4

Strategic Research and Innovation Agenda 2024

LONG-TERM VISION

4. LONG TERM VISION

4.1 INTRODUCTION

In this Chapter, we present research subjects that need to be addressed by European organizations to enable and support effective development of European industry in about a decade from today. The previous chapters have presented status, trends, and plans for the near future, including challenges that are foreseen to require special attention within the coming decade. We build upon these identified challenges and specify long-term industrial needs. These needs are the basis for research programs for effective research and development in appropriate technological and/or application domains, so that European technological strength increases continuously in time and at the appropriate rate. Since lead-time from a first scientific breakthrough (TRL1) to market presence of related products (TRL9) is typically 10 years or more, the effective identification of the future industrial needs is a determining factor for the success and speed of innovation.

The long-term vision is shaped by three main factors: technology, application domains and policies. Clearly, all factors are drivers of innovation, because (i) anticipated technological advances lead to innovative applications of these advances and (ii) user needs lead to technological innovations that enable applications and services. At the same time, policies and politically established goals and processes lead technologies and applications towards common goals and targets.

Regarding policies, which lead many technologies and applications on a pan-European scale, the ECS community has specified its common objectives that influence and shape long-term innovation and must be considered in future research directions. As presented in the Introduction, these four 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.

These objectives, which are aligned with policies and European political priorities, address the need to establish unrestricted access to goods and services, free exchange of know-how and information, under trusted, protected and regulated multilateral agreements in the emerging international political and economic landscape. European Union’s policies to protect its strategic autonomy, and sustain its competitiveness are shaping and continuously advancing, especially for the ECS industry, which constitutes the backbone of the digital society.

European digital strategic autonomy – European Union's ability to maintain control and security of its products, overcoming disruptions and vulnerabilities – is one of the major challenges when considering that its major economic drivers, i.e., digitisation and connectivity, are strongly dependent on the supply of hardware and software from countries outside Europe. This challenge needs to be addressed immediately, for the short term as well as for the long term, by research programs on the following topics:

- Safety and security: development of rigorous methodologies, supported by evidence, that a system is secure and safe; safety and security are requirements for trustworthiness. These methodologies should enable certification through appropriate methods, such as testing and/or formal methods to prove trustworthiness guarantees.
- Artificial intelligence and machine learning (AI/ML): AI/ML-based techniques will contribute significantly to the development of robust ECS components, systems, and applications, with short development cycles. AI/ML will influence all major technologies in ECS development, from model-based engineering and embedded software to fabrication, and will constitute a major link between quality, reliability, safety, and security.
- Trustworthiness: development of methodologies that integrate traditional ECS technologies with AI/ML, from device level up to applications and human interface. Trustworthiness is key to the acceptance of such emerging systems. Advances in explainable AI models for human/ system interaction, safety, security, risk analysis and management, liability and certification are necessary for the 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, characterized by:

- Zero net emissions of greenhouse gases.
- Economic growth decoupled form resource use.
- Inclusion (no person and no place are left behind).

The ECS community is instrumental to the realization of the European Green Deal. The many challenges associated with energy management can be tackled only with ECS-based solutions, leading to energy-efficient ECS devices as well.

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[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

The first three high-level common objectives of the ECS community (competitiveness, robustness of ECS products and establishing value chains) can be achieved only by reaching the fourth one as well. The “unleashing” of intelligent and autonomous ECS-based systems requires the interdisciplinary effort and coordination of all stakeholders; academic, institutional, and industrial. In the effort to ensure effective and timely identification of effective exploitation of opportunities, a close cooperation of all stakeholders along the value chain is a prerequisite. This cooperation is traditionally strong in Europe and constitutes a valuable European strategic asset. This strength is based on the availability of many research facilities with excellent competence and extensive experience in the ECS domain. This comprehensive ecosystem of universities, RTOs, and industrial research organizations distributed across many countries in Europe forms a leading incubator for pioneering technologies that enable the creation of hyper-smart, safe, secure, and resource-efficient electronic components and systems. This ecosystem enables increasingly networked scientific work and is the base for maintaining the competitiveness of the European ECS industry now and in the future. Cooperation also offers the best opportunities for coping with the growing interdependencies and interdisciplinarity through strong coupling of basic and applied research within the European Research Framework Programme. This, in turn, creates the fertile soil, from which industry can receive substantial impulses to achieve breakthrough solutions with minimal time to market, leading to maintenance of European technological excellence and leadership, which is the cornerstone of long-term European technological leadership and a basis for prosperity and peace in our continent.

