- Climate-resilient crops and production systems.
- Soil–plant–atmosphere monitoring.
- Optimisation of irrigation and fertilisation.
- Carbon farming and monitoring of soil carbon.
- Integration of agronomic, environmental, and climatic data.
- Resilience assessment and predictive modelling of agricultural systems.

3.5.3.1.6 Horticulture/greenhouses, urban and vertical indoor agriculture, and agrovoltaics

Horticulture/greenhouses, urban and vertical indoor agriculture

Urban and vertical indoor farming - often using hydroponics - offer sustainable, resource-efficient food production.

Key development needs include:

- Low-cost nutrient sensors,
- Precision harvesting robots
- Edge AI-based autonomous cultivation systems using digital twin plant models.

Agrovoltaics

Combining solar panels with agriculture can increase yields, reduce water use, generate additional farm revenue, and support energy independence for small-scale farmers.

Key development needs include:

- Panel shading.
- Integrated environment sensors.
- Real-time edge AI irrigation systems improve both crop and livestock productivity.

3.5.3.2 Major Challenge 2: Food Safety, One Health and Trusted Food Chains

3.5.3.2.1 Status, vision and selected outcome

Application of high-tech sensors and real-time edge AI platforms to monitor, quantify and understand individual plants and animals, as well as their variability, is key to ensuring food safety in novel next-generation ecology-based agricultural systems. Smart sensors and edge AI 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 robotic manipulation and operation in ecology-based systems pose a huge challenge in environments that are only partially defined and structured. Furthermore, detection in the supply chain and "at the fork" should also be considered. This implies low-cost and power-autonomous compact sensors, real-time edge AI computing platforms connected to information processing systems used in the food supply chain and by consumers, that enable, for instance, freshness and food-safety assessment for meat and vegetables (which could be integrated into smartphones).

Food safety must increasingly be addressed across the complete food chain and within a One Health framework. Climate change, globalisation, emerging biological and chemical hazards, antimicrobial resistance (AMR), supply-chain complexity, and new production technologies create new requirements for monitoring and prevention.

3.5.3.2.2 Plant health, Crop Quality and Emerging Biological threats

Crop quality and health depend on timely detection of pests, diseases, and environmental stress. Smart sensors, real-time monitoring, and AI decision-support tools can help farmers track soil and plant conditions, improve spraying precision, and support more efficient crop management.

Key development needs include:

- ***Integrated pest management (IPM):***
    - Portable diagnostics, georeferenced disease alerts, and IoT/edge AI traps for rapid detection and risk forecasting.
    - Plant wearables and in-plant sensing for early detection of plant stress, diseases and pests.
    - AI-assisted image-based diagnosis.
    - Hyperspectral and multispectral crop-health monitoring.
    - Detection of invasive species and emerging biological threats.
    - Pathogen and pest surveillance.
    - Precision application of plant-protection measures.
    - Monitoring of pesticide residues and contaminants.
    - Predictive models for crop-health risks.
- ***Agroecology and pesticide reduction to move from conventional to organic, regenerative agriculture***
    - Herbicide-free robotic weeding with precise vision and edge AI.
    - Power-efficient quantum and advanced photonic sensors for soil/plant metrics (e.g., pH, NO_3, EC, moisture, CO_2, leaf wetness, pathogens), with miniaturised, low-cost, biodegradable designs to prevent e-waste in fields.
    - Integrated AI decision-support to simplify management, cut inputs, and improve quality.
    - Precision approaches to concentrate effort on the most productive areas while restoring marginal land.
    - Service models (deployment, maintenance, training) to scale adoption.

- ***Plant precision breeding and phenotyping:***
    - Tools supporting genomics, gene editing, and DNA-informed breeding.
    - High-throughput sensing of growth, architecture, and composition under variable biotic/abiotic conditions, including plant–microbiome interactions, to drive the 4R nutrient strategy.

3.5.3.2.3 Animal Health, Welfare and Antimicrobial Resistance

Livestock health is central to food safety because animal diseases can spread quickly and create economic and public health risks. Better sensing, behavioural monitoring, and early-detection systems can reduce antibiotic use, improve animal welfare, and lower the chance of contamination in the environment and food chain.

- ***Continuous animal-health monitoring for early disease detection and welfare***: Wearables and ambient sensors use non-invasive sensing to track behaviour, temperature, transport stress and welfare; biosensors and AI-assisted technologies enable rapid diagnostic capabilities and real-time welfare insights, thereby ***reducing*** antibiotic usage.
- ***Precision livestock farming.***
- ***AMR surveillance and reduction.***
- ***Integration of veterinary, environmental, and food-chain data.***
- ***Microbiome-based risk mitigation:*** Beneficial microbes for soil and feed enhance nutrition, block pathogens, and support animal health.
- ***Emissions monitoring:***
    - Methane measurement (breath/rumen) and verification to target rapid climate gains.
    - Nitrogen emissions tracking (NH_3, N_2O, NO_3) with smart sensors for environmental and public health protection.
- ***Farmer-centric design for One Health integration:*** Ensure tools fit workflows, improve economic sustainability, and support informed decisions on prevention, treatment, and breeding.

3.5.3.2.4 Food Safety Sensing and Rapid Diagnostics

Food safety also depends on transport and storage conditions, especially for perishable products. Smart logistics systems can monitor temperature, moisture, and other variables in real time, helping reduce losses and maintain product quality from farm to consumer.

- ***Intelligent logistics***:
    - Real-time sensing of temperature, moisture, gases, and atmosphere to preserve quality and cut losses.
    - Predictive quality models combining sensor data and AI for routing and storage decisions.
    - Route and warehouse optimisation; AR for training, transparency, and customer experience.

- ***Systems must be reliable, contaminant-free, secure, interoperable, and power-efficient, with options like contactless powering in tanks.*** They should include the following technological aspects:
    - Rapid, portable, and in-line food-safety sensors.
    - Biosensors and advanced analytical technologies.
    - Detection of biological, chemical, and physical contaminants.
    - Emerging contaminants, mycotoxins, allergens, and residues.
    - Pathogen detection and identification.
    - Genomic and metagenomic approaches.
    - AI-assisted interpretation of analytical data.
    - Real-time and near-real-time monitoring.

3.5.3.2.5 End-to-end traceability and trusted food chains

Traceability is essential for consumer confidence, regulatory compliance, and fraud prevention. Digital tools, including smart tags and blockchain-enabled systems, can record product origin, movement, and handling so that food information is more transparent and reliable.

- Comprehensive origin and process transparency across fragmented global chains to meet regulation, protect brands, and satisfy consumer expectations.
- Distributed Ledger Technologies (DLT)/blockchain for tamper-resistant records of inputs (seeds, feeds, medications) and process steps, expediting recalls and building trust.
- Consumer access via smart tags/AR; alignment of production with individualised nutrition and proximity-to-market goals.
- Support smallholders via shared ecosystems; address gaps in regulation, standards, and interoperability to enable scalable adoption.
- Architectures should include the following aspects:
    - End-to-end digital traceability.
    - Interoperable food chain information systems.
    - Secure data sharing across the value chain.
    - AI-supported food-fraud detection.
    - Digital certification.
    - Smart packaging and intelligent labels.
    - Product-condition and shelf-life monitoring.
    - Provenance, authenticity, cybersecurity, and data integrity.

3.5.3.3 Major Challenge 3: Climate-Smart, Nature-Positive and Circular Production

3.5.3.3.1 Status, vision and selected outcome

EU regulations together with consumers' increased interest in organic food are compelling farmers to drastically decrease the use of pesticides to reduce risks and impacts on human health and the environment, as well as to remain below the maximum residue levels of pesticides. Pesticides are

found not only in drinking water[21] 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.

The EU Farm-to-Fork strategy 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 AgRI 2040 strategy, confirmed in February 2025, puts a major focus on preservation of landscapes, biodiversity, and environmental protection, in a results-oriented model aligned with the Green Deal[22]. 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 with 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).

Agrifood and natural-resource systems must simultaneously reduce environmental pressures, adapt to climate change, and contribute to restoration of natural resources. The challenge extends beyond conventional environmental monitoring towards integrated systems capable of measuring, predicting and reducing emissions, restoring degraded resources, and closing material and nutrient loops. Areas of interest are often remote without sufficient connectivity - new approaches are required to flexibly deploy sensors that harvest their energy and collect data.

3.5.3.3.2 Soil Health and Nutrient Management

Improving soil health depends on accurate in-situ measurement of nutrients, moisture, and herbicide impact. New low-power sensors, smart actuators, and AI-based decision support can help optimise fertiliser use, reduce chemical inputs, and support targeted interventions such as weed detection and crop protection.

- **In-situ, real-time nutrient and herbicide monitoring:**
    - Miniaturised, ultra–low-power quantum and biosensors for continuous soil-health monitoring: measure soil moisture, temperature, nutrients (N, P), and contaminants at ppm levels, with packaging that reliably interfaces with soil water.
    - Long-lived buried sensors combined with optical/hyperspectral and proximal sensing for a complete soil-health picture including nutrient availability and nutrient-loss monitoring as well as salinity, contamination and erosion detection.
    - Precision fertilisation through smart micro-actuators to deliver inputs precisely at the roots, maximising efficacy, and reducing total agrochemicals.
    - Sustainable "green" ECS: biodegradable substrates, non-toxic materials, and minimal packaging to avoid e-waste and soil contamination.

[21] Journal of Food Engineering: Machine Learning Approches for Food Quality Assessment ». (2022)
[22] https://www.notre-environnement.gouv.fr/themes/sante/la-pollution-de-l-eau-douce-ressources/article/les-pesticides-dans-les-eaux-souterraines?lien-ressource=5193&ancreretour=lireplus

- **Decision support:**
    - IoT with edge/cloud AI to translate measurements into fertilisation and weed-control actions, prioritising organic inputs and reducing chemical dependence.
    - Low-cost vision (RGB/3D/hyperspectral) and on-edge models for weed recognition and selective eradication.
    - AI-based soil-health assessment: Soil organic carbon and soil biodiversity monitoring, and digital soil mapping; hyperspectral crop monitoring for early disease detection and yield prediction.
    - Soil digital twins and MRV for soil-health and carbon-farming practices.

3.5.3.3.3 Air Quality, Greenhouse Gases and Emissions Monitoring

Air quality monitoring is needed in indoor, urban, and rural environments because pollution affects health and productivity. Real-time multi-sensor systems, digital twins, and GHG monitoring tools can help measure pollutants, track emissions, and support mitigation actions in agriculture and industry.

- **Air-quality sensing** (indoor, urban, rural):
    - Distributed sensing of air pollutants, microsensors/mini-stations with embedded calibration and high selectivity; address power, data transmission, storage, and assessment constraints.
    - Indoor monitoring integrated into building infrastructure, paired with real-time digital twins to predict pollutant diffusion and trigger targeted mitigation.
- **GHG control and verification:**
    - Digitalisation to improve industrial, mobility, and agricultural efficiency and cut emissions.
    - Livestock-focused sensing (breath/rumen) and analytics to guide mitigation via feed or management changes.
    - Distributed sensing of greenhouse gases and verification tools for emissions and sequestration; advanced photonics and quantum sensors for CO_2, NOx, methane, ammonia, and PM with rapid response to spikes.
- **Decision support:**
    - Emissions monitoring from agricultural and livestock systems.
    - Atmospheric sensing modelling.
    - AI-based emission-source identification.
    - Integration of atmospheric, meteorological, and production data.
    - Emission forecasting and continuous MRV.

3.5.3.3.4 Circular Bioeconomy and Smart Waste Management

Waste management needs smarter collection, sorting, and treatment systems to reduce environmental burden and improve circularity. Connected bins, RFID, automated segregation, and AI-enabled monitoring can improve recycling, routing, and waste treatment efficiency, including in remote or low-power settings.

- **Integrated waste systems:**
  - Real-time monitoring of waste streams, treatment units, landfill gas, and anaerobic digestion;
  - AI-supported waste classification and forecasting for autonomous sorting and processing to ensure recyclability.
  - Smart bins (radio-frequency identification (RFID), compaction, fullness sensors), automated segregation, robotic picking, optimal routing, and vehicle tracking—designed for off-grid operation.
  - End-to-end integration into product life cycles to enable circularity.
- I**ntelligent sustainable/biodegradable packaging:**
  - Agricultural and food-processing by-product valorisation.
  - Nutrient recovery and biomass conversion.
  - Circular use of water and materials.
  - Eco-friendly materials paired with sensors to track freshness/contaminants while minimising plastic waste.
  - Hybrid integration of sensors, energy harvesting, and storage on biodegradable substrates to reduce electronics waste.
- **Decision support:**
  - Digital tracking of material flows.
  - Life-cycle assessment and circular bioeconomy digital twins.

3.5.3.3.5 Decarbonisation, Carbon Farming and Environmental Remediation

Remediation technologies are important for reducing pollutants in soil, air, and water, but they must be efficient enough for remote and continuous use. AI-supported monitoring, carbon verification tools, and advanced sensing can help identify when and where remediation is needed and support decarbonisation goals.

- **Targeted, efficient remediation**:
  - Edge/cloud AI platforms to detect when/where water, air, or soil remediation is needed, addressing mobile and intermittent pollution sources with antifouling designs.
  - Low-carbon agricultural production.
  - Carbon farming and soil/biomass carbon monitoring.
  - Carbon-removal measurement and verification.
  - Greenhouse gas reduction technologies.
  - Renewable and low-carbon energy for agricultural operations.
  - On-site CO_2 capture/conversion materials and coupled sensor–remediation systems for responsive operation.
  - Tools to verify carbon emissions and sequestration; enhance soil-based sequestration (e.g., “4 per 1000”) and rigorously evaluate performance.
  - Energy-harvesting approaches (solar/thermoelectric) for in situ pollutant removal in remote deployments.

- Environmental remediation of contaminated soils and water.
- AI-supported remediation optimisation.
- Digital twins for environmental remediation.

3.5.3.4 Major Challenge 4: Water Resilience, Quality and Circular Management

3.5.3.4.1 Status, vision and selected 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 and, along with floods, impact or endanger the quality of water bodies, human activities in energy production, data centres, 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. These human activities have released pollutants of emerging concern such as PFAS (per- and polyfluoroalkyl substances) and medicinal products into water bodies, with detrimental consequences for human health and biodiversity. Moreover, the outdated and deteriorating water infrastructure is also 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 increase the amount of sediment nutrients and pollutants in water sources, and human activities release pollutants of emerging concern that end up in all types of water bodies and have a direct impact on drinking water quality. Therefore, climate change jeopardises the quality and safety of our water, making the development of new tools to deal with this problem more critical than ever.

Water availability and water quality are becoming critical constraints for agriculture, food production, rural communities, ecosystems, and industry. The future challenge is integrated management of water resources across catchments, agricultural systems, urban areas, and natural ecosystems.

3.5.3.4.2 Water Quality, Availability and Resilient Water Infrastructure

Access to clean water depends on reliable monitoring of water quality, flow, and distribution losses. Low-power sensors, smart metering, leak detection, and automated control systems can help reduce waste, improve safety, and support fairer water allocation between domestic, agricultural, and industrial uses.

- **Healthy water monitoring and anomaly response:**
  - Monitoring of chemical, biological, and physical parameters.
  - Detection of emerging pollutants and pathogens.
  - Nutrient and pesticide monitoring.
  - Groundwater and aquifer monitoring.
  - Drought and water-availability prediction.
  - Leakage and loss detection.
  - Remote and autonomous water monitoring.

  - Self-powered, low-power multi-parameter quantum/optical sensors for temperature, conductivity, pH, turbidity, nitrates, heavy metals, and biofilm growth in distribution and treatment plants.
  - AI-assisted water-quality monitoring for rapid leak/contamination detection, reduced backhaul, and real-time pollutant-diffusion prediction via compact digital twins.
- **Demand reduction and conservation:**
  - Smart metering with time-of-use pricing and gamification to shift behaviour.
  - Low-cost flow/leak sensors with auto shut off and remote valve control; AI optimisation of household, farm, and industrial water use.
  - Automated leak localisation using in-pipe inspection plus dense, fine-grained sensing networks.
- **Efficient, intelligent distribution:**
  - Use-based quality management and pricing, balancing safety with application needs (drinking, industry, cooling).
  - Miniaturised electrochemical and optical sensors with high stability and anti-fouling for continuous control.
  - Robust IoT and AI manage large data volumes; storage strategies (e.g., intentional flooding) guided by forecasting and early warning.

3.5.3.4.4 Water Efficiency, Reuse, and Circular Water Systems

To ensure water efficiency and circular water systems, it is crucial to consider the following elements during the implementation phase:

- **Precision irrigation.**
- **Water-use optimisation.**
- **Intelligent irrigation systems.**
- **Wastewater treatment monitoring.**
- **Safe water reuse.**
- **Industrial and agricultural water recycling.**
- **Nutrient recovery from wastewater.**
- **Distributed water treatment systems.**
- **AI-based treatment optimisation.**
- **Digital twins for water infrastructure.**

3.5.3.4.5 Water Ecosystems and Catchment-scale Intelligence

Water Ecosystems and Catchment-scale Intelligence also include better storage, flood prediction, irrigation optimisation, and circular use of wastewater and rainwater. AI-assisted monitoring and digital twins can support real-time decisions, improve resilience to climate extremes, and increase recovery of water, energy, and useful by-products from treatment systems. Smart treatment systems are needed to remove pollutants efficiently and support reuse in a circular water economy. Advanced

sensors, automated monitoring, and energy-harvesting remediation technologies can make treatment more continuous, cost-effective, and suitable for remote deployment.

- **Smart irrigation management:**
  - Self-powered, low-cost sensors and edge-ready models to monitor soil moisture and plant stress; UAV/satellite narrow-band spectral data coverage.
  - Low-cost actuators to deliver the right dose at the right place; integrated leak detection in irrigation networks.
  - Integrated catchment monitoring.
- **Flood management:**
  - River, lake, groundwater, and coastal water monitoring.
  - Flood and drought prediction.
  - Integration of meteorological, hydrological, and environmental data.
  - Networked water-level sensors plus predictive models/digital twins combining hydrology, terrain, and weather for early warnings.
  - Interoperable IoT to inform responders, communities, and operators in real time.
- **Circular water treatments (wastewater, rainwater, stormwater):**
  - Ecosystem health indicators.
  - Biodiversity and habitat monitoring.
  - Cross-sector water demand modelling.
  - Multi-sensor monitoring of levels, flows, temperature, pressure, chemical/biological residues with decision support for real-time actions and forecasting.
  - IoT-enabled plant reliability (failure prediction, remote operations), groundwater mapping, and sustainable abstraction monitoring.
  - Expanded recycling and reuse in cities and water-intensive industries (e.g., closed-loop processes, district heating from data centres), cutting the total water footprint.
  - AI-supported resource allocation.

3.5.3.5 Major Challenge 5: Biodiversity, Ecosystem Restoration and Nature-Positive Systems

3.5.3.5.1 Status, vision and selected outcome

It has been stated that: “Biodiversity boosts ecosystem productivity where each species, no matter how small, all have an important role to play”[23]. For example, increasing the number of plant species means greater biodiversity, supporting natural sustainability for all life [24]. 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, the new EU agriculture strategy AgRI 2040 promotes sustainable farming practices that help to protect the

[23] https://aioti.eu/wp-content/uploads/2022/02/AIOTI-Role-of-IoT-in-addressing-agroecological-focus-of-Green-Deal-Final.pdf
[24] https://www.sciencedirect.com/science/article/abs/pii/S0012825214002086

environment and preserve landscapes and biodiversity. This is a consequence of the well-recognised 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 can provide continuous, scalable monitoring and targeted interventions that lower environmental impact while sustaining livelihoods for the four ecosystems described below.

Biodiversity is an essential component of resilient agricultural, aquaculture, fisheries, and forestry systems. The challenge is evolving from biodiversity monitoring and conservation towards active ecosystem restoration and measurable Nature-positive outcomes.

3.5.3.5.2 Nature-Positive Agriculture

Among the key focus areas, Agriculture is one of the economic activities that has the highest dependence on nature and biodiversity[25]. On average, global mean crop yields of rice, maize and wheat are projected to decrease between 3% and 10% per degree Celsius 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 agricultural activity on the environment must be as low as possible to preserve biodiversity. Efforts to conserve existing land resources (e.g. forests) and expand nature-based solutions (e.g. peatland restoration) are required to reduce GHG emissions, or to improve resistance by microbial biofertilisers [26,27]. In this regard, the EU Biodiversity Strategy 2030 establishes several objectives[28], for instance, to protect ecosystems while maintaining productivity. To address these objectives, there is a need to develop:

- Precision farming systems to minimise fertilisers/pesticides and optimise inputs using in situ soil sensing and connected traps.
- Landscape-scale monitoring to track pollinators, soil biodiversity, and habitat quality and landscape connectivity assessment; Precision management supporting biodiversity including remote sensing of biodiversity indicators; Monitoring of agroecological practices.
- Integration of microbial biofertilisers and peatland/forest conservation to reduce GHGs and build resilience.
- AI-based species identification.
- Ecological digital twins.

3.5.3.5.3 Aquaculture Ecosystem Resilience

Aquaculture impacts biodiversity negatively in several ways[29]: (i) where antibiotics and hormones are used to reduce farm stock mortality and improve growth rates, 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

[25] Anup Shah « Why is biodiversity important? Who cares?
https://www.globalissues.org/article/170/why-is-biodiversity-important-who-cares
[26] https://www.pnas.org/doi/10.1073/pnas.2203385119
[27] European Commission. The business case for biodiversity. May 2020.
https://ec.europa.eu/commission/presscorner/detail/en/fs_20_907
[28] https://www.fao.org/3/nd651en/nd651en.pdf
[29] Prisa, D, Fresco, R, Spagnuolo, D. 2023. Microbial Biofertilisers in plant production and resistance: a review. Agriculture 13(9), 1666 - MDPI

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 cleaner, more efficient aquaculture through:

- Continuous water quality monitoring.
- Animal health and welfare sensing.
- Disease and pathogen detection.
- Environmental DNA and biodiversity monitoring.
- AI-based aquaculture management.
- Autonomous feeding and production optimisation.
- Ecosystem-impact monitoring.
- Nutrient and waste monitoring.
- Digital twins of aquaculture production and surrounding ecosystems.
- Precision feeding and water-use optimisation to cut waste and eutrophication.
- Multi-sensor water-quality monitoring of facilities and effluents; reduce antibiotics/hormones via targeted controls.
- IoT/satellite/UAV data fused with AI/ML for predictive health, early warnings, and automation.

3.5.3.5.4 Fisheries and Marine Ecosystem Monitoring

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 this strategy, the preservation of marine stocks could increase the annual profits of the European seafood industry. Recent reports[30] show that the European seafood market will reach US $69.19 billion in 2025 and is expected to rise to US $71.72 billion by 2030.

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, bycatch 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 and support sustainable fishing while protecting marine biodiversity, there is a need to develop:

- Autonomous marine and oceanographic observation, sensing and monitoring solutions (including unmanned vessels, UXVs) to estimate biodiversity indices, fish stocks and species distribution, and to build fishery management systems consistent with conservation

[30] European Commission. EU Biodiversity Strategy for 2030: bringing nature back into our lives. May 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX%3A52020DC0380

objectives and rules, also related to the tropicalisation process that is becoming increasingly evident in recent times.

- Species identification and abundance estimation for selective, low-impact gear and technologies to reduce bycatch and seabed damage.
- Service models to deploy, maintain, and exploit information from monitoring systems at scale.
- AI-based ecosystem modelling.

3.5.3.5.5 Smart and Resilient Forestry

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 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, with a much better understanding and continuous assessment of EU forests. To this end, there is a need to develop:

- A precision forestry system with remote self-powered sensing and satellite-based AI/ML monitoring capabilities to map and assess the condition of EU forests, as well as to enable early detection and prevention of threats to forests (wildfires, pests, diseases, etc.).
- Autonomous forest management systems for continuous forest-health and CO2 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and timely warnings of illegal poaching activity.
- Climate-resilience modelling.
- Digital twins of forests. Service models to deploy, maintain, and exploit information from monitoring systems at scale.
- AI-assisted restoration planning.

3.5.3.5.6 Cross-ecosystem biodiversity intelligence

Given the interdependence between agricultural, forestry, freshwater, and marine ecosystems, new tools and methods are necessary to ensure effective cross-ecosystem biodiversity interactions. Consequently, developments are required in the following elements:

- Integrated biodiversity data infrastructures.
- Interoperability between agriculture, forestry, freshwater, and marine datasets.
- AI-based biodiversity assessment.
- Automated species identification.
- Environmental DNA and advanced biological sensing.
- Satellite, drone, acoustic and in-situ observations.
- Ecosystem digital twins.
- Biodiversity indicators and ecological forecasting.
- MRV for restoration.

3.5.4 Timeline

MAJOR CHALLENGE	TOPIC	SHORT -TERM 2027 - 2031
Major Challenge 1: Food security and resilient food production systems	**Topic 1.1:** Intelligent, adaptive and autonomous food production	● Farm/food-process edge-AI pilots demonstrate calibrated multi-source sensing, grounded advice and measured yield, quality or resource benefits.
	Topic 1.2: Autonomous and robotic farming systems	● Task-specific robotic weeding, spraying or harvesting systems validated in representative fields with obstacle protection and human intervention.
	Topic 1.3: Climate-resilient and resource-efficient production	● Precision irrigation/input and extreme-weather decision tools validated against local agronomy, forecasts and measured resource use.
	Topic 1.4: Digital agricultural infrastructure and inclusive adoption	● Farmer-controlled data-sharing and rural edge services demonstrated with semantic profiles, offline fallback, secure updates and affordable support.
Major Challenge 2: Food safety, One Health and trusted food chains	**Topic 2.1:** Plant health, crop quality and emerging biological threats	● Crop-health diagnostics and multi-source alerts validated for specified pests/pathogens with measured sensitivity, specificity and field robustness.
	Topic 2.2: Animal health, welfare and antimicrobial resistance	● Livestock sensing and diagnostic workflows validated for defined health/welfare indicators and linked to veterinary and AMR surveillance.
	Topic 2.3: Food safety sensing and rapid diagnostics	● Portable/in-line food diagnostics validated for specified hazards and matrices against reference methods, including sampling and time-to-result.
	Topic 2.4: End-to-end traceability and trusted food chains	● Interoperable batch/condition traceability demonstrated with source verification, secure identifiers and tested recall workflows.
Major Challenge 3: Climate-smart, Nature-positive and circular production	**Topic 3.1:** Soil health and nutrient management	● Calibrated soil/nutrient sensing and sampling workflows demonstrated with spatial coverage, seasonal drift and uncertainty quantified.
	Topic 3.2: Air quality, greenhouse gases and emissions monitoring	● Distributed GHG/air-quality monitoring demonstrated with reference calibration, source attribution and quantified temporal/spatial uncertainty.
	Topic 3.3: Circular bioeconomy and smart waste management	● Sensor/AI waste classification and biomass-flow tracking demonstrated with measured sorting quality, recovery yield and resource use.
	Topic 3.4: Decarbonisation, carbon farming and environmental remediation	● Carbon-farming MRV and targeted remediation pilots validated with reference measurements, baselines, uncertainty and applicable methodology checks.
Major Challenge 4: Water resilience, quality and circular management	**Topic 4.1:** Water quality, availability and resilient water infrastructure	● Multi-parameter water and leak-warning systems demonstrated with reference checks, antifouling maintenance and reliable incident escalation.
	Topic 4.2: Water efficiency, reuse and circular	● Precision irrigation and monitored reuse systems validated for defined applications with measured water,

MAJOR CHALLENGE	TOPIC	SHORT -TERM 2027 - 2031
	water systems	energy and quality performance.
	Topic 4.3: Water ecosystems and catchment-scale intelligence	• Catchment-monitoring and flood/drought tools demonstrated with combined weather, hydrological and in-situ data and quantified forecast uncertainty.
Major Challenge 5: Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems	**Topic 5.1:** Nature-positive agriculture	• Farm/landscape biodiversity sensing validated against ecological surveys with representative species coverage and transparent indicator uncertainty.
	Topic 5.2: Aquaculture ecosystem resilience	• Aquaculture sensing and feeding/health support demonstrated with reference validation, welfare indicators and measured effluent/resource impacts.
	Topic 5.3: Fisheries and marine ecosystem monitoring	• Autonomous marine observation and species/bycatch analytics demonstrated with calibrated sensors, representative sampling and uncertainty estimates.
	Topic 5.4: Smart and resilient forestry	• Forest sensing and fire/pest/health alerts validated against field inventories with measured coverage, false alarms and operational response.
	Topic 5.5: Cross-ecosystem biodiversity intelligence	• Interoperable biodiversity observations demonstrated using field, acoustic, imaging or eDNA methods with taxonomic validation and provenance.

MAJOR CHALLENGE	TOPIC	MEDIUM -TERM 2032 - 2036
Major Challenge 1: Food security and resilient food production systems	**Topic 1.1:** Intelligent, adaptive and autonomous food production	• Integrated production of twins and adaptive control qualified across seasons and sites with monitored validity and operator approval.
	Topic 1.2: Autonomous and robotic farming systems	• Multi-machine fleets qualified across vendors, weather and field conditions with verified coordination and safe recovery.
	Topic 1.3: Climate-resilient and resource-efficient production	• Climate-adaptation decision systems qualified through multi-season field evidence and uncertainty-aware crop/soil models.
	Topic 1.4: Digital agricultural infrastructure and inclusive adoption	• Interoperable agricultural data spaces qualified across machinery, advisers and public services with tested rights and conformance.
Major Challenge 2: Food safety, One Health and trusted food chains	**Topic 2.1:** Plant health, crop quality and emerging biological threats	• Predictive plant-health services qualified across crops and regions with confirmed diagnostic pathways and targeted interventions.
	Topic 2.2: Animal health, welfare and antimicrobial resistance	• Interoperable One Health analytics qualified across veterinary, food and environmental datasets with provenance and controlled access.
	Topic 2.3: Food safety sensing and rapid diagnostics	• Multi-hazard monitoring qualified through processing, storage and transport with validated detection limits, false alarms and corrective workflows.

MAJOR CHALLENGE	TOPIC	MEDIUM -TERM 2032 - 2036
	Topic 2.4: End-to-end traceability and trusted food chains	● Cross-company provenance and recall services qualified across fragmented chains with verified data quality and access rights.
Major Challenge 3: Climate-smart, Nature-positive and circular production	**Topic 3.1:** Soil health and nutrient management	● Soil decision twins qualified across sites/seasons using reference samples and measured agronomic/environmental outcomes.
	Topic 3.2: Air quality, greenhouse gases and emissions monitoring	● Emission forecasting and mitigation feedback qualified across representative operations using independently verified measurements.
	Topic 3.3: Circular bioeconomy and smart waste management	● Automated recovery and valorisation processes qualified across variable feedstocks with product-quality and lifecycle-benefit evidence.
	Topic 3.4: Decarbonisation, carbon farming and environmental remediation	● Scaled carbon/remediation services qualified with additionality, permanence/reversal tracking and independently assessed net benefits.
Major Challenge 4: Water resilience, quality and circular management	**Topic 4.1:** Water quality, availability and resilient water infrastructure	● Predictive water-quality/availability services qualified across networks with validated forecasts, fault coverage and safe control.
	Topic 4.2: Water efficiency, reuse and circular water systems	● Circular water/recovery systems qualified with fit-for-purpose treatment verification and controlled response to variable contaminants.
	Topic 4.3: Water ecosystems and catchment-scale intelligence	● Hydrological twins qualified for selected catchments with calibration, data assimilation and validated early-warning performance.
Major Challenge 5: Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems	**Topic 5.1:** Nature-positive agriculture	● Restoration decision support qualified through multi-season field evidence linking management actions to measured ecological outcomes.
	Topic 5.2: Aquaculture ecosystem resilience	● Production/ecosystem twins qualified for selected species and sites with disease-warning, feeding and water-quality validation.
	Topic 5.3: Fisheries and marine ecosystem monitoring	● Regional marine decision services qualified on interoperable ocean-twin infrastructure with validated ecological models and fishery observations.
	Topic 5.4: Smart and resilient forestry	● Forest twins and restoration-planning tools qualified across regions with calibrated growth, disturbance and biodiversity indicators.
	Topic 5.5: Cross-ecosystem biodiversity intelligence	● Cross-ecosystem data services qualified with harmonised indicators, representative coverage and independently tested model transfer.

MAJOR CHALLENGE	TOPIC	LONG -TERM 2037 AND BEYOND
Major Challenge 1: Food security and resilient food production systems	**Topic 1.1:** Intelligent, adaptive and autonomous food production	● Federated production optimisation qualified under changing crops, climate and supply constraints with bounded authority and independently verified resilience.
	Topic 1.2: Autonomous and robotic farming systems	● Adaptive multi-task farm robots qualified within defined operating envelopes with maintained safety, uptime and intervention evidence.
	Topic 1.3: Climate–resilient and resource-efficient production	● Adaptive resource allocation qualified across farm networks under extremes with transparent trade-offs, ecological limits and human authority.
	Topic 1.4: Digital agricultural infrastructure and inclusive adoption	● Cross-domain farm-service federation qualified across successive technologies with maintained governance, resilience and small-farm accessibility.
Major Challenge 2: Food safety, One Health and trusted food chains	**Topic 2.1:** Plant health, crop quality and emerging biological threats	● Coordinated crop-health management qualified under emerging threats with bounded autonomous action, monitored uncertainty and expert escalation.
	Topic 2.2: Animal health, welfare and antimicrobial resistance	● Cross-sector early-warning services qualified for changing disease/AMR risks; treatment decisions retain veterinary authority and validated evidence.
	Topic 2.3: Food safety sensing and rapid diagnostics	● Predictive food-safety services qualified for defined hazards and chains with maintained assay validation; near-real-time coverage remains hazard-specific.
	Topic 2.4: End-to-end traceability and trusted food chains	● Adaptive fraud/risk detection qualified across evolving food chains with auditable source evidence and accountable decision-making.
Major Challenge 3: Climate-smart, Nature-positive and circular production	**Topic 3.1:** Soil health and nutrient management	● Adaptive soil-management services qualified under changing practices with long-term soil-health evidence and constrained interventions.
	Topic 3.2: Air quality, greenhouse gases and emissions monitoring	● Sustained environmental MRV and bounded mitigation control qualified across sites with traceable uncertainty, maintenance and independent audits.
	Topic 3.3: Circular bioeconomy and smart waste management	● Integrated circular production qualified across value chains with traceable material balances and measured residual waste; no universal zero-waste claim.
	Topic 3.4: Decarbonisation, carbon farming and environmental remediation	● Integrated low-carbon resource services qualified across sites with durable verification and ecological safeguards; climate neutrality is not assumed from digitalisation.
Major Challenge 4: Water resilience, quality and circular management	**Topic 4.1:** Water quality, availability and resilient water infrastructure	● Federated water operations qualified under contamination, drought and asset failures with bounded automation and accountable allocation.
	Topic 4.2: Water efficiency, reuse and circular water systems	● Cross-sector water-loop orchestration qualified with independently verified health/environmental protection, recovery and lifecycle resource benefits.
	Topic 4.3: Water ecosystems and catchment-	● Cross-catchment decision services qualified for extremes and competing demands with ecological constraints

MAJOR CHALLENGE	TOPIC	LONG -TERM 2037 AND BEYOND
	scale intelligence	and public/operator authority.
Major Challenge 5: Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems	**Topic 5.1:** Nature-positive agriculture	• Adaptive landscape-management support qualified across regions with long-term biodiversity evidence and accountable human decisions.
	Topic 5.2: Aquaculture ecosystem resilience	• Bounded autonomous aquaculture operations qualified with sustained welfare, ecological-impact and recovery evidence; regeneration remains an assessed outcome.
	Topic 5.3: Fisheries and marine ecosystem monitoring	• Federated marine-intelligence services qualified under ecosystem change with sustained observations and accountable fisheries/conservation decisions.
	Topic 5.4: Smart and resilient forestry	• Long-term forest decision services qualified under climate change with maintained field evidence, uncertainty and ecological safeguards.
	Topic 5.5: Cross-ecosystem biodiversity intelligence	• Federated ecological twins qualified for defined restoration decisions with long-term validation, uncertainty and sustained observation; no universal continuous nature intelligence.

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 digital innovations essential to an inclusive, healthy society, contributing to European challenges in sustainability, health, well-being, mobility, security and energy, and consequently to European economic prosperity.

Europe needs digital solutions that support both the individual and society as a whole, driven by technologies such as Artificial Intelligence (AI), robotics, 6G, extended reality (XR: virtual, augmented and mixed reality) and brain–computer interfaces (BCIs). Generative AI has reshaped how society interacts with technology, with agentic AI now emerging as a further transformative force, shaping how people interact with technology, each other, society and the environment. Digital innovations should facilitate individual self-fulfilment, empowerment and resilience, collective "inclusion" and safety, and a supportive infrastructure and environment. However, these technologies, especially AI, also bring risks: lack of transparency, bias and discrimination, privacy concerns, ethical dilemmas, security risks, unwanted dependence, job displacement, and misinformation and manipulation, to name the most important ones.[1]

These transformations also raise ethical considerations: digital innovations must address societal concerns sustainably, guaranteeing participation and reducing inequality. A human-centred approach is therefore key to the EU's approach to technological development, reflecting European social and ethical values, (social) inclusiveness, and the creation of sustainable, high-quality jobs through social innovation.

In summary, our four Major Challenges are: facilitating individual self-fulfilment, empowerment and resilience, inclusion and collective safety, and supportive infrastructures and sustainable environments.

3.6.2 Application Trends and Societal Benefits

3.6.2.1 External requirements

To guarantee economic and societal growth, digital inclusion and transformation require tools and infrastructures in the application-domain roadmaps described in other chapters. Digital technology permeates every aspect of society and is an important instrument of change.

People's expectations of technology's future impact are broadly positive but involve specific concerns around employment, income, safety, equality and trust. The impact of science and technological innovation on prosperity, individual well-being, sustainability, fairness and trust keeps growing, underlining the importance of investing in our digital strategy today.

The spectacular advent of AI illustrates this (see figure 3.6.1): the AI market has seen significant growth, offering numerous opportunities for new players. AI, a technology capable of tasks requiring human intelligence, is revolutionising sectors such as healthcare, finance, transportation and customer service, largely driven by rising demand for automation and efficiency as businesses

[1] The 15 Biggest Risks of Artificial Intelligence (forbes.com)

streamline operations, cut costs and boost productivity. Advances in machine learning and the abundance of big data further fuel this growth, letting systems improve over time and extract valuable insights for decision-making. The same trends appear in application domains such as content creation (television, mobile platforms, social media), where increasingly digitised and distributed workflows rely on advanced electronic components and systems for scalable, efficient operation across heterogeneous infrastructures.