Additionally, and independently of policies, long-term vision is shaped by technological and application evolution and revolution. Many future applications will be enabled by enhanced functional and non-functional properties provided by new technologies (both hardware and software), as projected in technology-application roadmaps such as the one shown in Figure 4.1. Typically, the advances that are foreseen through roadmaps are considered evolutionary. However, there have been several occurrences of revolutionary or disruptive developments in technology. These are not projected in roadmaps; they exploit and establish innovative technological models and have tremendous technological and societal impact. Often, they lead to paradigm shifts with significant impact to business and society. The World Wide Web is a typical example of disruptive technology.

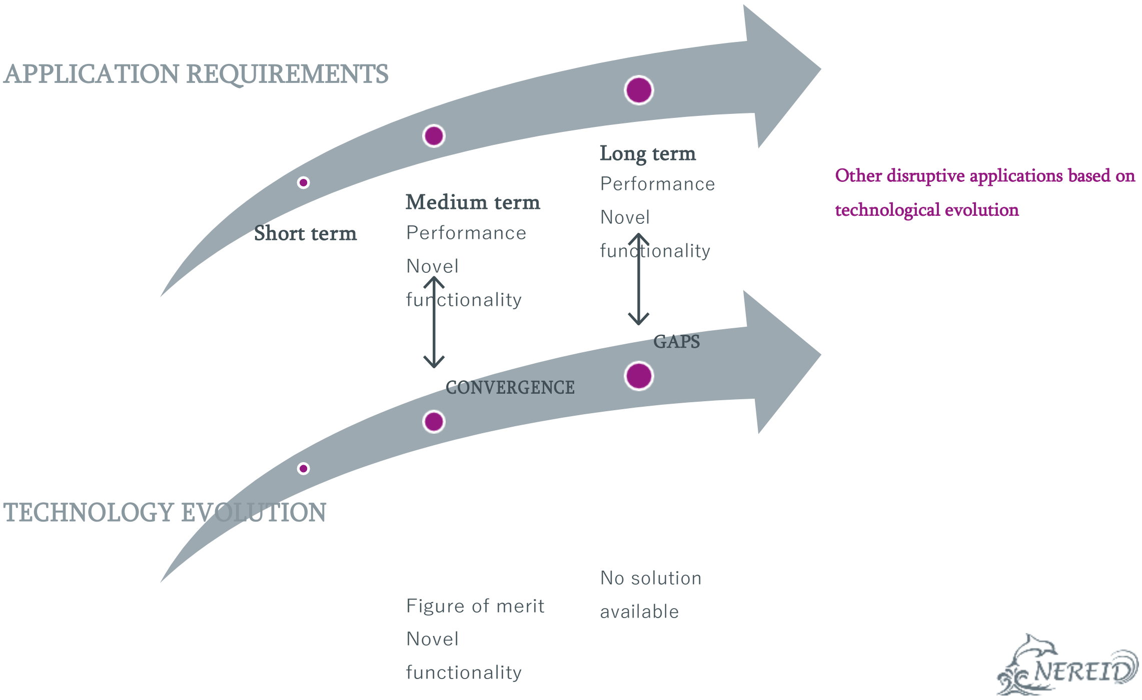

Figure 4.1 - Technology evolution and application requirements

Over the last decades, the ECS domain has evolved from a technology-driven field to an environment where societal needs and application requirements guide the research agendas of the 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 continuous offering of disruptive technologies that will preserve the European competitive position.

In this Chapter, we present the main research trends that are of particular importance to the European strategic research and innovation agenda. Clearly, presenting a complete list of anticipated evolutionary and revolutionary, or disruptive, technologies and challenges is infeasible, by its very nature. Considering the three factors that shape the long-term vision - technology, application domains and policy - in the following section we present a model that enables us to present challenges in a systematic way. We consider policies to provide the framework as well as parameters for technologies and applications and then, we present technological challenges and needs to be met in application domains.