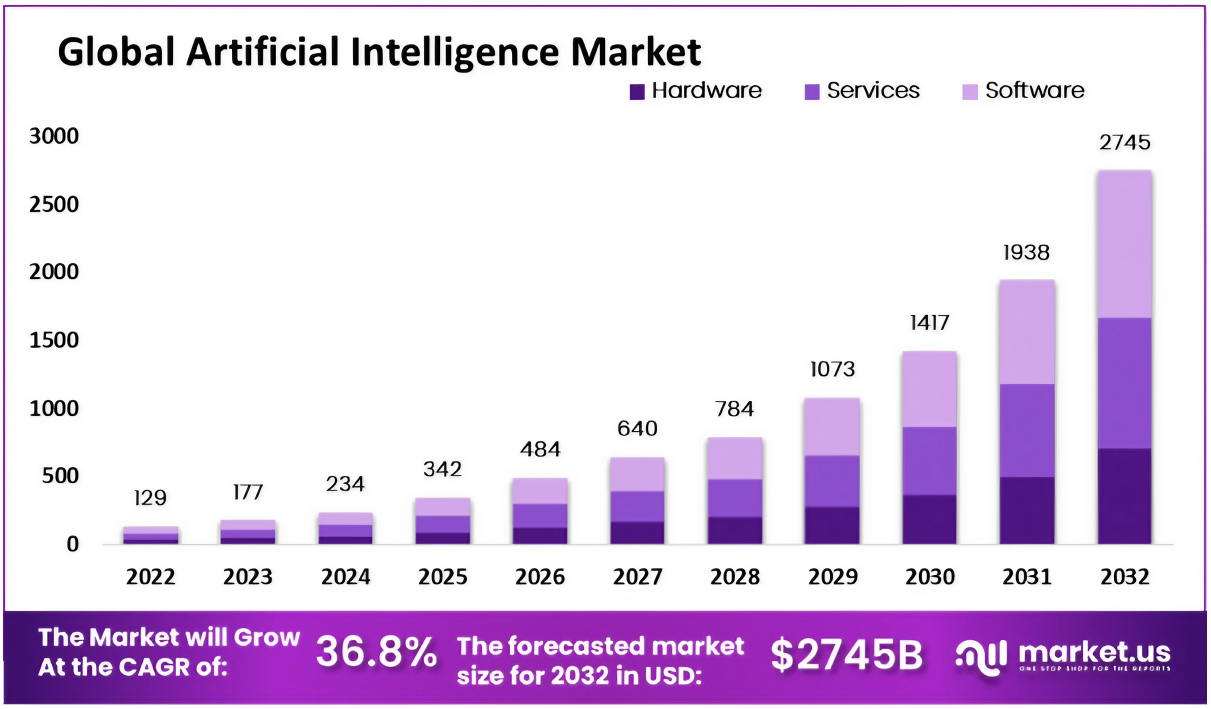

Figure 3.6.1 Growth of global AI market (source https://market.us/report/artificial-intelligence-market/)

To guarantee European sovereignty for European digital societal goals, safety, equality and trust are key requirements. For electronic components and systems (ECS), this means: ubiquitous connectivity ("everywhere and always on") and online services and social media ("always online") drive people to rely on intelligent applications; and public and private infrastructures will increasingly be connected, observed and controlled via digital infrastructures ("continuous monitoring").

Two further drivers for European society and economy, from a human-centred AI perspective, are lifelong learning and training, and being able to work anywhere. The trend towards working from home whenever possible (triggered by the Covid pandemic) has continued, letting people combine work and private life better. In both rural areas and cities, it should be easy to work from home or remotely in distributed groups, facilitated by living labs and learning factories at personal and collective levels.

3.6.2.2 Societal benefits

European society as a whole 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 includes employability through lifelong learning and training, and personal well-being. The key ambition is to maximise citizens' individual development.

    - How? By ensuring personal resilience, lifelong learning and employability. Human-centred solutions will optimise services for each individual's needs and capabilities, in healthcare, lifestyle, coaching, training, and working from home or remotely in a "distributed" workforce, boosting productivity, improving work/life balance, fostering mental health, and reducing commuter pollution.

- The overall individual benefit is "well-being". Prosperity encompasses job security, material living standards, and the right to quality education, accessible anytime, anywhere. At the individual level, well-being means health for every age, plus adequate housing, safety, protected privacy, reliable and ubiquitous digital infrastructure, social connectedness and social cohesion. Our key objective is to empower and protect the individual.
    - How? By ensuring acceptable, trustworthy AI technologies that increase inclusion and prevent exclusion, protecting citizens against identity theft, providing a protective environment against new virus infections, and enabling healthier lifestyles through lifestyle monitoring and coaching.

- The benefits of digital inclusion: a society resilient against setbacks, and societal acceptance of novel technologies, achieve the key ambition of safeguarding collective society and well-being for all.
    - How? By promoting societal and digital inclusion, providing societal access for all, and ensuring collective resilience against setbacks. The elderly will be supported to continue participating in society, reducing loneliness, improving well-being and health, and reassuring them that their experience remains valued.

- At the environmental level, the benefits are a physically and digitally sustainable environment, intelligent infrastructure management, stability and resilience against threats, and agreed fallback solutions in times of crisis. The main aim is a supportive infrastructure and environment.
    - How? By providing reliable, resilient infrastructures, protecting society against destabilising forces, establishing a sustainable environment, and securing controlled climate change. Monitoring and intelligent control of infrastructures will also support sustainability through optimal use of natural resources, pollution reduction and crisis management.

“Sustainability” in a wide sense implies both environmental and economic sustainability and equal opportunities for all, related to fairness and trust in our societies. AI-based systems must take European-style human values into account by design (to which the EU AI Act contributes), continuing the human-centred approach. “FAIRness” (findability, accessibility, interoperability and re-use) will also help shape future applications.

3.6.3 Major Challenges

Enabling and ensuring a digital society involves various aspects to be supported by trustworthy 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 3.6.2 below.

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.

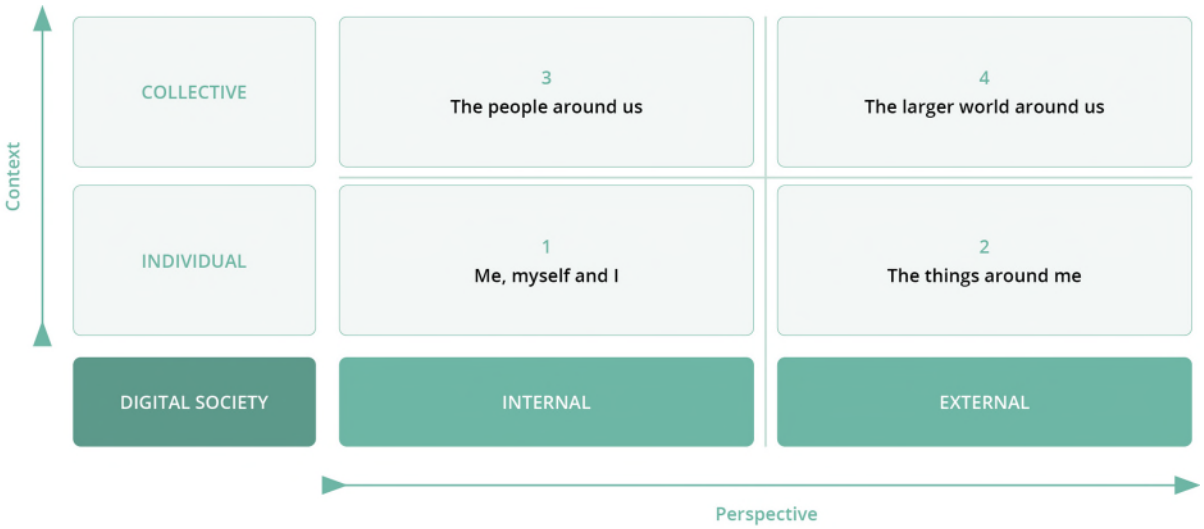

Figure 3.6.2 - Structuring the Major Challenges in scope and context

3.6.3.1 Major Challenge 1: Facilitate individual self-fulfilment

3.6.3.1.1 Status, vision and expected outcome

Ambition: to maximise the individual development of citizens.

- Provide empowerment to citizens and ensure personal resilience.
- Enable lifelong learning and development for both children and adults (serious gaming, including AI-based AR/VR).
- Give citizens more freedom to do their work wherever they want/need.
- Stimulate employability (e.g. through gamification, tools and means for supporting efficient remote work).[2]
- Improved human–machine interaction solutions for perception, reasoning, and autonomy, with interaction being adaptive to the user's abilities.

To maximise citizens' empowerment and self-fulfilment, Europe must strive for lifelong learning, employability and freedom to work wherever one resides, alongside optimal well-being in an independent, pluralistic media landscape. These enable lifelong empowerment by keeping citizens informed and facilitating the flow of educational content: media education develops skills that help

[2] Gamification: The application of game design elements and principles in a non- game context.

end violence and discrimination (e.g. sexism, racism), builds civic knowledge, and facilitates discussion of current issues, increasingly through on-demand, interactive and AR/VR formats backed by trustworthy 5G/6G connectivity.

The 30-year career is a thing of the past: education continues throughout working life as skills must adapt to a fast-changing world. Supporting lifelong learning requires technologies that encourage collaboration, autonomy and responsibility, and that implement learning initiatives. Cloud computing, mobile devices and web technologies are now deeply embedded in working practice, though their full pedagogical potential remains underexplored[3].

To give citizens freedom to work wherever they want, Europe must ensure trustworthy, high-bandwidth, secure connections (wired and wireless) at all possible work locations, reinforced by easy, secure access to cloud applications and AI-based automation that analyses data, guides decision-making and minimises repetitive work.

Smart automation and AI can raise productivity and GDP growth while also improving well-being, health, longevity and leisure time. Beyond income, individual well-being and life satisfaction depend on social life, leisure, health, relationships, job and housing[4] – factors that innovative technologies in the digital society can, and will, influence.

Gamified tools already offer free, open language learning and massive open online courses (MOOCs) to the public. AI tools based on large and small language models from a growing range of providers likewise support individual development, access to knowledge, skills development and critical thinking, though no tool can replace the richness of human interaction, creativity and experience in personal development.

3.6.3.1.2 Key focus areas

High-priority research, development and innovation (R&D&I) areas:

- Digital inclusion: tools, infrastructure, training and 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.
- The trusted element: how to ensure that nothing more is done (behind the scenes)

Smart systems can support personal well-being through body-awareness coaching, adaptive comfort control of the home and workplace (temperature, lighting, air quality), and immersive VR/AR experiences. At work, selective automation and AR-assisted tasks increase engagement and job satisfaction, while enabling audiences and workers to experience immediacy, individualisation and immersion without needing to be physically present, reshaping consumption patterns and opening new business opportunities.

[3] https://www.trainingjournal.com/articles/ opinion/how-promote-lifelong-learning- using-technology
[4] https://www.mckinsey.com/featured- insights/future-of-work/tech-for-good- using-technology-to-smooth-disruption- and-improve-well-being

Furthermore, we have to mitigate the risks of AI and other functionality that is based on massive data storage in the cloud. This can be done in different ways, such as:

- Introduce fake news detection by analysing AI-generated content on social media
- Develop technologies to prove the source of content creation, for instance by showing that a video was created with an actual camera. If part of the processing is done externally and/or in the cloud, add traceability of what was done where.
- Add watermarking to created content to prove that it is not artificial.
- Secure control of systems used for content creation, for instance by preventing production equipment from being taken over by external aggressors at major events such as Olympic Games, Eurovision song festival, European and World championships, etc.

3.6.3.1.3 Microelectronics and integrated photonics for XR applications

Currently, commercial head-mounted display solutions rely upon high-end microdisplays deploying various technologies such as organic light-emitting diodes (OLEDs), micro-LEDs, lasers, and LEDs with liquid crystal on silicon (LCoS), or microelectromechanical systems (MEMS). Nonetheless, these microdisplays will still need to undergo further improvements regarding size, power consumption (<300 mW; full display system), device efficiency, resolution (8K and beyond, pixel densities > 10kppi), high dynamic range (HDR), colour gamut, contrast, and refresh rate. Besides utilising classical visualisation modes, plenoptic modes such as light field, multifocal and holography are gaining ground, holding the promise for truly immersive experiences and potentially improving vergence-accommodation behaviour for head-mounted devices (HMDs) and autostereoscopic displays. Both the classical approach and the plenoptic solutions require not only a significant evolution regarding the capabilities and features of the opto-nanoelectronic display devices, such as multi-ridge lasers and associated waveguide combiners, light-field (micro)displays, multifocal light engines, spatial light modulators (SLMs) based on LCOS, and MEMS, but also state-of-the-art drivers and optical systems and architectures.

These complex optical systems must support the required field of view (FoV), be lightweight and safe for the user, and provide excellent colour uniformity and high brightness efficiency. Furthermore, they must satisfy the use case requirements for both professional use and mass adoption, i.e., be scalable to large volumes (cost-effective). The optical system will determine the image quality and, therefore, the end-user experience and market adoption of XR devices.

Within this optical system, the design and fabrication of waveguide optics, holographic elements, diffractive optics, reflective light guides, freeform optics, and meta-surfaces with optimal optical properties and behaviour are crucial. They will be crucial in achieving the required form factors and user experience for the envisioned display devices. Furthermore, photonic integrated circuits and light-shaping optics based on liquid crystal devices, enabling the miniaturisation of, e.g., waveguides, couplers, and lasers, combined with more macroscale components such as lenses, will also be essential to reach these goals.

Other key parts of XR solutions include a variety of integrated sensors that create an immersive and interactive experience. Vital-sign sensors additionally contribute to personal health monitoring and wellness.

Eye tracking can serve as hands-free communication between the user and the system; it allows for adaptive image colour correction and rendering at the gaze point; and can provide gaze-point prediction and user sensing functionality. However, it faces challenges relating to accuracy in diverse

lighting conditions and with different eye physiologies. The precision in detecting subtle eye movements or distinguishing between intentional gaze and casual looking remains a limitation.

Other sensors such as ambient light sensors, spectral sensors or depth sensors must cope with the high dynamic range of ambient light (1 lux … 100 klux).

Intelligent LED/laser drivers control their respective emitting devices but are also a crucial part of the optical eye-tracking system to monitor correct operation of the LEDs/lasers. They constantly monitor illumination time and power, thereby ensuring that the light output does not exceed safe limits even under single-fault conditions.

In general, integrating these systems seamlessly into mixed-reality devices without increasing bulk or reducing comfort is challenging. In addition, differences in spectral behaviour between modern light sources, display technologies, and image capture systems are becoming increasingly relevant in content creation and viewing workflows. New LED-based lighting systems often exhibit narrow and structured spectral power distributions, while display technologies such as LCD and OLED produce colour through different emission and filtering mechanisms. At the same time, image capture in live content production typically combines cameras based on single-sensor (Bayer) architectures with cameras using three sensors behind a colour-splitting prism, each having different spectral sensitivities. As these technologies are frequently combined, e.g. LED lighting in scenes together with mixed camera systems and LCD/OLED displays in capture and viewing chains, mismatches in spectral response can lead to visible colour inconsistencies and reduced fidelity across devices.

In line with the increasing digitalisation and distribution of application domains (see 3.6.2.1), ensuring consistent visual quality across such heterogeneous imaging systems is becoming a key challenge. This requires advanced colour processing and matching solutions capable of operating across different sensor architectures and under varying spectral conditions, contributing to a consistent and high-quality user experience across platforms, including XR environments.

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 3.6.3.

Specific R&D developments necessary	**ECS technologies**							
Major challenge 1: "Facilitate individual self-fulfilment"	Process techn, equipm, materials & manufact.	Components, modules and system integration	Embedded SW & Beyond	System of Systems	Edge Comp. & emb. AI	Connectivity	Architecture & Design	QRSC
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Reliable, dependable and secure SW and HW	x	x	x	x	x	x	x	x
Mature human systems interaction methods				x			x	x
Trustworthy AI/Machine Learning algorithms		x			x			x
Energy-efficient HW and SW solutions (e.g. for IoT devices, wearables)	x	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
Spectrally consistent imaging across heterogeneous capture, lighting and display systems		x	x	x	x		x	

Figure 3.6.3 - Required R&D&I developments within ECS – Major Challenge 1

3.6.3.2 Major Challenge 2: Facilitate empowerment and resilience

3.6.3.2.1 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 theft; provide privacy.
- Enable safe smart homes with ubiquitous connectivity.
- Ensure acceptable AI technologies.

Diversity and inclusion are increasingly recognised as crucial for workplace equality and economic development, with global indicators showing a direct link between gender equality and workforce participation. Technology, when properly governed, is a critical lever to close these gaps, e.g. data analytics that expose pay disparities, mitigating recruitment bias, and cloud infrastructure that scales microfinance for underserved populations[5]. It can also equalise access to essential services (biometrics and cloud technology expanding microfinance to women and underserved populations), help enforce inclusive legal rights, policies and social norms, and support diversity through e-voting for vulnerable and marginalised groups, despite cybersecurity challenges. It can further improve physical security and autonomy for minority groups, e.g. connected smart bracelets that allow women to signal an assault and call for help.

Reliance on technology brings benefits but also new risks. The speed of the current digital and AI transition creates systemic risks that legacy frameworks cannot manage, demanding a fundamental recalibration of civic identity, digital rights and safety. Because unlocking AI's potential relies on automated data processing beyond human verification capacity, building public trust requires urgent, technically enforceable solutions for algorithmic explainability, accountability and intersectional ethics[6].

The pandemic years demonstrated the necessity of a connected smart home and adequate home office, though high-bandwidth connectivity remains unevenly distributed across Europe.

Machine learning is essential for a resilient future. AI succeeds best when focused on four areas: augmented intelligence (improving human productivity), intelligent automation (integrating humans and machines rather than just replacing humans), assessed intelligence (making models robust through rigorous, continuous evaluation), and adaptive intelligence (building systems that adapt to change via causal inference).

These developments are increasingly reflected in content creation, where AI and distributed system architectures contribute to empowerment and resilience: AI and deep learning enable automation of complex workflows, improve situational awareness in distributed environments, and reduce dependency on on-site personnel, while a shift to cloud-based, virtualised infrastructures enables scalable, flexible operation across locations, underlining the need for ECS technologies supporting real-time distributed processing, reliable connectivity and robust orchestration under strict latency and reliability constraints.

[5] UN Women & United Nations Statistics Division. (2025). *Progress on the Sustainable Development Goals: The Gender Snapshot 2025.* United Nations.
[6] Mathipa-Mdakane, M. (2025). *Closing the Gender Gap in Digital, Education, STEM and AI.* T20 South Africa Policy Brief.

3.6.3.2.2 Key focus areas

High-priority R&D&I areas:

- Reliable and ubiquitous digital infrastructures
- Access control/intrusion detection/surveillance
- Provide a protective environment and tools against virus infections
- Protect individual citizens against cyber-fraud (scams), identity theft and AI-generated voice/deepfake fraud
- Consumer cybersecurity tooling: security and privacy software for connected devices, privacy-preserving threat detection at scale, and European cybersecurity vendors as strategic enablers of a trustworthy digital society
- Off-grid living and emergency survival
- AI-enabled automation and situational awareness
- Distributed and virtualised (video) processing architectures
- Depth-aware sensing and perception

Secure, high-bandwidth connectivity must reach every worker regardless of location, backed by resilient cloud services for latency-sensitive tasks such as remote robotic surgery, industrial robot control, security-camera operation and live-production feeds.

Assistive technologies create equal opportunities: speech-generating devices, exoskeletons and semi-autonomous vehicles for people with sensory impairments, geolocation-linked safety tools, communication aids for paralysed patients, VR for people with physical disabilities, and smart glasses supporting people with autism.

Technology itself is neutral, but its misuse, disinformation, cyber-attacks and consumer fraud are growing risks as IoT, robotics, automation and AI scale up. Consumer cybersecurity must therefore be treated as a core R&I priority: security and privacy tooling for connected devices, privacy-preserving threat detection at scale, and strong European vendors are essential to keep the human layer of Europe's digital infrastructure trustworthy and under European jurisdiction.

AI-based automation and monitoring reduce repetitive tasks and strengthen situational awareness in distributed, mission-critical settings. Edge-cloud architectures with real-time orchestration support scalable, resilient operation across dispersed systems, while advanced sensing (e.g. phase-detection autofocus, real-time depth estimation) enriches the data available to these AI-driven systems, improving robustness and adaptability.

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 3.6.4.

Specific R&D developments necessary	ECS technologies							
Major challenge 2: "Facilitate empowerment and resilience"	Process techn, equipm, materials & manufact.	Components, modules and system integration	Embedded SW & Beyond	System of Systems	Edge Comp. & emb. AI	Connectivity	Architecture & Design	QRSC
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Reliable, dependable and secure SW and HW	X		X			X	X	X
Trustworthy AI/Machine Learning algorithms					X			X
Advanced cyber-security and privacy methods and tools		X	X			X	X	X
Ensuring 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	X
AI-enabled automation and situational awareness in distributed and mission-critical environments		X	X	X		X	X	X
Distributed and virtualised real-time processing and orchestration across edge-cloud infrastructures		X	X	X		X	X	X

Figure 3.6.4 - Required R&D&I developments within ECS – Major Challenge 2

3.6.3.3 Major Challenge 3: Facilitate inclusion and collective safety

3.6.3.3.1 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.
- ECS as a means of providing affordable solutions.

European welfare models vary but share a history of robust social protection and inclusive growth, now under stress: governments cut social welfare (longer working times, later retirement, less public funding) while parts of society resist, fuelling demonstrations and a shift to the political right. Ageing,

global competition, migration, climate change, digital technology/automation/AI, and shifting geopolitics are combining to raise inequality and divergence within Europe.

Inequality at work can emerge from automation substituting for labour, and from corporate diffusion dynamics that disadvantage non-adopting firms. To avoid reduced employment and secure real wage growth, automation using AI, robotics and other technologies must deliver significant productivity gains; workers with low levels of education and skills in repetitive, non-digital roles will otherwise be the first to face wage pressure.

Collective growth and well-being depend not only on workplace equality but also on individual development supported by collective interaction. Active social relationships improve health, longevity and key biomarkers; isolation subtly harms mental health by reducing attention, learning, memory and decision-making. Direct contact – family, friends, team sports, shared events – remains irreplaceable by technology, but the Covid pandemic forced a rethink of how technology can increase and improve social interactions between individuals and groups, raising the question of how technology can support and secure healthy digital social interaction, including during future setbacks.

Trustworthiness of the underlying Electronic Components and Systems is a non-negotiable boundary condition for all digital society solutions deployed in Europe.

Collective safety can also be enhanced by solutions addressing specific communities – families, friends, neighbourhoods, regions and clubs – either through warning/alerting functions (contamination, local fire, air pollution, violence) or supporting functions such as alerts or instructions combined with collective devices (e.g. automated external defibrillators, diagnostics, measurement).

3.6.3.3.2 Key focus areas

High-priority R&D&I areas:

- Digital inclusion: tools, infrastructure, training and 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.
- Affordable trustworthy ECS tools, miniaturisation and energy management of ECS-enabled services for society

Ensuring EU-wide digital inclusion means guaranteeing access to remote education, training and assessment in both cities and rural areas, using simple, low-barrier human-machine interfaces that avoid a digital split between citizens. Priority research directions include AI-driven personalised learning journeys, curriculum adaptation, admin-reducing nudging tools, dyslexia-friendly tablet learning, real-time support wearables and eye-tracking, together with AR/VR for remote and under-served communities. The EU highlights that science, technology, social sciences, humanities and the creative sector must work together to make these solutions genuinely human-oriented and inclusive.

Scaling AI for video-based inclusion applications still faces practical hurdles: the volume of data needed for accurate models, the cost of manual labelling (partly addressed by reinforcement learning,

GANs, transfer and one-shot learning), the need for continuous model refreshes in consumer applications, and the risk of selection bias skewing results.

Collective safety requires further research on secure access control, intrusion detection and (video) surveillance. Access-control-as-a-service, combining biometrics with building automation and occupancy data, supports both routine security and emergency evacuation. Heightened security concerns are driving demand for thermal and multi-sensor screening at entrances, while AI-based video/audio analysis, including face, object and event recognition, and drone-based aerial surveillance over 5G/6G, can multiply the effectiveness of human security operators.

Better video quality (spectral range, colour gamut, dynamic range) improves both AI performance and the viewing experience. Explainable AI, watermarking and processing metadata are needed to trace and counter deepfakes and other AI-generated misinformation, alongside stronger security of the cloud-connected equipment used to create and process content.

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 3.6.5.

Specific R&D developments necessary	**ECS technologies**							
Major challenge 3: "Facilitate inclusion and collective safety"	Process techn, equipm, materials & manufact.	Components, modules and system integration	Embedded SW & Beyond	System of Systems	Edge Comp. & emb. AI	Connectivity	Architecture & Design	QRSC
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	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/Machine Learning	X		X		X	X	X	
Advanced cyber-security 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 3.6.5 - Required R&D&I developments within ECS – Major Challenge 3

3.6.3.4 Major Challenge 4: Facilitate supportive infrastructure and a sustainable environment

3.6.3.4.1 Status, vision and expected outcome

Ambition: contribute to a supportive infrastructure and environment for society.

- Provide trustworthy, reliable, and resilient infrastructure.
- Establish a sustainable and secure environment.
- Provide means for controlled climate change.

To fully benefit from digitisation, Europe must enable a supportive infrastructure and environment, requiring companies to ready their technology, people and culture for digital transformation. This means a reliable, resilient digital infrastructure with ubiquitous, continuous connectivity; protecting society against destabilising forces, including harmful internet use such as election manipulation, deepfakes/cheapfakes, identity theft and phishing (covered under Major Challenge 3); and establishing a secure, sustainable environment, including controlled climate change (per the Green Deal) through means available to citizens. Monitoring and intelligent control of infrastructures, resources and recycling, especially in urban environments, will further support sustainability.

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 the largest areas of energy and materials consumption and CO_2 production. In addition to air quality monitoring systems, these solutions need to address lighting, heating and computing with reduced use of energy and other resources. In addition, solar panels and batteries, home-grown vegetables and city farming systems are key.
- Providing smart systems based on IoT and unmanned/robotic platforms that provide secure environments and support digital business life using the minimum amount of resources (energy, water, paper, travelling, etc.), ensuring a highly efficient, productive, and sustainable working environment.
- 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. Reduction of (food) waste in supermarkets and restaurants, as well as resource recycling.
- Development of new digital solutions that can be used by citizens themselves or that can stimulate societal attitudes and activities towards sustainability and addressing climate change, e.g. car sharing, use of public transportation, bikes, and e-scooters.

Europe's approach to digitalisation focuses on preserving the democratic system and values such as trust and cooperation, with ethical requirements including fairness, accuracy, confidentiality, transparency, accountability, explainability, trustworthiness and absence of bias. This includes AI capability maturity programmes that coach companies using AI in their designs on best ethical practice, making products more resilient, accessible, reliable and trustworthy, ready for the new European digital society, in compliance with the EU AI Act, whose provisions apply progressively through 2026 and beyond.

3.6.3.4.2 Key focus areas

High-priority R&D&I areas:

- Physical infrastructure management/physical resilience and security.
- Intelligent infrastructure management (intelligent buildings, city-owned infrastructure, synergies with industry, etc.).
- Digital solutions and infrastructure for resource management, digital resilience, sustainability, e-government and citizen support.
- Resource and environment monitoring (air, water, etc.) and feedback to enable more effective management.

New digital tools using IoT, unmanned vehicles/robots and AI/ML-enhanced algorithms need to be deployed into existing infrastructure, backed by adequate investment, standards and compliance with the EU Cyber Resilience Act. For buildings, this means smart lighting, air-quality control, IoT-based utility monitoring and predictive maintenance (e.g. sensors on radiators, boilers and pumps) to cut costs and carbon footprint, with digital twins increasingly used to simulate, monitor and optimise buildings and city infrastructure in real time.

With up to 90% of the global population expected to live in cities by 2050, digital solutions for sustainable urban development are needed at every scale, from small municipalities to megacities. To avoid vendor lock-in and protect data sovereignty from dominant non-EU platforms, Europe needs widely available open-source and sovereign-cloud solutions (e.g. FIWARE, Gaia-X-aligned platforms, the Eclipse Arrowhead Framework), which can also draw on Europe's industrial heritage given the frequent overlap between industry sites and city areas.

Technology's contribution to environmental sustainability spans retail (IoT-enabled reduction of food waste through temperature and expiry management, support for new products such as plant- or insect-based food) and manufacturing (smart energy and wastewater management, carbon capture, biofuel generation).

ECS also plays a structural role in financial markets and insurance: low-power asset-tracking and telematics enable usage-based insurance and automated payments, while secure hardware wallets and NFC support cryptocurrency and digital-product-passport use cases. Trading and market-data infrastructures depend on traceable, high-precision timing and deterministic, low-latency networking (oscillators, hardware timestamping, SmartNICs, FPGA-enabled switches, optical interconnects), creating demand for European capability in programmable logic, domain-specific accelerators and secure hardware/software co-design.

Required R&D&I developments within ECS

The development of supportive infrastructure and a sustainable environment within the EU requires 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 techn, equipm, materials & manufact.	Components, modules and system integration	Embedded SW & Beyond	System of Systems	Edge Comp. & emb. AI	Connectivity	Architecture & Design	QRSC
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	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 cyber-security 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		X
Distributed (production) systems		X		X	X	X	X	X

Figure 3.6.6 - Required R&D&I developments within ECS – Major Challenge 4

3.6.4 Key Enabling Methodologies

Key Enabling Methodologies[7] bridge the opportunities of Key Enabling Technologies in ECS with the four Major Challenges for the Digital Society: they are the 'instruments' that direct and structure collaborative ways of working, giving direction and delivering impact through useful applications and meaningful interventions.

KEMs integrate the technological opportunities of ECS with knowledge from design, social sciences and the humanities about the Digital Society.

KEM categories cover Vision & Imagination, Participation & Co-creation, Behaviour & Empowerment, Value Creation & Upscaling, and Institutional & System Change, helping answer questions such as: how can technological tools, infrastructure and training empower citizens towards digital inclusion? How can we anticipate setbacks and build collective resilience? How can relevant societal stakeholders be included in ECS R&D&I?

[7] https://kems-en.clicknl.nl/

3.6.5 Timeline

The following table illustrates the roadmaps for Digital Society.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
Major Challenge 1: facilitate individual self- fulfilment	Topic 1.1: improved human–machine interaction solutions	Accessible multimodal HMI demonstrated with measured usability, workload, privacy and effective user control.	Adaptive HMI qualified across user groups, with transparent personalisation and safe intervention.	Lifecycle-adaptive interfaces qualified under changing abilities and contexts with sustained accessibility evidence.
	Topic 1.2: online education and examination	AI-assisted online teaching and assessment demonstrated with pedagogical validation, accessibility, provenance and teacher oversight.	Interoperable learning/assessment services qualified across institutions with measured learning outcomes and robust integrity controls.	Lifelong learning ecosystems qualified across institutions and changing curricula with portable evidence and maintained learner agency.
	Topic 1.3: VR/AR training and support	XR training and remote support demonstrated with task-performance, accessibility and visual-fidelity validation.	Interoperable XR training qualified across devices with validated transfer to real tasks and calibrated sensing/display chains.	Adaptive multisensory training qualified over repeated field use with maintained skill transfer and user-safety evidence.
	Topic 1.4: support devices (wearables, robots, cobots, etc)	Assistive wearables and collaborative robots demonstrated in real tasks with safe interaction and measured user benefit.	Context-aware assistive devices qualified across care, work and daily-living settings with reliable handover and privacy controls.	Coordinated assistive ecosystems qualified for long-term personalisation, maintenance and safe adaptation to changing user needs.
	Topic 1.5: nudging, gamification (for development or health reasons)	Nudging and gamification prototypes validated for education or health with informed participation and measured benefits.	Personalised interventions qualified in longitudinal studies with safeguards against manipulation and unequal outcomes.	Adaptive intervention services qualified across changing populations with sustained benefit, user choice and independent evaluation.
Major Challenge 2: facilitate empowerment and resilience	Topic 2.1: access control/ intrusion detection/ surveillance	Privacy-preserving multimodal intrusion detection demonstrated with measured false alarms, adversarial robustness and human review.	Multi-site access and intrusion systems qualified with interoperable identity, bounded data retention and tested degraded operation.	Federated protection services qualified across operators with accountable data sharing and lifecycle threat adaptation.
	Topic 2.2: reliable and ubiquitous digital infrastructures	Resilient 5G/edge services demonstrated with application-specific latency, availability and secure local fallback; first 6G capabilities assessed in pilots.	Interoperable edge/cloud services qualified for selected critical applications with bounded latency and recovery under network disruption.	Cross-operator digital infrastructure qualified under evolving traffic, threats and failures with measured service guarantees and resource limits.
	Topic 2.3: social media/serious gaming/AR/VR	Adaptive serious games and immersive media demonstrated with user controls, content provenance and protected media workflows.	Multimodal learning/media services qualified across platforms with validated personalisation and interoperable provenance verification.	Adaptive immersive services qualified through longitudinal learning and well-being evidence, preserving provenance, privacy and user agency.
Major Challenge 3: facilitate inclusion and collective safety	Topic 3.1: digital inclusion: tools, infrastructure, training, connectivity	Inclusive digital services demonstrated across sensory, cognitive and connectivity needs with representative user trials and accessible alternatives.	Interoperable hybrid participation systems qualified across devices and institutions with measured inclusion and usable support.	Immersive collective participation qualified across changing abilities and contexts with sustained accessibility and equitable access evidence.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2027–2031)	MEDIUM TERM (2032–2036)	LONG TERM (2037 and beyond)
	Topic 3.2: resilient society against setbacks	Multi-agency crisis tools demonstrated with interoperable communications, localisation confidence and disruption-tolerant operation.	Coordinated crisis-response services qualified across agencies through representative exercises, privacy controls and human command.	Federated crisis services qualified for cascading cross-border disruptions with independently tested recovery and information provenance.
	Topic 3.3: societal acceptance of novel technologies	User-participation and oversight methods demonstrated in deployed pilots with measurable acceptance, workload and calibrated trust.	Human-centred AI adoption methods qualified across communities with longitudinal evidence of agency, accessibility and contestability.	Lifecycle participation frameworks qualified across changing technologies and populations with independently evaluated social outcomes.
Major Challenge 4: facilitate supportive infrastructure and environment	Topic 4.1: physical infrastructure management/ physical resilience	AI-assisted IoT and robot inspection demonstrated on operating assets with measured defect coverage, safe access and maintenance integration.	Multi-asset inspection services qualified with uncertainty-aware diagnosis and verified links to maintenance decisions.	Coordinated autonomous inspection qualified across asset classes with human authority, verified fault coverage and lifecycle evidence.
	Topic 4.2: intelligent infrastructure management	Local digital twins and resource-control systems demonstrated using interoperable operational data and measured water, heat or lighting benefits.	Cross-domain infrastructure orchestration qualified with validated models, operator authority and safe resource trade-offs.	Federated infrastructure management qualified across operators with evidence of lifecycle resource savings and recovery under cascading failures.
	Topic 4.3: digital infrastructure management/digital resilience and cybersecurity	Secure-by-design infrastructure management demonstrated with authenticated updates, monitored dependencies and exercised incident recovery.	AI-assisted defence qualified across interoperable infrastructure systems against defined threats with privacy controls and operator review.	Federated cyber-resilience services qualified under evolving threats with bounded autonomous response and independently tested recovery.
	Topic 4.4: surveillance, homeland security and emergency response systems	Multi-agency situational-awareness prototypes demonstrated with interoperable mission-critical voice/data/video, localisation confidence and accountable sensing.	Operational emergency-support platforms qualified across agencies and unmanned systems with tested degraded communications and human command.	Cross-border emergency-support ecosystems qualified through sustained exercises with verified information sharing, privacy and coordinated recovery.

4



Strategic Research and Innovation Agenda

LONG-TERM VISION

4.1 INTRODUCTION

In this chapter, we present research subjects that need to be addressed by European organisations to enable and support the effective development of European industry over the next decade. 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 programmes for effective research and development in appropriate technological and/or application domains, so that European technological strength increases continuously over time and at the appropriate rate. Since the 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 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 presented in the Introduction, these five high-level common objectives are:

- Boosting industrial competitiveness through interdisciplinary technology innovations.
- Ensuring EU digital autonomy 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.
- Unleashing the full potential of intelligent and autonomous ECS-based systems for the European digital era.
- Enable the ECS Engineering Ecosystem

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, within trusted, protected and regulated multilateral agreements in the emerging international political and economic landscape. The European Union’s policies to protect its strategic autonomy and sustain its competitiveness are continuously evolving, especially for the ECS industry, which constitutes the backbone of the digital society. European digital strategic autonomy – the 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 programmes 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 demonstrate 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 interfaces. 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 required 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, characterised by:

- Zero net emissions of greenhouse gases.
- Economic growth decoupled from resource use.
- Inclusion (no person and no place are left behind).

The ECS community is instrumental in the realisation 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 and fifth one as well. The “unleashing” of intelligent and autonomous ECS-based systems requires interdisciplinary effort and coordination among all stakeholders: academic, institutional, and industrial. In the effort to ensure timely identification and effective exploitation of opportunities, close cooperation among 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 expertise and extensive experience in the ECS domain. This comprehensive ecosystem of universities, RTOs, and industrial research organisations 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 basis for maintaining the competitiveness of the European ECS industry now and in the future. Cooperation also offers the

[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

best opportunities for addressing growing interdependencies and interdisciplinarity through strong coupling of basic and applied research within the European Research Framework Programme. This, in turn, creates fertile ground from which industry can gain substantial impetus to achieve breakthrough solutions with minimal time to market, helping to maintain European technological excellence and leadership, which is the cornerstone of long-term European technological leadership and a basis for prosperity and peace on our continent.

Additionally, and independently of policies, the 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 on business and society. The World Wide Web is a typical example of a disruptive technology.

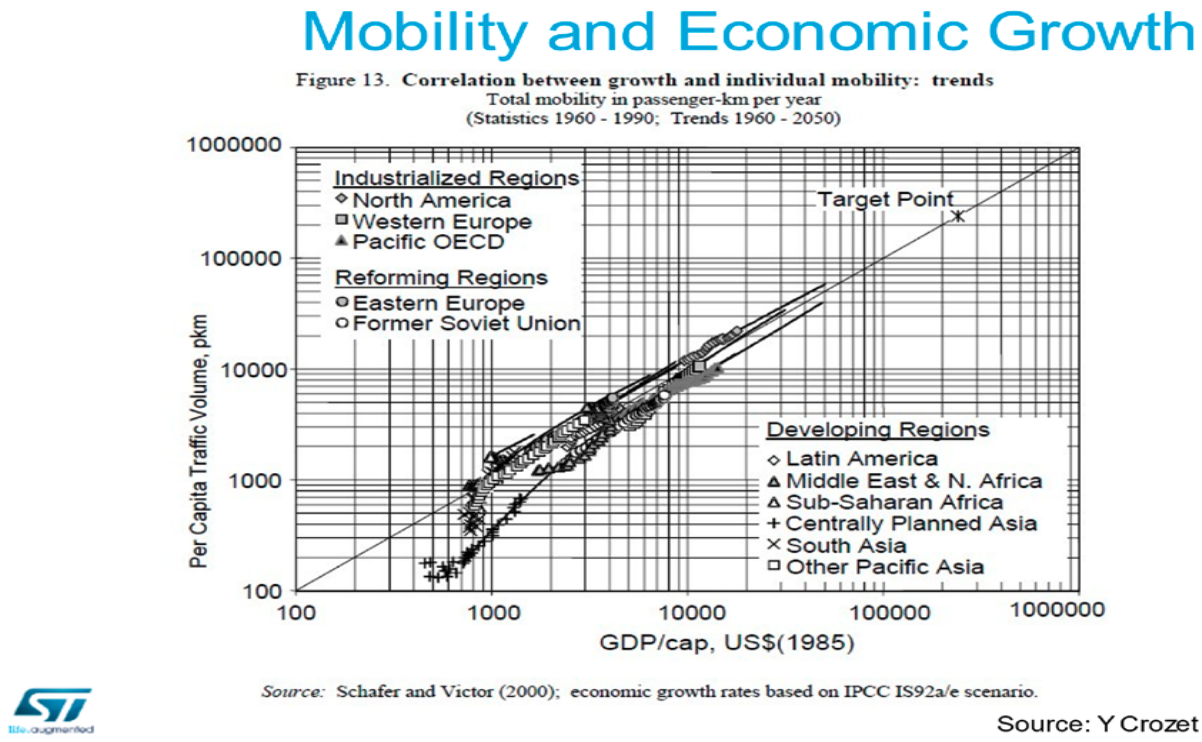

Figure 4.1 - Technology evolution and application requirements

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 centres 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 continued provision 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 inherently infeasible. 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 present technological challenges and needs to be met in application domains.