4.2

MODEL

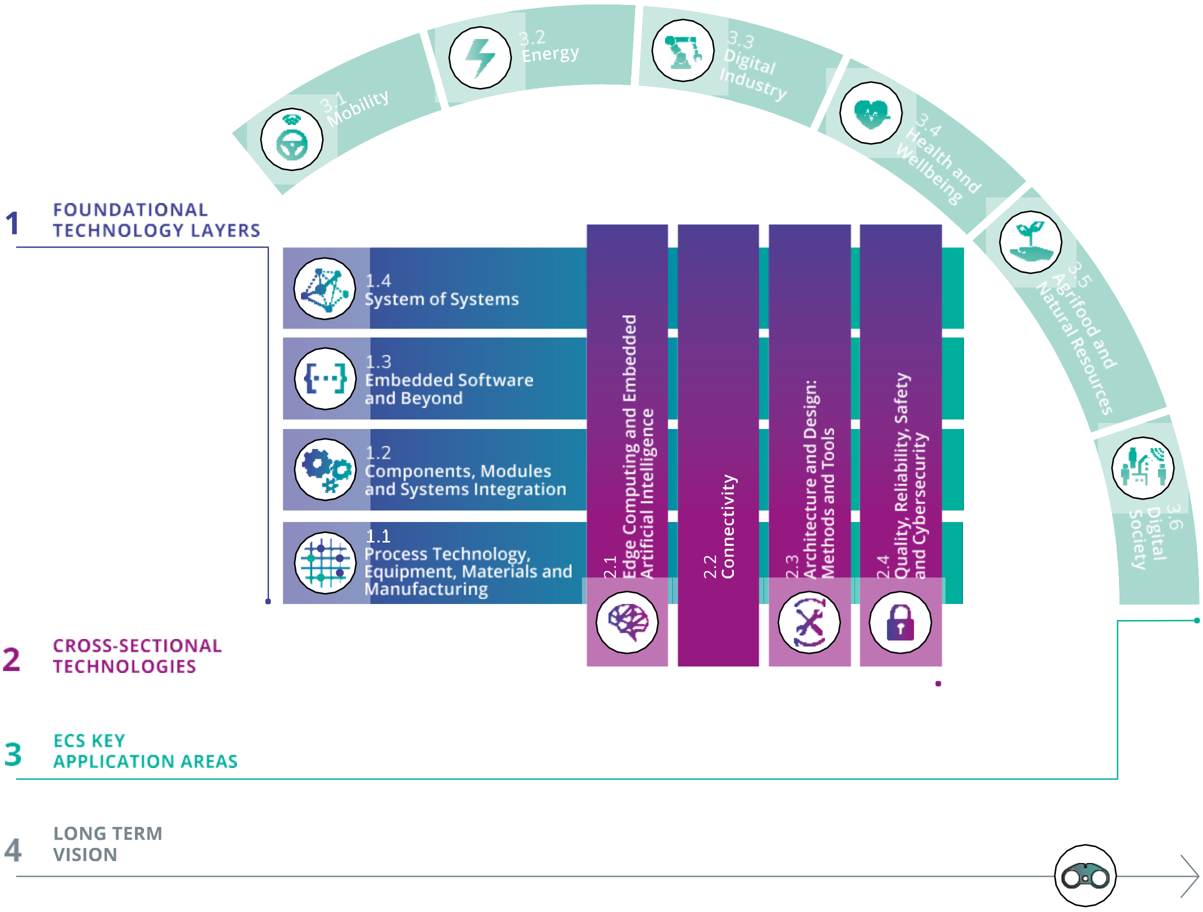

Figure 4.1 - Technology domains evolution and application requirements

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 4.1.

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 4.1, with the understanding that our presentation addresses evolutionary and revolutionary technologies based on conventional technological and societal understanding. Independently, our expectation is that disruptive innovations will be readily integrated in our long-term view, since they will affect part or parts of the layered model which we exploit for abstraction, understanding, presentation and openness.

4.3
TECHNOLOGY LONG-TERM CHALLENGES

4.3.1 Process technology, equipment, materials, and manufacturing

Europe has a strong competence in ECS process technology, enabled by the presence of an industrial, institutional, and academic ecosystem with a long tradition in multidisciplinary collaborative research in regional, transnational and European cooperative projects. With the growing complexity of ECS-based devices and systems, this multidisciplinary collaborative approach along the value chain is one of the major assets for Europe in maintaining its competitiveness.