4.2 MODEL

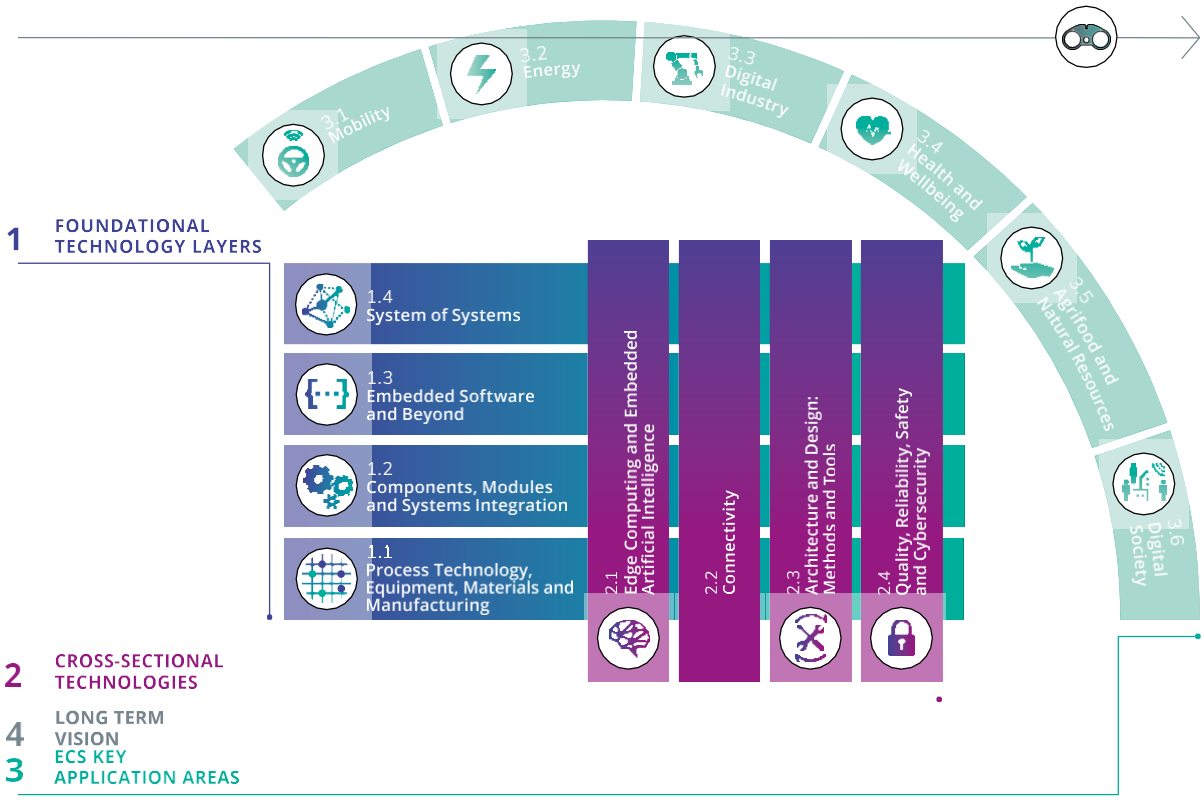

Figure 4.2 - Technology domains evolution and application requirements

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, on 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 one or more parts of the layered model which we exploit for abstraction, understanding, presentation and openness.

4.3 TECHNOLOGY LONG-TERM CHALLENGES

4.3.1 Process technology, equipment, materials, and manufacturing

Europe has 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 is strong interest in Europe in specific activities that involve very-low-power devices, leading to possible disruptive applications – for instance, for future IoT systems, devices for AI/ML, neuromorphic and photonic computing devices, 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, advanced 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 and THz 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 characterisation of optimal architectures and design strategies.
- For nano-electro-mechanical FETs (NEMS-FET), reliable low-voltage devices have to be developed.
- Spin-based devices for switching and sensing.

In the field of alternative memories, resistive RAM, magnetic RAM (SOT and VCMA) and ferroelectric RAM/FeFET/FTJ 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 devices, and innovative device–architecture interactions.

Brain-inspired, or neuromorphic, computing is one of the beyond-von Neumann approaches, which co-locates processing and memory to overcome the memory–processor separation of conventional architectures and exploits the spatio-temporal sparsity characteristic of biological neural systems. Memristive elements can supplement conventional transistors to combine computation and storage at the device level, offering the prospect of drastically improved energy efficiency for large-scale AI/HPC workloads as well as for constrained edge applications. Research in this area is interdisciplinary, requiring the co-design of neuroscience concepts, hardware and algorithms including more efficient, brain-inspired learning schemes, and a common software stack spanning from device to application level. Sustained European effort in this direction is important for maintaining sovereignty in energy-efficient computing and supporting the sustainability goals of the Green Deal.

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 computing.

The emerging field of Quantum computing poses its own challenges in process technology, equipment, and materials:

- As there are still several candidates for the standard quantum computing technology (such as semiconductor quantum dots, superconductor junctions, photonic circuits, ion-traps, cold atoms, topological states, etc.), a wide range of materials is relevant, together with innovations in process technology.
- New metrology capabilities are required, particularly for measuring electrical properties, such as local carrier mobility.
- To achieve practical applications, reliable fabrication, connection, and read-out of qubits need to be developed. The low temperatures at which most quantum systems operate require the development of cryogenic devices to interface with 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 advances in chips are contributing to industries across sectors, and are crucial to achieving the Green Deal objectives, significant efforts are needed to tackle the direct environmental impact of chips and more generally ECS manufacturing. Issues to be addressed include waste generation, resource usage, CO2 and GHG emissions, hazardous materials use, including PFAS, and the use of scarce materials.

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 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 CO2 and GHG emissions, will strongly increase. This consumption and these emissions 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 increasing frequency 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 are needed 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 require more R&D effort to improve the effluent segregation systems and hence increasing the use of recycled water in semiconductor manufacturing lines.

European semiconductor manufacturing should mainly 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 CO2 and GHG emissions, for instance.

CO2 and greenhouse gas (GHG) emissions

In the semiconductor industry, CO2 and greenhouse gas (GHG) emissions 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, NF3, and N20, have high global-warming potential. Recycling unused 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 emissions. 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 essential 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 to chemicals with a lower environmental impact than the aforementioned fluoride gases, such as on-site generation of molecular F2 for replacing NF3, since molecular F2 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 with additive manufacturing 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 associated with PFAS

PFAS comprise a class of thousands of synthetic substances known as 'forever chemicals' since they do not break down in the environment. Most are either persistent themselves or are transformed into persistent compounds in the environment. These substances are hazardous to human health as they accumulate in the body, as well as in water, soil, 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 components added to photoresists as 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, excluding some dedicated applications, there is no PFAS-free alternative for most of the aforementioned applications.

As of today, 1485 tons 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 at least 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 involves an exchange of data, which is curated into information that either results in a gain in knowledge and/or enables purposeful action or reaction to a given situation.

The width and breadth of such data exchange 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 comprise the HW and SW ensembles that at different levels of integration and organisation 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 system functions and applications that are to emerge from the integration of:

- New sensitive and structural materials.
- Physical-to-digital (and vice versa) transducer 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 dependent on energy use 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 assembly 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. Integrating intelligence into these inherently power-restricted devices requires novel power-efficient

computational platforms, such as neural networks and analogue computing approaches in parallel with CMOS and other traditional semiconductor devices as commented in the previous chapter.

Next generation computing devices, using physical processes to perform computation, pose challenges in integration as well as in development. In such approaches, envisaged in Chapter 3.1, and made possible within the framework of processes of Chapter 2.1, other ways of encoding information besides bits will be used, e.g. using qubits or encoding in time, as in 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 specialised 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, maximising performance and minimising e-waste, and particularly for slowing down, reversing climate change or making human environments resilient to it.

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 already been recognised that a combination of nanoelectronics, photonics (optoelectronics), electronic smart systems, including AI/ML subsystems, and flexible, organic and printed electronics

[2] https://www.microsoft.com/en-us/research/project/dna-storage/

is setting the path for future enabling functional electronics[3], which will be characterised by aspects such as:

- A shift from physical to functional integration.
- The use of novel substrates and structural systems.
- Seamless integration into 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 between monolithic and heterogeneous integration, and what can be achieved with them, is subject 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 customised 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, characterisation 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 optimisation 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

Next-generation cyber-physical systems will play a key role in future AI, IoT and SoS implementations, 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

[3] https://5e-project.eu

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 ensuring inclusiveness.

To overcome challenges related to efficient software engineering, 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 handling 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 large-scale digital twins at the edge, as well as their deployment along with systems, will contribute to 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 world, 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 property 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. In 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.

The use of safe, trustworthy and 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, the 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 in the 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 digitalisation and automation solutions across integrated and optimised operations of engineering, production, logistics, infrastructures, etc. The inherent heterogeneity of SoS is expanded by new, emerging computational models that include accelerators, AI/ML subsystems, approximate computing, organic systems and others, posing 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 standardisation 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 use of SoS technology is further expected to be a significant contributor to the Green Deal through distributed and intelligent solutions that provide a significant reduction in 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 applications and services run across them 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 methods adopted to address conflicting functional and non-functional requirements.

[4] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Available online at: https://artemis-ia.eu/publication/download/advancy-report.pdf.

- Engineering support for emerging behaviours in complex SoS:
    - Model-based engineering.
    - Predictability, controllability, monitoring and diagnosis.
- 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 across 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 for 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 on all fronts.

AI technology is becoming increasingly demanding in terms of 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 require further 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.

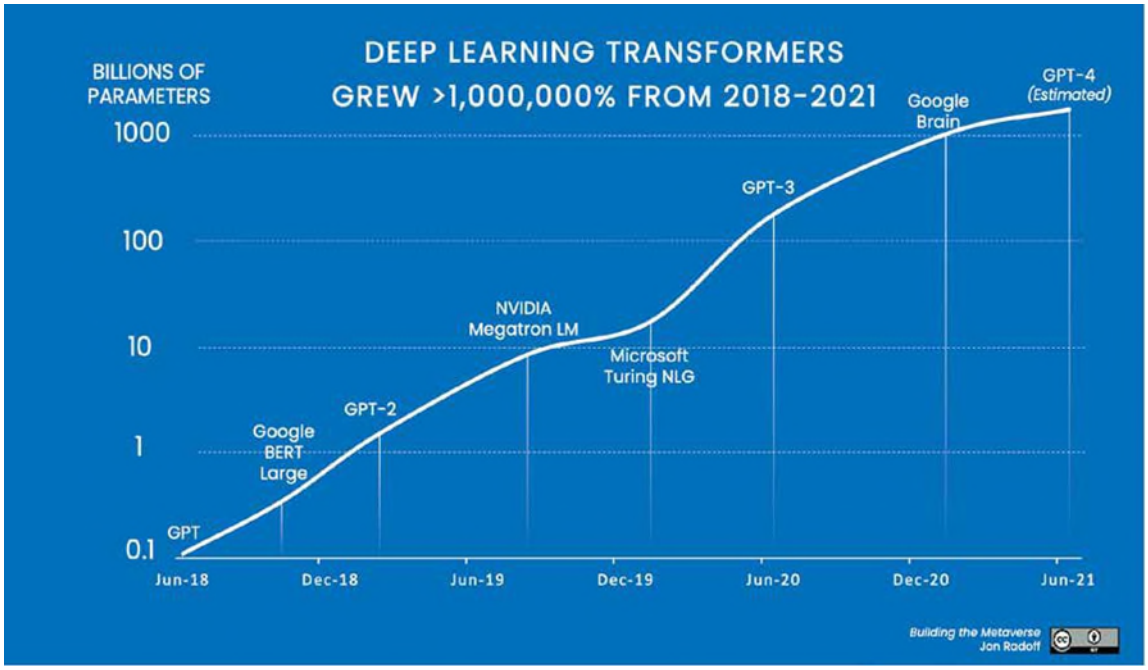

Figure 4.3 - The increase of parameters employed for deep learning systems (2018-2021)

AI accelerators will appear in many devices from the deep edge to home servers, allowing the processing of all kinds 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 recent years. Computing systems will become embedded in their 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 applications 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 can decrease the need for large databases 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.

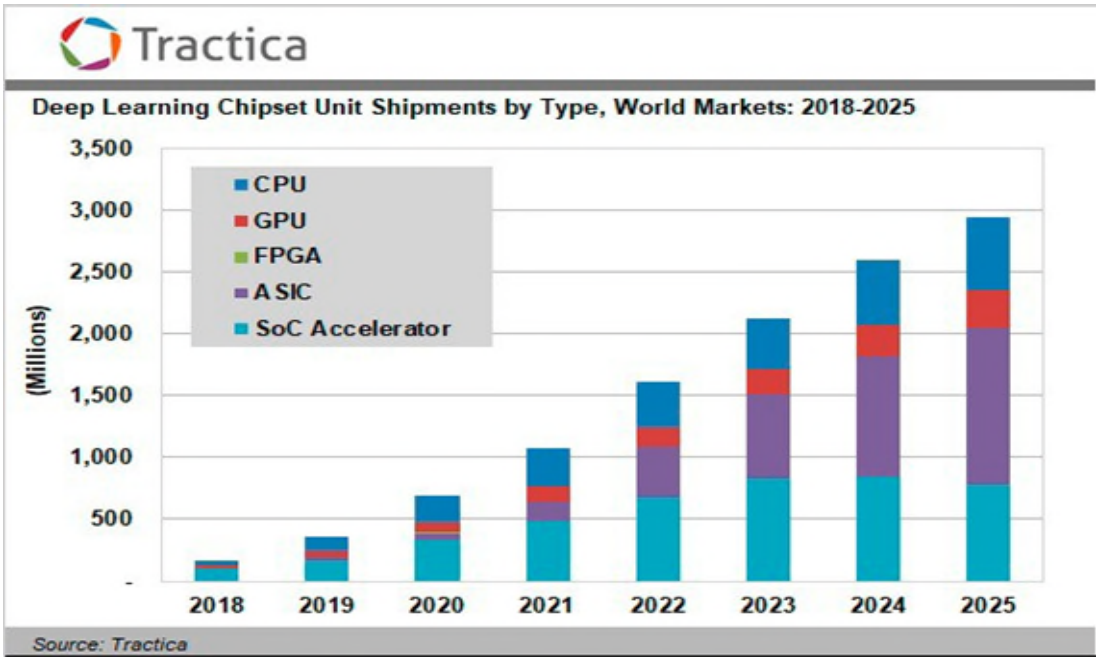

Figure 4.4 - The growth of deep learning chip shipments (2018-2025)

The mass market for smart systems will still be served by highly 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 often do not 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 organisations to have their own "device manufacturing" that do not need high-quality cleanrooms. 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 to be connected anywhere, by any means and at any time. 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 digitalisation and automation activity to strengthen Europe's position and enable the European industry to capture new business opportunities associated with the connected world in which we live. It is vital to support European technological leadership in

[5] https://www.nature.com/articles/s41586-021-03625-w

connectivity, fostering digitisation 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, 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 virtualised, relying on run-time design, deployment, and management of integrated edge and cloud network architectures. This will enable the connectivity from the cloud to the 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 standardisation 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 customised 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 standardisation 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 utilisation 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

[6] Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Available online at: https://artemis-ia.eu/publication/download/advancy-report.pdf.

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 virtualised 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 characterised 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 characterised by new functionalities, increased complexity, and diversity on all fronts, ranging from methods and paradigms to modelling and analysis. As the competition from 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 realise 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 analysed 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 modelling 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). Advances in mobile systems and applications enable a person with a mobile phone to buy a flight ticket, make a money transfer, or maintain social contacts; new services are becoming continuously 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 daily life. In the near future, highly automated and autonomous systems supported by AI will have a constantly 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 external environmental control to work as intended. 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 must make every effort to provide innovative products of the well-known high quality, reliability, safety and cybersecurity to our customers. From this perspective we expect the following challenges to be considered in the long term:

- Development and integration of new materials for advanced packaging and interfaces, new characterisation techniques, and new failure modes caused by new use-case scenarios.
- AI/ML methods, including digital twins, to be a cornerstone of maintaining leadership

regarding quality and reliability of ECS made in Europe and be an enabler for new data-driven business models.

- Model-based engineering (incl. standardisation 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 (including standardisation 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”).
- Attention to the environment and privacy has 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 organisations on suppliers and contractors for provisioning of hardware as well as software components and systems. Trust among them is not a given. 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 and 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 4.2.

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 optimisation 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 of 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 optimise 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 data 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 referred to as the "far edge") are ever increasing, ML-based inference

[7] M. Rapp, H. Amrouch, Y. Lin, B. Yu, D.Z. Pan, M. Wolf and J. Henkel, "MLCAD: A Survey of Research in Machine Learning for CAD." In IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems, 41(10), Oct. 2022.

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 perspectives in the Internet of Things (IoT). Distributed ML will involve several aspects, including latency, bandwidth utilisation, data safety, data quantisation, 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 specialised 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.

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[8] V. Sze, Y. Chen, T. Yang, and J. S. Emer, "Efficient Processing of Deep Neural Networks: A Tutorial and Survey." Proceedings of the IEEE, 105(12), Dec. 2017, pp. 2295–2329.

[9] E. Wang et al., "Deep Neural Network Approximation for Custom Hardware." ACM Computing Surveys, 52(2), May 2019, pp. 1–39.

[10] F. P. Sunny, E. Taheri, M. Nikdast, and S. Pasricha, "A Survey on Silicon Photonics for Deep Learning." ACM Journal on Emerging Technologies in Computing Systems, 17(4), Oct 2021.

[11] A. Reuther, P. Michaleas, M. Jones, V. Gadepally, S. Samsi and J. Kepner, "AI and ML Accelerator Survey and Trends." 2022 IEEE High Performance Extreme Computing Conference (HPEC), MA, USA, 2022, pp. 1-10.

[12] IMEC, "AnIA: a novel AI IC." Available online: https://www.imec-int.com/en/expertise/cmos-advanced/compute/accelerators#ania

[13] Synopsys, "Infineon and Synopsys Collaborate to Accelerate Artificial Intelligence in Automotive Applications." Available online: https://news.synopsys.com/2019-09-17-Infineon-and-Synopsys-Collaborate-to-Accelerate-Artificial-Intelligence-in-Automotive-Applications

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 commercialization, 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 factoring 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 maximise the probability of measuring the correct answer.

There are two main quantum computing models today:

- Analogue or adiabatic quantum computing, and
- Gate-based quantum computation.

Analogue 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. Analogue 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 108 and 105 "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 104-106 "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 102 to 104 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 quantum computer will serve as an accelerator that solves the 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 benefits in a larger problem.

Figure 4.5 shows the expected evolution of the number of "logical" qubits for both FTQC and NISQ approaches.

[14] National Academies of Sciences, Engineering, and Medicine. 2019. *Quantum Computing: Progress and Prospects*. Washington, DC: The National AcademiesPress.

[15] B. de Jong, How about quantum computing?, Berkeley labs. Available at: https://cs.lbl.gov/assets/CSSSP-Slides/20190624-deJong.pdf [Last access: Oct. 15, 2023)

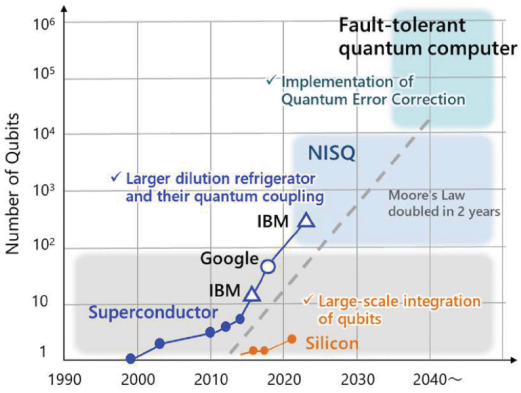

Figure 4.5 - Historical and projected number of physical qubits and the goal for NISQ and FTQC approaches[16]

The number of qubits, and qubit and quantum gate fidelity in a system are the defining parameters 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, colour centres, trapped ions, cold atoms, photons and topologically protected Majorana modes. These alternative qubit technologies differ significantly in physical aspects, operational and miniaturisation 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 4.6 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.

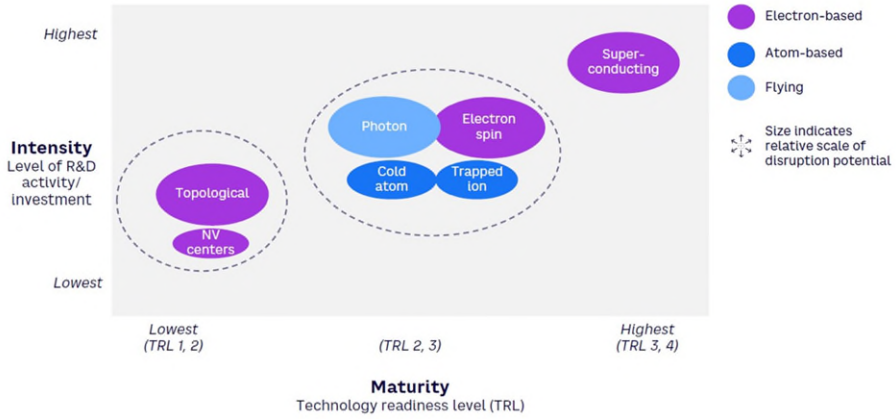

Figure 4.6 - Core qubit technologies mapped by maturity, intensity, and disruption potential

[16] H. Mizuno, "Quantum Computing from Hype to Game Changer," 2023 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits), Kyoto, Japan, 2023, pp. 1-4, doi: 10.23919/VLSITechnologyandCir57934.2023.10185419

Table 1: Properties of various qubit manufacturing technologies for quantum compu					
Qubit technology	Superconductor	Trapped ion	Si e^- spin	Cold atom	Photon
Qubit size	100µm²	1mm²	100nm²	1-10µm²	5-25µm²
Quantum gate	Microwave Magnetic field	Laser Microwave	Magnetic field	Laser Microwave	Interference
1-qubit fidelity	99.96%	99.999%	99.93%	99.9%	

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 at an early stage and present significant challenges. The goal of user-friendly quantum computers that can be programmed effectively and efficiently requires significant advances in algorithms and software tools. Recent advances in specialised 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 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: higher income means greater travel distances as Figure 4.7 indicates. Will this very simple equation still work in the future?

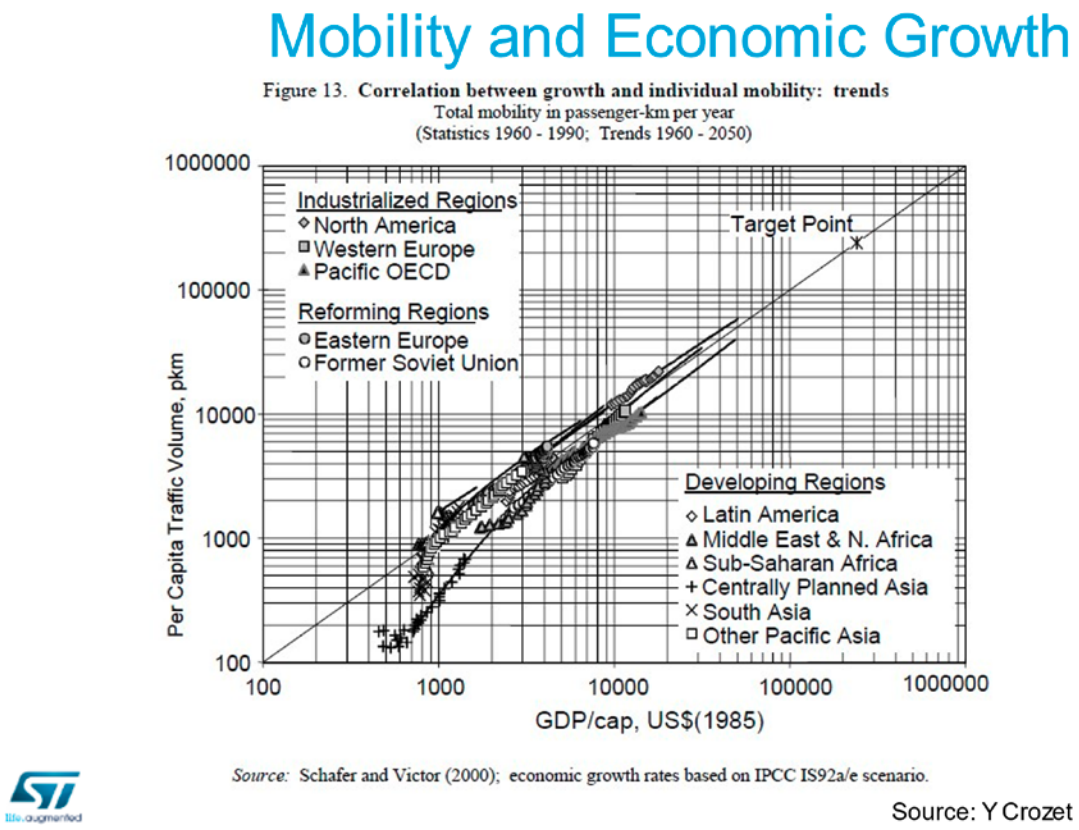

Figure 4.7 - The correlation between growth and individual mobility

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.Global mobility is undergoing a significant change triggered by the increasing threat 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 by using a connected, shared and energy-efficient 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, buses, airplanes, ships, buses, 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 of six. 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 centres 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 an ageing 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 optimised 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 stabilisation 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 are 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 Ga2O3, 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 of achieving 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 utilising 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 realise 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 increase the share of renewable energy generation, self-consumption (mainly heating/cooling and EV) and building optimisation, 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 cybersecurity to increase 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 essential to the evolution of European production and commerce over the next decade, following and empowering the EU policy related to digitalisation. Digital capabilities and functions will enable a safer, greener, more sustainable, lower-cost, more productive, autonomous and competitive EU industrial ecosystem.

The EU planned strategic investments, particularly following the experience and lessons of Covid, to address digitalisation, including industrial production, edge-technology engineering, development and deployment efficiency and services, as well as logistics, transport, health and critical EU infrastructure.

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[17] 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 redesigned processes.
- Complete redesign of industrial parks to realise industrial symbiosis.
- The Factories of the Future (EFFRA[18]) roadmap summarises 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[19] 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 characterised 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.

[17] https://www.spire2030.eu/what/walking-the-spire-roadmap/spire-Roadmap
[18] https://www.effra.eu/factories-future-roadmap
[19] https://www.effra.eu/connectedfactories

- Networked, autonomous operations complemented by software solutions (incl. AI).
- Seamless integration into 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 behaviours 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), powerful edge computing 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 ageing 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 decentralized 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 personalised monitoring, mentoring and treatment.

ECS will remain key enablers to realise 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 ageing population.

In the long term, personalised and patient-tailored healthcare will be at the forefront of technology advancement. Further miniaturisation 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 localised 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, must 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 digitisation 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 personalised 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 personalised and accurate health data will be available anywhere, anytime.
- Drug development will be assisted by emerging methodologies such as ‘organ-on-chip’ and advanced life science tools such as massively parallel, high-throughput and/or highly multiplexed omics technologies, all leaning on a strong co-creation of ECS multi-modal technology platforms leveraging photonics, imaging, electrochemical read-out, nanopores, and others with biochemistry, biology and AI.
- 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 personalised 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 representation 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[20] 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.

[20] https://www.health-lighthouse.eu/emerging-medical-domains

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. Digitalization 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 optimised. 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.

The European Green Deal is a response to these challenges, considering the huge negative impact of climate change. It includes two main programmes "From farm to fork" and "Biodiversity 2030" having a strong impact in the goals of this Chapter, which should contribute to reaching the targets defined by these two programmes 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 fertilization, 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[21], putting our food security and nutrition at risk. Biodiversity also underpins healthy and nutritious diets and improves rural livelihoods and agricultural productivity[22]. 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 the EU's competitiveness.

To contribute to reaching the targets of these two programmes, 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 enable the monitoring, quantification and understanding of 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 optimise 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 also be 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.

[21] World Economic Forum (2020), The Global Risks Report 2020.

[22] Food and Agriculture Organization (2019), State of the World's Biodiversity for Food and Agriculture (http://www.fao.org/state-of-biodiversity-for-food- agriculture/en/)

- Environmental protection and sustainable production:
    - In-situ, real-time monitoring of soil nutrients and herbicides should be carried out through intelligent and miniaturised 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. The focus should be on GHG emissions 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 miniaturised systems, at a low cost, are also required.
- Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation:
    - Biodiversity restoration for forestry ecosystems should involve precision forestry systems with remote sensing and AI/ML monitoring capabilities to map and assess the condition of EU forests, as well as enable early detection and prevention of threats to forests (wildfires, pests, diseases, etc.). Furthermore, smart systems are required for environment monitoring of forests and fields, as well as CO2 footprint monitoring. Remote monitoring of wildlife behaviour and habitat changes, and timely warnings of illegal poaching activity, are also needed.

4.4.6 Digital society

Ubiquitous connectivity (“everywhere and always on(line)”) drives 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 towards combining 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

endeavour 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 and 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 localisation.

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-centred, 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, has been a world leader in research, development and innovation for decades. Competition from 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 the 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 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 restrictive. 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.

5

Strategic Research and Innovation Agenda

APPENDIX

5.1 Acronyms used in the document

2D	*Two-dimensional*
2Zero	*Towards Zero Emission Road Transport (European partnership)*
3D	*Three-dimensional*
3GPP	*3rd Generation Partnership Project*
4G	*Fourth-generation mobile communications*
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*
AD	*Autonomous driving*
ADAS	*Advanced driver-assistance system*
AEB	*Automated Emergency Braking*
AF-EAF	*Air Force Enterprise Architecture Framework*
AFIoT	*Architecture Framework for the Internet of Things*
AFM	*Atomic force microscopy*
AI	*Artificial Intelligence*
AIAct	*Artificial Intelligence Act (EU AI Act)*
AIB	*Advanced Interface Bus*
AIoT	*Artificial Intelligence of things*
AIOTI	*Alliance for the Internet of Things Innovation*
ALD	*Atomic layer deposition*

AlN	*Aluminum nitride*
ALU	*Arithmetic logic unit*
AM	*Legacy/incomplete abbreviation for connected and automated mobility; use CCAM (Cooperative, Connected and Automated Mobility)*
AMD	*Age-related macular degeneration*
AMR	*Autonomous mobile robot*
AMS	*Analogue/mixed signal*
ANC	*Active noise cancellation*
ANN	*Artificial Neural Network*
API	*Application programming interface*
AR	*Augmented reality*
AS	*Autonomous system*
ASIC	*Application-specific integrated circuit*
ASIL	*Automotive Safety Integrity Level*
ATE	*Automated test equipment*
ATO	*Automatic Train Operation*
AUTOSAR	*AUTomotive Open System Architecture*
B2B	*Business-to-business*
B2C	*Business-to-consumer*
BATX	*Baidu, Alibaba, Tencent and Xiaomi*
BCD	*Bipolar CMOS DMOS*
BCI	*Brain–computer interface*
BDVA	*Big Data Value Association*
BEOL	*Back end of line*
BESS	*Battery Energy Storage System*
BEV	*Battery electric vehicle*

BGA	*Ball grid array*
BiCMOS	*Bipolar CMOS*
BIM	*Building Information Modelling*
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*
CAP	*Common Agricultural Policy*
Cath lab	*Catheterisation laboratory*
CAV	*Connected autonomous vehicle*
CB	*Conductive-bridge*
CBRAM	*Conductive-bridging RAM*
CCAM	*Cooperative, Connected and Automated Mobility*
CDR	*Carbon dioxide removal*
CEAP	*Circular Economy Action Plan*
CEI	*Cloud–Edge–IoT*
CFD	*Computational fluid dynamics*
CFET	*Complementary Field Effect Transistor*
CI/CD	*Continuous integration and continuous delivery or deployment*
CI/CT/CD	*Continuous integration, continuous testing and continuous delivery or deployment*
CIS	*CMOS Image Sensors*
CMOS	*Complementary metal–oxide–semiconductor*
CMS	*Components, Modules and Systems*

cMUT	*Capacitive micromachined ultrasound transducer*
CNN	*Convolutional neural network*
CNT	*Carbon nanotube*
COTS	*Commercial off-the-shelf*
COVESA	*Connected Vehicle Systems Alliance*
CPO	*Co-packaged optics*
CPS	*Cyber-physical system*
CPU	*Central processing unit*
CRA	*Cyber Resilience Act (EU)*
CRISPR	*Clustered regularly interspaced short palidromic repeats*
CRM	*Critical Raw Material*
CrMMC	*Carbon-reinforced metal matrix composites*
CSA	*Climate Smart Agriculture*
CT	*Computed tomography*
CVD	*Chemical vapour deposition*
D2D	*Device-to-device*
D2W	*Die to wafer*
DC	*Direct current (electrical context)*
DCS	*Distributed control systems*
DEF	*Design Exchange Format*
DevOps	*Development and operations*
DfA	*Design for assembly*
DfM	*Design for manufacturing*
DfR	*Design for reliability*
DfX	*Design for excellence*
DL	*Deep learning*
DMA	*Direct Memory Access*

DNA	*Deoxyribonucleic acid*
DNN	*Deep neural network*
DPP	*Digital Product Passport*
DPU	*Data Processing Unit*
DRAM	*Dynamic random access memory*
DRC	*Design Rule Check*
DSA	*Directed self-assembly*
DSL	*Domain-specific language*
DSP	*Digital signal processor or digital signal processing (depending on context)*
DSS	*Decision-support system*
DT	*Drug-targeted*
DUV	*Deep ultraviolet*
E/E	*Electrical/electronic*
E2CCC	*Edge-to-cloud compute continuum*
EC-RAM	*Electrochemical RAM*
ECAVA	*European Connected and Autonomous Vehicle Alliance*
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”*
EIS	*Electrochemical impedance spectroscopy*
EMC	*Electromagnetic compatibility*
EMI	*Electromagnetic interference*

EMR	*Electronic medical record*
EMS	*Energy management systems*
eNVM	*Embedded non-volatile memory*
EOL	*End of life (also written EoL)*
EP	*Engineering process*
EPD	*Environmental product declaration*
EPI	*European Processor Initiative*
EPLCA	*European Platform on Life Cycle Assessment*
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 (distinct from FAIR data principles)*
FAIRness	*Findability, accessibility, interoperability and reusability (FAIR data principles)*
FC-BGA	*Flip-chip ball grid array*
FCC	*Federal Communications Commission*
FDSOI	*Fully depleted SOI*
FeFET	*Ferroelectric Field Effect Transistor*
FEM	*Finite element method*
FEOL	*Front end of line*
FeRAM	*Ferroelectric random-access memory*
FET	*Field-effect transistor; also Future and Emerging Technologies (EU research programme), depending on context*

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*
FTJ	*Ferroelectric tunnel junction*
FTQC	*Fault-tolerant quantum computation*
GAA	*Gate All Around*
GaAs	*Gallium Arsenide*
GAFAM	*Google, Apple, Facebook, Amazon and Microsoft*
GAMAM	*Google, Apple, Meta, Amazon and Microsoft (successor name to GAFAM after Facebook was renamed Meta)*
GaN	*Gallium Nitride*
GDP	*Gross Domestic Product*
GDPR	*General data protection regulation*
GenAI	*Generative artificial intelligence*
GeoAI	*Geospatial Artificial Intelligence*
GHG	*Greenhouse gas*
GIS	*Geographic Information System*
GNSS	*Global Navigation Satellite System*
GPS	*Global Positioning System*
GPU	*Graphics processing unit*
GWP	*Global warming potential*
HAD	*Highly automated driving*

HAL	*Hardware abstraction layer*
HBM	*High bandwidth memory*
HCI	*Human–computer interaction*
HEMT	*High-electron-mobility transistor*
HEV	*Hybrid electric vehicle*
HF	*High-frequency*
HFC	*Hydrofluorocarbons*
HIL	*Hardware-in-the-loop*
HIR	*Heterogeneous Integration Roadmap*
HMI	*Human–machine interface*
HMLV	*High mix low volume*
HPC	*High-performance computing*
HSI	*Human-Systems Integration*
HTA	*Hexagon Tensor Accelerator*
HTF	*Heat transfer fluid*
HVAC	*Heating, ventilation and air conditioning*
HVDC	*High-voltage direct current*
HW	*Hardware*
I/O	*Input/output*
I4.0	*Industry 4.0*
IC	*Integrated circuit*
ICT	*Information and communications technology; also in-circuit test, depending on context*
IDM	*Integrated device manufacturer*
IEA	*International Energy Agency*
IEC	*International Electrotechnical Commission*
IEEE	*Institute of Electrical and Electronics Engineers*
IGBT	*Insulated-gate bipolar transistor*

IHI	*Innovative Health Initiative*
IIA	*Industrial Internet Architecture*
IIoT	*Industrial IoT*
IIRA	*Industrial Internet Reference Architecture*
IMC	*In Memory Computing*
IMT	*International Mobile Telecommunications*
INCOSE	*International Council on Systems Engineering*
iNEMI	*International Electronics Manufacturing Initiative*
InGaAs	*Indium Gallium Arsenide*
InP	*Indium Phosphide*
IoMT	*Internet of Medical Things*
IoT	*Internet of Things*
IP	*Intellectual property (legal and licensing context)*
IP	*Internet Protocol (networking context)*
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*
ISA	*Instruction set architecture*
ISO	*International Organization for Standardization*
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	*Life cycle assessment*
LCOE	*Levelised cost of electricity*
LCP	*Liquid crystal polymers*
LDS	*Laser direct structuring*
LED	*Light Emitting Diode*
LEF	*Library Exchange Format*
LEO	*Low Earth orbit*
LiDAR	*Light detection and ranging*
LLM	*Large Language Model*
LoC	*Lab-on-a-chip*
LV	*Low voltage*
LVS	*Layout versus schematic*
M2M	*Machine-to-machine*
MaaS	*Manufacturing as a service (industrial context)*
MaaS	*Mobility-as-a-Service (transport context)*
MBSE	*Model-based systems engineering*
MC	*Major Challenge (ECS SRIA terminology)*
MCM	*Multi-chip module*
MCU	*Microcontroller unit*
MDM	*Multi-dimensional metrology*
MEC	*Multi-access edge computing (current term)*
MEC	*Mobile edge computing (former name for multi-access edge computing)*
Medtech	*Medical technology*
MEMS	*Micro-electromechanical systems*
MES	*Manufacturing execution system (production context)*
MES	*Multi-energy system (energy context)*

MIL	*Model-in-the-loop*
ML	*Machine learning*
MM-ENS	*Multimodal energy system*
mmW	*Millimetre wave*
MNBS	*Micro-nano-bio system*
MNS	*Micro-nanosystems*
MoA	*Mixture of agents*
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*
MR	*Mixed reality*
MRAM	*Magnetic RAM*
MRI	*Magnetic resonance imaging*
MRV	*Measurement, reporting and verification*
MUT	*Micromachined ultrasonic transducer*
MV	*Medium voltage*
NB	*Narrowband*
NDT	*Non-destructive testing*
NEMS	*Nano-electromechanical systems*
NFV	*Network functions virtualisation*
NFVI	*Network functions virtualisation infrastructure*
NISQ	*Noisy intermediate-scale quantum*
NIST	*National Institute of Standards and Technology (United States)*
NLP	*Natural language processing*
NLU	*Natural language understanding*