In the More Moore field, there are strong interests in Europe for specific activities that involve very low power devices, leading to possible disruptive applications – for instance, for future IoT systems, 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, ultimate processing technologies and novel nanodevice structures for logic and memories are mandatory for different applications as well as new circuit architectures, design techniques and embedded software. Some of these nanostructures are also very interesting for advanced sensors, energy harvesters and photonics. All of these are key for future high performance/ultra- low power tera-scale integration and autonomous nanosystems.

These promising technologies that could underpin numerous future applications will allow us to overcome a range of challenges being faced for future ICs – in particular, high performance, low/very low static and dynamic power consumption, device scaling, low variability, and affordable cost. Many long-term challenges must be addressed to ensure successful application of these nanotechnologies. A number of these are described briefly in the following:

- Nanowires and nanosheets, for high performance and very low-power nanoscale devices, the best material and geometry options for logic (high speed as well as low power) need to be identified.
- Millimetre-wave 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 characterization of optimal architectures and design strategies.
- For nano-electro-mechanical FETs (NEMS-FET), low-voltage reliable devices have to be developed.
- Spin-based devices also for switching and sensing.

In the field of alternative memories, resistive RAM, magnetic RAM (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 device, and innovative device-architecture interaction.

Integrated photonics, evolving from silicon photonics, are 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 becoming 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, especially the measurement of electrical properties, such as local carrier mobility, is needed.
- To achieve practical applications, reliable fabrication, connection, and read-out of qubits need to be developed. The low temperatures at which most quantum systems are operated requires the development of cryogenic devices, to interface conventional electronics.

Importantly, all quantum technologies related to sensing, communications and computing, including software, present significant challenges today.

Reducing the environmental impact of semiconductor manufacturing

While the chip advancements are contributing to the industries across verticals, and are crucial to achieve the Green Deal objectives, significant efforts must be made to tackle the direct environmental impact of chips and more generally ECS manufacturing. Issues to be addressed include waste generation, resource usage, CO_2 and GHG emissions, hazardous materials use, including PFAS, and scarce materials use.

Waste generation

Fabricating a small 2g microchip (≈ 14-10nm technology node) requires 32-35 kilograms of water, 1.6kg of petroleum and 72g of chemicals. Since advanced technology nodes will require more metal layers and lithography steps, and, as the chip production could nearly double to satisfy chip demand in the coming years, the environmental impact of the semiconductor industry on power/energy and water consumption, and on CO_2 and GHG emission, will strongly increase. This consumption and emission can reach unacceptable levels to cope with the Green Deal sustainability objectives.

Natural resource consumption

Regarding water, each chip needs to be rinsed with ultrapure water (UPW) to remove various debris (ions, particles, silica, etc.) from the manufacturing process and prevent the chips from becoming contaminated. The semiconductor industry has been working for more than twenty years to reduce the amount of water needed to manufacture a chip for economic reasons as well. Nowadays, due to the most frequent occurrence of droughts, the water issue is a high priority in the sustainable development plans of major semiconductor companies. Semiconductor manufacturers must focus their efforts on new ways to recycle, reduce, and reuse the water used in their production. Nevertheless, new advancements in water treatment must emerge to allow semiconductor manufacturers to recover and reuse wastewater, remove targeted contaminants, and even reclaim valuable products from waste streams. New long-term approaches will deserve more R&D efforts for improving the effluent segregation systems and hence increasing the use of recycled water in semiconductor manufacturing lines.

The main European semiconductor manufacturing should use 100% of renewable energy sources in 2030. Likewise, the water and carbon footprints of the semiconductor industry must be strongly reduced to achieve near-zero CO_2 and GHG emission, for instance.

CO_2 and Green House Gas (GHG) emission

In the semiconductor industry, CO_2 and Green House Gas (GHG) emission arise from process gases used during wafer etching, chamber cleaning, and other tasks. Furthermore, they rise as node size shrinks. These gases, which include PFCs, HFCs, NF_3, and N_20, have high global-warming potential. Gas recycling of unutilized process gases and by-products through various means, such as membrane separation, cryogenic recovery, adsorption, and desorption can be a long-term approach to reducing GHG emission. In collaboration with equipment suppliers, semiconductor fabs could refine them into pure process gases that can be used again, potentially reducing process-gas emissions. For this lever to become economically viable, collaboration between semiconductor companies, equipment suppliers and researchers will be compulsory to address these major challenges related to the separation of process-gas outflows and purification.