NMC	*Near Memory Computing*
NoC	*Network on Chip*
NPU	*Neural processing unit (AI accelerator; distinguish from neuromorphic processing units)*
NTN	*Non-terrestrial networks*
NV	*Nitrogen vacancies (in diamond)*
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*
ONNX	*Open Neural Network Exchange (an open standard file format for ML)*
OOC	*Organ-on-a-chip*
OPV	*Organic Photovoltaics*
OSC	*Oxide semiconductor channel*
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*
PCR	*Polymerase chain reaction*

PCRAM	*Phase-change RAM*
PCT	*Product category rules*
PDK	*Process design kit*
PDMS	*Polydimethylsiloxane*
PEALD	*Plasma-enhanced atomic layer deposition*
PEBB	*Power electronics building blocks*
PEF	*Product Environmental Footprint*
PFAS	*Per- and Polyfluorinated Substances*
PFC	*Perfluorocarbons*
PFI	*Physical and functional integration*
PGHD	*Patient-generated health data*
PHM	*Prognostic health management*
PI	*Polyimide*
PIC	*Photonic Integrated Circuit*
PIII	*Plasma-immersion ion implantation*
PLC	*Programmable logic controllers*
PLM	*Product lifecycle management*
PMIC	*Power management integrated circuit*
PMUT	*Piezoelectric micromachined ultrasound transducer*
PNN	*Photonic neural network*
PoC	*Point-of-care*
PoCT	*Point-of-care testing*
PoF	*Physics of failure*
POI	*Piezoelectric-on-insulator*
PPAC	*Power, performance, area and cost*
PPE	*Personal protective equipment*
ppm	*Parts per million*
PPP	*Public/private partnership*

PQC	*Post-quantum cryptography*
PSiP	*Power supply in package*
PTEMM	*Process technologies, equipment, materials and manufacturing*
PTP	*Precision Time Protocol*
PV	*Photovoltaics*
PVD	*Physical vapour deposition*
PwrSoC	*Power supply on chip*
PZT	*Lead zirconate titanate*
QEC	*Quantum error correction*
QIP	*Quantum information processing*
QKD	*Quantum key distribution*
QoS	*Quality of service*
QRSC	*Quality, reliability, safety and cybersecurity*
Qubit	*Quantum bit*
qZSI	*Quasi-Z-source inverter*
R&D	*Research and development*
R&D&I	*Research, Development and Innovation (also written RD&I)*
RAG	*Retrieval augmented generation*
RAM	*Random-access memory*
RAMI 4.0	*Reference Architecture Model for Industry 4.0*
RD&I	*Research, Development and Innovation (also written R&D&I)*
RDI	*Research, Development and Innovation (alternative abbreviation; prefer RD&I)*
REACH	*Registration, Evaluation, Authorisation and Restriction of Chemicals (EU regulation)*
ReRAM	*Resistive RAM*
RES	*Renewable energy system*
RF	*Radio frequency*
RFID	*Radio-frequency identification*

RISC-V	*Open-standard instruction set architecture based on reduced instruction set computer (RISC) principles*
RL	*Reinforcement learning*
RNN	*Recurrent neural network; may also denote recursive neural network (specify at first use)*
RoHS	*Restriction of Hazardous Substances Directive*
ROI	*Return on investment*
RPA	*Robotic process automation*
RRAM	*Resistive RAM*
RT-PCR	*Real-time reverse transcription polymerase chain reaction*
RTE	*Run-time environment*
RTL	*Register-transfer level*
RTO	*Research and technology organisation*
RTOS	*Real-time operating system*
RUL	*Remaining useful life*
SaaS	*Software as a service*
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 (semiconductor context)*
SCM	*Supply chain management (industrial and business context)*
SDDS	*Smart drug delivery system*
SDG	*Sustainable Development Goal*
SDK	*Software development kit*
SDLC	*Software development life cycle*
SDN	*Software-defined networking*
SDR	*Software-defined radio*
SDV	*Software-defined vehicle*

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*
SiGe	*Silicon Germanium (alloy)*
SIL	*Software-in-the-loop*
SiN	*Silicon Nitride*
SiP	*System in a package*
SKC	*Skills, knowledge and competence*
SLM	*Small language model*
SME	*Small and medium-sized enterprise*
SNN	*Spiking Neural Network*
SoA	*Service-oriented architecture (also written SOA)*
SOAFEE	*Scalable Open Architecture for Embedded Edge*
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*
SQUID	*Superconducting quantum interference device*
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*
SWaP-C	*Size, weight, power and cost*
SWM	*Smart Water Management*
TCM	*Threshold change memory*
TCP	*Transmission control protocol*
TEV	*Through-encapsulant via*
TinyML	*Tiny machine learning*
TOPS	*Tera operations per second*
TOU	*Time of use*
TPU	*Tensor processing unit (AI hardware context)*
TPU	*Thermoplastic polyurethane (materials context)*
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 (aviation context)*
UAV	*Unmanned autonomous vessel (maritime context; use USV for surface vessels where appropriate)*
UCIe	*Universal Chiplet Interconnect Express*
ULP	*Ultra-low power*
UN	*United Nations*

UPS	*Uninterruptible power supply*
USV	*Unmanned surface vessel (maritime context; preferred over UAV for surface vessels)*
UWB	*Ultra-Wide Band*
UWBG	*Ultra-Wide bandgap*
UXV	*Unmanned vehicle*
V&V	*Verification & validation*
V2G	*Vehicle to grid*
V2I	*Vehicle-to-infrastructure*
V2V	*Vehicle-to-vehicle*
V2X	*Vehicle-to-everything*
VCMA	*Voltage-controlled magnetic anisotropy*
VDA	*Verband der Automobilindustrie (German Association of the Automotive Industry)*
VIL	*Vehicle-in-the-loop*
VIS-NIR	*Visible – Near infrared*
VLA	*Vision-language-action (model)*
VLM	*Vision-language model*
VLSI	*Very large-scale integration*
VOC	*Volatile organic compound*
VR	*Virtual reality*
W2W	*Wafer to wafer*
WASM	*WebAssembly*
WBG	*Wide bandgap*
WHO	*World Health Organization*
WLP	*Wafer-level packaging*
WLTP	*Worldwide Harmonised Light Vehicle Test Procedure*
WRC-23	*World Radiocommunication Conference 2023*

WSN	*Wireless sensors network*
XAI	*Explainable artificial intelligence*
XIL	*X-in-the-loop*
XR	*Extended reality*

5.2 Glossary

Introduction

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 properties derive from this structure; 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 cellular communication technology, supporting higher data rates, capacity, reliability and a broader range of services than earlier generations. Its capabilities depend on the spectrum, network architecture, deployment and service configuration. 5G includes support for enhanced mobile broadband, massive machine-type communications and low-latency applications. See also: 6G; Non-terrestrial network (NTN).

6G: the next generation of cellular communication technology beyond 5G, under research and standardisation. Research objectives include improved capacity, coverage, reliability, energy efficiency, positioning, integrated sensing and support

for intelligent and distributed services. The final capabilities and performance depend on future standards and deployments; proposed frequencies and latency targets should not be regarded as general guarantees. See also: 5G; Non-terrestrial network (NTN).

Advanced packaging: a set of technologies, processes and competences that enable the physical, electrical and functional integration of semiconductor dies and other components within packages. This includes advanced interconnection, chiplet assembly, heterogeneous integration, thermal management and testing, with attention to cost, reliability and resource efficiency. See also: Heterogeneous integration (HI); System-in-package (SiP); Co-packaged optics (CPO).

Agentic AI: artificial intelligence systems that pursue defined goals by selecting and executing actions, using information, models and tools, and adapting their behaviour based on feedback within specified constraints. Agentic AI may involve one or more AI agents, but is not synonymous with a multi-agent system. See also: Artificial intelligence (AI); Foundation model; Physical AI.

AI agent: an autonomous or semi-autonomous software or embodied entity that perceives information, selects actions and acts to pursue specified goals. AI agents may use learning models, planning methods or external tools and may interact with other agents. See also: Agentic AI.

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 perception, learning, reasoning, decision-making and language processing, with different degrees of autonomy. AI includes approaches based on rules, machine learning and other computational methods. See also: Machine learning (ML); Foundation model; Generative AI (GenAI); Agentic AI; Physical AI.

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: a technical system capable of performing specified tasks and making operational decisions, within defined conditions and constraints, without continuous human guidance. The degree of autonomy depends on the application, environment and applicable safety requirements. The abbreviation AS is avoided here because it also has another established meaning in networking. See also: Physical AI; Operational design domain (ODD).

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: a distributed ledger in which records are grouped into blocks and linked by cryptographic mechanisms. Participating nodes apply agreed protocols to validate and update the ledger, providing a shared and tamper-evident history of transactions or other information. The choice of governance and consensus mechanisms depends on the application.

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 that a patient receives during an episode of care or over the course of managing a condition, including prevention, diagnosis, treatment, monitoring and rehabilitation as appropriate.

Chiplet: a separately manufactured integrated-circuit die providing a defined subset of functions and intended to be integrated with one or more other dies or components. Chiplets can use different process technologies and are connected by suitable interconnect and packaging technologies to form a larger electronic assembly or system. Their use enables modular design and heterogeneous integration, subject to performance, cost, test and reliability constraints. See also: Advanced packaging; Heterogeneous integration (HI); System-in-package (SiP).

Circular economy: an economic approach seeking to retain the value of products, components and materials through long use, maintenance, repair, reuse, remanufacturing and recycling, while reducing waste and resource consumption. See also: Life cycle assessment (LCA); Digital product passport (DPP).

Climate-smart agriculture (CSA): an approach to agricultural development aimed at increasing productivity and resilience to climate variability and change while reducing or removing greenhouse-gas emissions where feasible. It combines practices and technologies suited to local environmental, social and economic conditions. See also: Geospatial AI (GeoAI); Measurement, reporting and verification (MRV).

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: an element or assembly of elements providing a specified electrical, electronic, sensing, actuation or other function within a larger design. Depending on the design level, a component may be a die, packaged device, passive element or functional subassembly; it need not always be a combination of devices. See also: Device; Module; System.

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: microelectronics that can conform to curved or non-planar surfaces.

Contract-based design: a design methodology in which a system and its constituents are described by contracts specifying required functionality and properties. Contracts are often expressed in an assume–guarantee form: when stated assumptions about the environment or other constituents hold, specified guarantees must be met. System-level correctness requires compatible contracts whose combined guarantees satisfy overall requirements. The approach supports composability, verification and design across multiple organisations. See also: Model-based design; Verification and validation (V&V).

Co-packaged optics (CPO): an integration approach in which optical communication components are packaged in close proximity to electronic integrated circuits, enabling high-bandwidth interconnections with shorter electrical signal paths. Its implementation requires coordinated design of optical, electrical, thermal and packaging functions. See also: Advanced packaging; Integrated photonics; Photonics.

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.

Cyber resilience: the ability of a system or organisation to prepare for, withstand, respond to, recover from and adapt to cyber incidents while maintaining or restoring essential functions. It complements but is not synonymous with cybersecurity. See also: Cybersecurity; Dependability.

Cybersecurity: the protection of electronic components, systems, software, communications and information against cyber threats and unauthorised access, manipulation, disruption or disclosure. Cybersecurity addresses confidentiality, integrity and availability, together with appropriate protection, detection, response and recovery measures. It also supports safety, dependability and trustworthiness, without being identical to them. See also: Cyber resilience; Security of ECS; Robust root of trust systems.

Deep-edge: an intermediate edge-computing level comprising controllers, gateways, industrial computing units and other devices that aggregate and process information from sensors or actuators. In this SRIA taxonomy, deep-edge lies between micro-edge, closest to the data source, and meta-edge, typically providing higher-performance local computing. Other publications may use different edge classifications. See also: Edge computing; Micro-edge; Meta-edge.

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).

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: a physical unit performing a defined function, for example a packaged integrated circuit, MEMS device, intelligent sensor, actuator or connected electronic product. In semiconductor contexts, device often refers to a chip or packaged element; in edge and IoT contexts it may refer to a complete embedded unit. The intended level of abstraction should be clear from the context. See also: Component; Module; Embedded system.

Digital infrastructure: foundational services necessary to the IT capabilities of a nation, region, city or organisation.

Digital product passport (DPP): a digital record providing access to specified information on a physical product, its characteristics, composition, origin, use, repair, reuse and end-of-life handling, as appropriate to the product category and applicable requirements. It supports traceability, transparency and circular-economy practices. See also: Circular economy.

Digital sovereignty: the ability of an organisation, society or political entity to exercise effective control over the use, governance and critical dependencies of digital technologies, infrastructure, services and data. It is related to, but narrower than, strategic autonomy. See also: Technological sovereignty; European strategic autonomy.

Digital thread: a connected and traceable flow of digital information linking requirements, design, manufacturing, operation, maintenance and other life-cycle activities. It supports consistency and reuse of data, models and decisions throughout development and use. See also: Digital twin; Product lifecycle management (PLM); Model-based systems engineering (MBSE).

Digital twin: a digital representation of an actual or intended physical entity, process or system, using models and relevant data to describe its properties and behaviour. Depending on its purpose, a digital twin can be connected to measurements and operational information and be used for simulation, analysis, prediction or control throughout the life cycle. Its scope and degree of synchronisation should be specified. See also: Digital thread; Model-based design; Tracking-mode simulation.

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 AI: artificial intelligence processing performed at or close to the sources of data, rather than exclusively in a remote cloud. It can reduce communication needs and latency while supporting local privacy and autonomy. Edge AI may be implemented in embedded devices, gateways or edge servers. See also: Embedded AI; Edge computing; Edge–cloud continuum.

Edge–cloud continuum: a distributed computing environment comprising resources from embedded devices and local edge infrastructure to remote cloud services. Functions, data and applications can be placed or moved between these resources according to requirements for performance, energy, cost, privacy, resilience and connectivity. See also: Edge computing; Cloud; Micro-edge; Deep-edge; Meta-edge.

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 AI: artificial intelligence functions implemented within embedded systems, typically subject to constraints on computation, memory, power, timing, safety or communication. Embedded AI may operate autonomously or cooperate with edge and cloud resources. See also: Edge AI; Embedded system; Physical AI.

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.

Embodied AI: artificial intelligence implemented in an agent with a physical or simulated body through which it perceives and acts on an environment. The term overlaps with physical AI; this SRIA uses physical AI as the broader preferred term for physical-world applications. See also: Physical AI; Autonomous system.

Energy harvesting: the conversion of energy available in the surrounding environment, such as light, heat, vibration or electromagnetic fields, into usable electrical energy. It can support autonomous or low-maintenance devices where a suitable source and power-management system are available. See also: Power management integrated circuit (PMIC); Embedded system.

Enzyme-linked immunosorbent assay (ELISA): Enzyme-Linked Immunosorbent Assay. A laboratory technique commonly used to detect and quantify the presence of specific substances such as antibodies, antigens, proteins, or hormones in a liquid sample.

European strategic autonomy: the ability of the European Union and its economic and industrial ecosystem to pursue strategic objectives and maintain essential capabilities while managing critical external dependencies. In ECS, this includes resilient access to technologies, materials, design, manufacturing and software capabilities. See also: Technological sovereignty; Digital sovereignty.

Explainable AI (XAI): methods and properties that enable aspects of an AI system's outputs or behaviour to be understood and interpreted by people, with an explanation appropriate to the application and users. Explainability can support assessment and trust but does not alone demonstrate that an AI system is safe or correct. See also: Trustworthiness; Verification and validation (V&V).

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).

Foundation model: an artificial intelligence model trained on broad datasets, often at scale, which can be adapted to a range of downstream tasks. Foundation models may process language, images, signals or other data types. A large language model is one category of foundation model. See also: Large language model (LLM); Generative AI (GenAI).

Functional safety: the part of overall safety that depends on a system or equipment operating correctly in response to its inputs, including the detection and handling of faults where required. Functional safety aims to reduce risks arising from malfunctioning behaviour to an acceptable level. See also: Safety; Reliability; Cybersecurity.

Generative AI (GenAI): artificial intelligence methods that generate new content, such as text, images, audio, code or structured data, by learning statistical patterns from training information. Generative AI may be incorporated into foundation models, embedded applications or agentic systems. See also: Foundation model; Large language model (LLM); Agentic AI.

Geospatial AI (GeoAI): the application of artificial intelligence to geospatial information, combining data from geographic information systems, Earth observation, positioning systems and field measurements for spatial analysis, prediction and decision support. See also: Climate-smart agriculture (CSA); Sensor fusion.

Grid-forming inverter: a power-electronic converter controlled to establish or support voltage and frequency in an electrical network, including operation with high shares of inverter-based resources. Its capabilities depend on converter design, controls, storage and grid conditions. See also: Sector coupling.

Healthcare: the preservation of mental and physical health by preventing or treating illness through services offered by the health profession.

Healthcare 4.0: the application of connected digital systems, artificial intelligence, automation, data-based decision support and related technologies in healthcare, with attention to clinical processes, safety, privacy and human-centred delivery. See also: Care pathway; Digital twin; Point of care.

Heterogeneous integration (HI): the integration of separately manufactured elements based on different materials, technologies, processes or functions into higher-level assemblies. In this SRIA, the term includes integration at chip, package, module and system levels. In semiconductor packaging contexts, it commonly refers more specifically to the integration of diverse elements within one package. See also: Physical and functional integration (PFI); Advanced packaging; System-in-package (SiP).

Human systems integration (HSI): is a transdisciplinary sociotechnical and management approach of systems engineering (SE) used to ensure that system's technical, organisational, and human elements are appropriately addressed across the whole system life cycle, service, or enterprise system. HSI considers systems in their operational context together with the necessary interactions between and among their human and technological elements to make them work in harmony and cost effectively, from the early design to disposal.

Industrial metaverse: a collection of interconnected virtual representations, simulations and interaction environments used for the design, operation, training or optimisation of industrial systems and processes. It may combine digital twins, virtual or augmented reality and collaborative engineering. See also: Digital twin; Extended reality (XR); Industry 5.0.

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.

Industry 5.0: an approach to industrial development that complements Industry 4.0 by emphasising human-centricity, sustainability and resilience alongside productivity and digital transformation. See also: Industry 4.0; Industrial metaverse.

In-memory computing: computing methods that perform certain operations within or using the physical structures of memory devices, reducing the movement of data between separate memory and processing units. See also: Near-memory computing; Neuromorphic computing.

Integrated circuit (IC): 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. See also: Photonics; Co-packaged optics (CPO).

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.

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.

In vitro diagnostics (IVD): the examination of specimens derived from the human body, such as blood or tissue samples, outside the body to provide information on a physiological or pathological state, a condition or a response to treatment. Diagnostic tests may be performed in a laboratory or at the point of care. See also: Point-of-care testing (POCT); Lab-on-a-chip (LOC).

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.

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 large datasets 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.

Life cycle assessment (LCA): a systematic method for assessing potential environmental impacts associated with the life cycle of a product, process or service, from resource extraction through manufacturing and use to end-of-life, according to the defined system boundaries and assessment method. See also: Circular economy; Safe-and-sustainable-by-design (SSbD).

Machine learning (ML): 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.

Measurement, reporting and verification (MRV): processes and tools used to quantify, document and independently assess information on environmental or other performance indicators, such as greenhouse-gas emissions, water use or biodiversity impacts, under specified methods and requirements. See also: Life cycle assessment (LCA); Climate-smart agriculture (CSA).

MEMS, MOEMS, NEMS, MNS, MNBS: micro-electromechanical systems (MEMS) integrate miniaturised mechanical structures and electrical functions, commonly for sensing or actuation. Micro-opto-electromechanical systems (MOEMS) involve optical interactions, while nanoelectromechanical systems (NEMS) use nanoscale functional structures. The broader terms micro-nanosystems (MNS) and micro-nano-bio systems (MNBS) cover related technologies and interactions with

chemical or biological domains. The overall device size can be larger than its critical internal features. These technologies connect physical phenomena with electronic information processing. See also: Device; Heterogeneous integration (HI).