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

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

Sustainability issues in semiconductor manufacturing induced by PFAs

PFAS is a class of thousands of synthetic substances known as ‘forever chemicals’ since they do not break down in the environment. Most of which are either persistent themselves or are transformed into persistent compounds in the environment. These substances are hazardous for human health as they accumulate in the body, but also in water, ground, and then the seas and oceans.

PFAS are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–). Due to the C-F bond strength compared to C-C bond, PFAS offer a unique set of technical characteristics, which include exceptional heat and chemical resistance, high electrical insulation resistance, high purity, low-outgassing and low coefficient of friction.

Those intrinsic properties are the basis of many of the technical benefits of fluorinated materials in semiconductor processing, but this also leads to their chemical stability and environmental persistence. Fluorination brings unique physicochemical properties and consequent qualitative improvements that are the enablers of semiconductor, performance and manufacturing advancements.

PFAS are used in the semiconductor manufacturing industry in the lithography process, as a component added to the photoresist to generate photo-acid generators (PAG), improve its adhesion to the silicon wafer, increase its durability, and enhance its resistance to harsh chemicals and high temperatures. In addition to their use in photolithography, PFAS are crucial in producing other semiconductor components. They are used in wet chemistries as surfactants (cleaning, stripping and etching, and metal plating), dry etching, chamber plasma cleaning, CVD and ALD. PFAS are paramount in packaging materials to improve thermal stability and moisture resistance. They are also used as a coolant in the chip etching process, as working fluids for vacuum pumps…

Besides their application in chipmaking, PFAS are also essential for semiconductor manufacturing equipment and factory infrastructure. Their exceptional properties, such as heat resistance and chemical inertness, make them useful in equipment components (tubing, gaskets, containers, filters, etc.) and lubrication (such as various oils and greases).

Up to now, 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 features a trade of data, which is curated into information that either results in a gain of knowledge and/or the enabling of purposeful action or reaction to a given situation.

The width and breadth of such data trading is expected to increase in the future in terms of space and time density. Seamless integration / interaction with the environment and agents involved, based on evolved human-machine interaction (e.g. haptic and brain-computer interfaces) or machine-to-machine interaction, is expected in scenarios that either empower or substitute humans in decision loops.

ECS conform to the HW and SW ensembles that at different levels of integration and organization complexity, mediate the different elements of such information trading: acquisition, management, and exploitation. Indeed, HW and SW integration schemes are the ones ultimately responsible for substantiating the expected increasing number of systems functions and applications that are to emerge from the reunion of:

- New sensitive and structural materials.
- Physical-to-digital (and vice versa) transducers architectures.
- Local (on-system) intelligence.
- Communication/interaction interfaces with users or higher instances of the decision chain.

In addition to the continuous improvement of semiconductor processes and materials, increasing the level of proficiency of elements managing information, integration of more diverse components will be essential to make systems aimed at monitoring the condition of people, assets, processes, and environments less dependable on the use of energy and on external supervision. Making these devices and systems faster, more sensitive, efficient, robust, functional, and apt to different application scenarios will demand higher levels of heterogeneity of materials and fabrication and assembling processes.

Self-powering, energy harvesting and storage will become more and more important and significant advances are expected in solid-state devices to cover the needs of edge and IoT devices. Integration of intelligence to these inherently power-restricted devices requires novel power-efficient computational platforms, such as neural networks and analog computing approaches in parallel with CMOS and other traditional semiconductor devices as commented in the previous chapter.

Next generation computing devices, using physics to make computation, pose challenges in integration as well as in development. In such approaches, envisaged in Chapter 3.1, and made possible in the frame of processes of Chapter 2.1, other modes of coding information besides bits will be used, e.g. using qubits or encoding in time, like for neuromorphic architectures where information is coded in a succession of spikes, or their coincidence in time. Another massively parallel approach using biological technology (based on proteins, DNA construction, etc.) can also emerge for niche applications, or for storage[2]. Most of these technologies will be used first in servers for very specialized acceleration but will slowly improve to be integrated into edge devices.

Moreover, ECS are pivotal elements of the digital transition that supports the current and future quest for making our civilization sustainable, maximizing performance and minimizing e-waste, and particularly for slowing down, reverting or making human environments resilient to climate change.