Meta-edge: the edge-computing level comprising higher-performance local processing resources, typically on premises, such as edge servers and computing clusters handling data analytics, AI, storage or coordination. In this SRIA taxonomy, it is above the deep-edge and below or alongside remote cloud infrastructure. See also: Micro-edge; Deep-edge; Edge–cloud continuum.

Micro-edge: the edge-computing level closest to the physical data source, comprising intelligent sensors, actuators, microcontrollers and small connected devices capable of local processing or inference. In this SRIA taxonomy, the micro-edge is below the deep-edge controller and gateway level. See also: Deep-edge; Meta-edge; Edge AI.

Mixed reality (MR): interactive experiences in which real and computer-generated elements are combined and can interact in a shared perceived environment, typically using spatial sensing and suitable visual or other interfaces. See also: Augmented reality (AR); Virtual reality (VR); Extended reality (XR).

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. See also: Model-based systems engineering (MBSE).

Model-based systems engineering (MBSE): the formalised application of modelling to support systems-engineering requirements, design, analysis, verification and validation throughout the life cycle of a system. Models provide connected representations of system properties and relationships across disciplines. See also: Model-based design; Digital thread; Verification and validation (V&V).

Module: an integrated assembly of components and, where required, software providing a defined function, such as sensing, communication, control or power management. Modules are often designed for reuse or interchangeability, although the degree of independence depends on the application and architecture. See also: Component; Device; System.

Near-memory computing: a computing architecture in which processing is placed close to memory resources to reduce communication distance, latency and energy

consumption associated with data movement. Unlike in-memory computing, the operations are not necessarily executed within the memory structure itself. See also: In-memory computing.

Neuromorphic computing: computing architectures inspired by biological neural information processing, often using event-driven operation and closely coupled computation and memory to improve efficiency for suitable workloads. Implementations may use digital, analogue or mixed-signal technologies. See also: In-memory computing; Embedded AI.

Non-terrestrial network (NTN): a communication network in which one or more links or network components operate from satellites or airborne platforms, complementing terrestrial systems for coverage, connectivity or resilience. See also: 5G; 6G; Interoperability.

Open-source hardware: hardware designs for which design documentation is made available under licences granting specified rights to study, use, modify and redistribute the designs. Mere access to a blueprint does not by itself make hardware open-source. The openness of associated software, tools and proprietary components must be considered separately. See also: Open-source software; RISC-V.

Open-source software: software whose source code is made available under a licence granting specified rights to use, study, modify and redistribute it. Public access to source code without appropriate licensing rights is not sufficient for the software to be considered open-source. See also: Open-source hardware.

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.

Over-the-air (OTA) update: the remote delivery and installation of software, firmware or configuration changes to devices and systems using a communication network. Secure update mechanisms must address authenticity, integrity, reliability

and recovery where appropriate. See also: Cybersecurity; Software-defined vehicle (SDV).

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.

Physical AI: the integration of artificial intelligence into physical systems that perceive their environment, make decisions and act upon the physical world through sensing, control and actuation. It overlaps with embodied AI, especially in robotics, but is used in this SRIA as the broader preferred term. See also: Agentic AI; Autonomous system; Embedded AI.

Physical and functional integration (PFI): the combination of physical elements and functions into components, modules or systems to achieve specified functionality, performance, reliability, manufacturability and other application requirements. See also: Heterogeneous integration (HI); Advanced packaging; Smart systems integration (SSI).

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 healthcare services are delivered to a patient, including hospitals, clinics, other care facilities and the patient's home. See also: Point-of-care testing (POCT); Care pathway.

Point-of-care testing (POCT): performance of clinical laboratory testing at the site of patient care rather than in a laboratory, often by non-laboratorians.

Post-quantum cryptography (PQC): cryptographic algorithms designed to resist attacks using large-scale quantum computers as well as relevant classical attacks. The term does not imply that quantum physical effects are used in the cryptographic implementation. See also: Cybersecurity; Quantum technology.

Power management integrated circuit (PMIC): a number of power management circuits (e.g. conversion, storage, conditioning, communication) integrated onto silicon.

Predictive maintenance: techniques designed to help determine the condition of in-service equipment to estimate when maintenance should be performed.

Privacy by design: the integration of privacy and data-protection requirements into the design, development and operation of systems and services from the outset, including appropriate controls over data collection, processing, access and retention. As an adjective, the form privacy-by-design is used. See also: Cybersecurity; Digital sovereignty.

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: methods that assess how an item's condition is likely to develop under expected operational and environmental conditions, including estimates of the time until a defined failure or loss of required function. Prognostics is one part of the wider field of prognostics and health management. See also: Predictive maintenance; Reliability.

Prosthetics: the branch of medicine or surgery that deals with the production and application of artificial body parts.

Quality: the degree to which the characteristics of a product, process or system fulfil specified requirements. In design and manufacturing, quality includes conformance to relevant specifications and process requirements, supported by appropriate assurance and control methods. Reliability, dependability, safety and cybersecurity are related but separately considered properties in this SRIA. See also: Dependability; Reliability; Safety; Cybersecurity.

Quantum computing: a computing paradigm using quantum states and operations to represent and process information, typically through qubits, quantum gates and

measurements. Superposition, interference and, for many approaches, entanglement enable computational methods different from classical computing. Potential advantages depend on the algorithm, hardware and practical error-correction capabilities. See also: Quantum technology.

Quantum-safe cryptography: cryptographic approaches intended to provide security against attacks by quantum computers. This includes post-quantum cryptographic algorithms and, in relevant applications, other quantum-resistant key-establishment methods. See also: Post-quantum cryptography (PQC); Cybersecurity.

Quantum sensing: the use of quantum states, coherence, interference or other controlled quantum effects to measure physical quantities such as magnetic fields, time, acceleration or temperature with application-specific sensitivity or precision. See also: Quantum technology; Photonics.

Quantum technology: technologies that prepare, manipulate or measure quantum states or exploit controlled quantum effects for computing, communication, sensing and related applications. Some implementations require cryogenic conditions, while others operate at or near room temperature. See also: Quantum computing; Quantum sensing; Post-quantum cryptography (PQC).

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 of an item to perform its required functions under given conditions for a given time interval (IEC 60050-192). Reliability is one of the attributes contributing to dependability. See also: Dependability; Prognostics.

RISC-V: an open standard instruction-set architecture that specifies how software communicates with a processor. RISC-V implementations may be open-source or proprietary; the open architecture does not by itself determine the licence of a particular processor design. See also: Open-source hardware; System-on-chip (SoC).

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.

Safe-and-sustainable-by-design (SSbD): an approach that considers safety and environmental sustainability throughout the design and development of materials,

technologies, products and processes, using assessment and design choices to reduce risks and impacts across the life cycle. See also: Life cycle assessment (LCA); Circular economy; Safety.

Safety: freedom from unacceptable risk of harm to people, property or the environment, in accordance with the applicable operational context and risk criteria. Safety includes but is not limited to risks arising from malfunctioning electrical or electronic systems. See also: Functional safety; Dependability; Cybersecurity.

Sector coupling: the coordinated integration of energy use and conversion across sectors such as electricity, heating, transport and industry, including the use of storage and flexible demand to improve overall energy-system efficiency and flexibility.

Security of ECS: the protection of electronic components and systems against unauthorised access, interference, manipulation or disruption that could compromise their intended operation or information. It includes physical and logical safeguards. Cybersecurity is the aspect concerned with cyber threats, digital information and connected systems. See also: Cybersecurity; Safety; Robust root of trust systems.

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.

Sensor fusion: the combination of measurements or information from multiple sensors or sources to produce a more useful estimate of a state, event or environment than may be possible from one source alone. See also: Geospatial AI (GeoAI); Autonomous system.

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): a drug-delivery system designed to provide controlled or targeted release of a therapeutic substance, for example by responding to biological signals or other operating conditions. Its purpose may be to improve delivery to the intended tissue, control dosage or reduce adverse

effects. Such systems can integrate materials, sensing, electronics and biological or chemical technologies.

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". See also: Physical and functional integration (PFI); Heterogeneous integration (HI).

Software bill of materials (SBOM): a structured inventory of software components and dependencies used in a product or system, supporting transparency, vulnerability management and maintenance throughout its life cycle. See also: Cybersecurity; Software-defined vehicle (SDV).

Software-defined vehicle (SDV): a vehicle architecture in which significant functionality is implemented, configured and managed through software, enabling updates, upgrades and adaptation during the vehicle's operational life. It requires appropriate computing, networking, safety and cybersecurity provisions. See also: Over-the-air (OTA) update; Embedded software.

Software-defined X (SDx): a collective term for systems in which substantial functionality and configuration are provided or modified through software rather than being fixed solely by hardware design. The concept includes software-defined vehicles and related approaches in other domains. See also: Software-defined vehicle (SDV); Embedded software.

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.

Synthetic data: data generated through simulation, procedural methods or computational models rather than directly observed or measured in the intended real-world setting. It can support development, testing and AI training, but its representativeness and limitations must be assessed for the intended use. See also: Digital twin; Machine learning (ML).

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 to perform a desired set of functions. Because ECS are constructed hierarchically, an assembly described as a module in one design may itself be called a system at another level. Unlike a system whose constituents are managed as parts of an integrated design, a system of systems is characterised by operationally and managerially independent constituent systems. See also: Component; Module; System of systems (SoS).

System-in-package (SiP): a number of integrated circuits and other electronics building blocks (e.g. MEMS, antennas) enclosed in one single package.

System of systems (SoS): a collection of independent and often distributed embedded and cyber-physical systems 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 typically exhibits 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 the first two characteristics is not considered an SoS. Geographical distribution is not mandatory, and integrating multiple chiplets does not in itself constitute an SoS.

System-on-chip (SoC): an integrated circuit combining multiple functional blocks of an electronic system, potentially including processors, memory, accelerators, interfaces and other logic on one chip. The functions integrated depend on the intended application. See also: Integrated circuit (IC); System-in-package (SiP).

Technological sovereignty: the ability to develop, access, control and maintain strategically important technologies and related expertise and value chains, while managing external dependencies. The term is related to digital sovereignty but is not limited to digital technologies. See also: European strategic autonomy; Digital sovereignty.

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 communication and interaction technologies that enable a person to experience or act in a remote environment as though present there. It

may use audio, video, robotics, virtual reality or other interfaces. See also: Teleoperation; Extended reality (XR).

Time-sensitive networking (TSN): a family of networking standards and mechanisms supporting bounded latency, time synchronisation and predictable delivery of traffic over compatible networks, particularly for industrial and other time-critical applications. See also: Interoperability; Cyber-physical system (CPS).

Tracking-mode simulation: simulation adapted or updated using measurements of its real-world counterpart. See also: Digital twin.

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): complementary activities for checking that a product, service or system meets specifications and fulfils its intended purpose. Verification checks whether the specified requirements have been implemented correctly ('are we building the product right?'); validation checks whether the resulting product meets the needs of its intended use ('are we building the right product?'). Both may involve analysis, inspection, simulation and testing.

Virtual commissioning: the use of simulated machines, plants or processes to test, validate and refine control functions or operating procedures before commissioning the corresponding physical system. See also: Digital twin; X-in-the-loop.

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, attached to the body or incorporated into clothing or accessories.

Wide-bandgap semiconductor (WBG): a semiconductor material with a relatively wide electronic bandgap, such as silicon carbide or gallium nitride, supporting device properties useful for power conversion, high-temperature operation or high-frequency applications. Performance depends on the material, device design and implementation. See also: Integrated circuit (IC).

X-in-the-loop: testing in which a model, software or hardware system under test interacts with a test environment that generates inputs and checks responses. Common forms are model-, software- and hardware-in-the-loop. See also: Verification and validation (V&V); Virtual commissioning.

EC Strat. Targets	Industrial Competitiveness	EU Sovereignty	Sustainability and Green Deal	Digital Age (AI, NGC)
ECS R&I Objectives	**Boost industrial competitiveness through interdisciplinary technology innovations**	**Ensure EU digital autonomy 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, in-memory, neuromorphic, photonic and quantum computing concepts	1.1.4 Advanced wafer fab equipment and manufacturing solutions	1.1.6 Sustainable semiconductor manufacturing	1.1.1 Advanced computing, in-memory, neuromorphic, photonic and quantum computing concepts
	1.1.2 Novel sensor, actuation and other devices that enable advanced functionality	1.1.5 Advanced packaging, assembly and test equipment solutions	1.2.3 Sustainability	1.1.2 Novel sensor, actuation and other devices that enable advanced functionality
	1.1.3 Advanced integration solutions	1.2.2 Advanced & Heterogeneous Integration	1.3.5 Support for Sustainability by embedded software	1.1.3 Advanced integration solutions
	1.1.4 Advanced wafer fab equipment and manufacturing solutions	1.3.6 Software reliability and trust	1.4.2 SoS interoperability	1.2.1 Functionality
	1.1.5 Advanced packaging, assembly and test equipment solutions	1.4.2 SoS interoperability	1.4.5 SoS monitoring and management	1.3.4 Embedding data analytics and AI
	1.2.1 Functionality	1.4.3 Evolvability of SoS composed of embedded and cyber-physical systems	2.1.1 Increasing the energy efficiency of computing systems and embedded intelligence	1.3.8 AI in Embedded Systems Engineering and Operations
	1.2.2 Advanced & Heterogeneous Integration	1.4.5 SoS monitoring and management	2.1.3 Supporting the Increasing Lifespan of Devices and Systems	1.4.5 SoS monitoring and management
	1.4.1 Open SoS architecture and infrastructure	2.1.4 Ensuring European Sustainability of Embedded Intelligence	2.2.1 Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain	2.1.1 Increasing the energy efficiency of computing systems and embedded intelligence
	1.4.2 SoS interoperability	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	2.1.4 Ensuring European Sustainability of Embedded Intelligence
	2.1.1 Increasing the energy efficiency of computing systems and embedded intelligence	2.2.4 Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	2.3.2 Sustainable Engineering for Sustainable ECS	2.2.3 Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics
	2.2.1 Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain	2.3.1 Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS	2.4.5 Ensuring safety and resilience	2.2.4 Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity
	2.2.2 Investigate innovative connectivity technology (new spectrum or improved spectral efficiency) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership	2.4.1 Ensuring quality in ECS design and manufacturing	3.1.3 Green deal: enable climate and energy optimal mobility	2.4.6 Human–systems integration
	2.2.5 Network virtualization enabling efficient and low-cost run-time and evolvable integration, deployment and management of edge-to-cloud network architectures	2.4.2 Ensuring hardware reliability in ECS design and use phases	3.2.1 Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems	3.1.4 Digitalisation: affordable and safe automated and connected mobility for passengers and freight
	2.3.1 Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS	2.4.3 Ensuring dependability in connected software	3.2.2 Energy Management from On-Site to Distribution Systems	3.1.5 Edge-to-Cloud Mobility Applications
	2.3.4 Managing diversity	2.4.4 Ensuring cybersecurity and privacy	3.2.3 Future transmission grids	3.1.6 AI-Enabled Engineering Toolchains
	2.4.1 Ensuring quality in ECS design and manufacturing	2.4.5 Ensuring safety and resilience	3.2.4 Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply	3.2.1 Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems
	3.1.1 SDV Hardware Platforms	3.1.1 SDV Hardware Platforms	3.2.5 Cross-Sectional Tasks for Energy System Management, Monitoring & Control	3.3.1 Responsive and smart production
	3.1.2 Software Platforms for the SDV of the Future	3.1.2 Software Platforms for the SDV of the Future	3.3.1 Responsive and smart production	3.3.3 Artificial Intelligence in Digital Industry
	3.2.2 Energy Management from On-Site to Distribution Systems	3.1.4 Digitalisation: affordable and safe automated and connected mobility for passengers and freight	3.3.2 Sustainable production	3.3.6 Autonomous systems, robotics
	3.2.3 Future transmission grids	3.2.2 Energy Management from On-Site to Distribution Systems	3.4.3 Support the development of home as the central location of the patient, building a more integrated care delivery system	3.4.2 Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies
	3.2.5 Cross-Sectional Tasks for Energy System Management, Monitoring & Control	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	3.4.4 Enhance access to personalized and participative treatments for chronic and lifestyle related diseases
	3.4.1 Enable digital health platforms based upon P4 healthcare	3.4.1 Enable digital health platforms based upon P4 healthcare	3.4.5 Ensure more healthy life years for an ageing population	3.4.5 Ensure more healthy life years for an ageing population
	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	3.5.1 Food Security and Resilient Food Production Systems	3.5.2 Food Safety, One Health and Trusted Food Chains
	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 Climate-Smart, Nature-Positive and Circular Production	3.5.3 Climate-Smart, Nature-Positive and Circular Production
	3.5.3 Climate-Smart, Nature-Positive and Circular Production	3.4.5 Ensure more healthy life years for an ageing population	3.5.4 Water Resilience, Quality and Circular Management	3.5.4 Water Resilience, Quality and Circular Management
	3.5.4 Water Resilience, Quality and Circular Management	3.5.1 Food Security and Resilient Food Production Systems	3.5.5 Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems	
	3.5.5 Biodiversity, Ecosystem Restoration and Nature-Positive Agrifood Systems	3.5.2 Food Safety, One Health and Trusted Food Chains	3.6.2 Facilitate empowerment and resilience	
	3.6.1 Facilitate individual self-fulfilment	3.6.3 Facilitate inclusion and collective safety	3.6.4 Facilitate supportive infrastructures and sustainable environments	
	3.6.2 Facilitate empowerment and resilience			
	3.6.3 Facilitate inclusion and collective safety			
	3.6.4 Facilitate supportive infrastructures and sustainable environments			

	Ensure engineering support across the entire lifecycle of complex ECS-based systems			
	Lifecycle engineering support			
Major Challenges in ECS Research and Innovation	1.2.1 Functionality	1.3.1 Efficient Engineering of Embedded Software	1.3.2 Continuous integration and deployment	1.3.3 Life-cycle management
	1.3.6 Software reliability and trust	1.3.7 Hardware virtualization for efficient SW engineering	1.4.1 Open SoS architecture and infrastructure	1.3.8 AI in Embedded Systems Engineering and Operations
	1.4.4 SoS integration along the life cycle	1.4.5 SoS monitoring and management	2.1.2 Managing the increasing complexity of systems	1.4.3 Evolvability of SoS composed of embedded and cyber-physical systems
	2.3.1 Enabling cost- and effort-efficient AI-supported Design and Validation Frameworks for High-Quality ECS	2.3.3 Managing Complexity	2.3.4 Managing diversity	2.1.3 Supporting the Increasing Lifespan of Devices and Systems
	2.3.2 Sustainable Engineering for Sustainable ECS	3.1.1 SDV Hardware Platforms	3.1.2 Software Platforms for the SDV of the Future	2.4.4 Ensuring cybersecurity and privacy
	2.4.6 Human–systems integration	3.3.4 Industrial service business, lifecycles, remote operations and teleoperation	3.3.5 Digital twins, mixed or augmented reality, telepresence	3.1.6 AI-Enabled Engineering Toolchains
	3.2.5 Cross-Sectional Tasks for Energy System Management, Monitoring & Control			3.3.6 Autonomous systems, collaborative robotics

ABOUT THE ASSOCIATIONS

AENEAS is a not-for-profit industry association representing over 600 members across the European Electronic Components and Systems (ECS) value chain. It provides networking opportunities, policy influence and facilitated access to RD&I funding. AENEAS represents the voice of its members on the Chips Joint Undertaking Governing Board and operates the Eureka Cluster Xecs, supporting transnational collaborative innovation.

See https://aeneas-office.org

EPoSS is the European Association leading the development and integration of intelligent and green Smart Systems technologies and solutions for a sustainable society. In our pan-European network of experts from industry and research, we jointly define R&D and innovation needs as well as policy requirements for Smart Systems Integration.

See https://www.smart-systems-integration.org/

INSIDE Industry Association, formerly ARTEMIS-IA, is Europe's Technology Platform for Intelligent Digital Systems, connecting 420+ organisations across the ECS value chain. It provides policy influence, networking, access to R&I funding, consortium building and opportunities to shape European innovation.

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