In addition to the sustainability of the ECS fabrication processes themselves, the scarcity of materials and the increasing demand for ECS imply that approaches and architectures that improve the chances of ECS modules to be repaired and/or reused, and of their material constituents to be reclaimed, need to be addressed. Single-use or disposable devices need to be designed with minimal, and minimally invasive, electronics. The same applies to install-and-forget systems to be deployed in natural remote locations. For example, organic and printed electronics can lead to biocompatible electronics and more effectively recyclable systems. Although there are widespread efforts to recycle computing systems, we are far from the goal of effectively recycling because of the lack of processes to support an appropriate circular economic and business model. Component and system level challenges range from homogenizing component and subsystem lifecycles to computing models and materials used. In a wide range of application domains, a significant challenge is the ability for global reconfiguration of system resources to satisfy diverse applications' functional and non-functional requirements, such as latency and energy, including re-training in AI/ML subsystems. Significant effort needs to be made to develop systems that are scalable linearly or functionally.

In terms of global resilience to climate change, multifunctional smart information systems will be in demand to react faster to such upcoming challenges and risks. For instance, globalization of human activity and large-scale weather changing patterns will ease the spread of known diseases beyond their usual geographical boundaries as well as spur the appearance of new ones. Swinging weather conditions will affect application fields directly exposed to climate conditions such as mobility, energy, or agrifood/ environmental applications. ECS helping these applications to react to those abrupt changes need to be integrated and packaged themselves in a way that can cope with these harsher environmental conditions.

Integration, as the art of recursively combining physical devices, components, and systems together to form a new entity with increased functionality in the minimum volume possible, will be key to leverage the different positive aspects of diverse technologies and their reference materials. It has been already appraised that a combination of nanoelectronics, photonics (optoelectronics), electronic smart systems, including AI/ML subsystems, and flexible, organic and printed electronics is setting the path for future enabling functional electronics[3], which will be characterized by aspects such as:

- A shift from physical to functional integration.
- The use of novel substrates and structural systems.
- Seamless integration in everyday objects for a broad spectrum of new applications.

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[2] https://www.microsoft.com/en-us/research/project/dna-storage/

[3] https://5e-project.eu

- Real-time capture and management of multi-physics data and contextual information.
- Safe and secure operation.
- Networked, autonomous operations complemented by software solutions (including AI).
- Eco-design approaches at product, process, and business model levels.

The distinction of monolithic and heterogeneous integration, and what can be achieved with them, is subjected to boundaries that will evolve with time. Particularly, monolithic integration at chip, chiplet, and SoC levels is progressing through the development and maximum exploitation of 3D sequential integration, a technology with important research activities in the EU that will impact applications with very high-density interconnections (IoT, neuromorphic computing, etc.). Heterogeneous integration, from non-CMOS materials and device processing on top of CMOS wafers to customized application platforms, is also progressing thanks to the evolution of scalable wafer-level or package-level integration schemes nurturing compact System-in-Package (SiP). Still, maximum versatility comes with integration of technologically dissimilar components (e.g. MEMS/MOEMS- NEMS and ICs, electronic and photonic elements, etc.) onto application-oriented platforms, which could be board-like or built on flexible/conformal substrates. To serve such versatility, 3D place-and-route tools with extended ranges of speed, precision, and gentleness for handling components that on occasions are fragile, will be needed. Modelling/simulation, characterization and reliability evaluation tools, which are also strong European domains, will be required to take all the new materials, technologies, device architectures and operation conditions into account, so that cost of development is reduced, and technology optimization is speeded up. All those encompassing schemes are expected to be beneficial for the integration of future high-performance sustainable, secure, ubiquitous, and pervasive systems, which will be of great added value for many applications in the field of detection and communication of health problems, environmental quality, secure transport, building and industrial monitoring, entertainment, education, etc.

4.3.3 Embedded software and beyond

The next generation cyber physical systems will play a key role in the future AI, IoT, SoS realisations, while they will need to be sustainable and easy to maintain, update and upgrade in a cost-effective way, across their complete lifecycle. Mature software platforms running on them will ensure safety and security by design and be available as a part of the European digital infrastructure to a wide audience for building services and business.

We envision an open marketplace for software frameworks, middleware and digital twins with a seamless integration and ubiquitous presence that will represent a backbone for the future development of one-of-a-kind products. While such artefacts need to exploit the existing software stacks and hardware, they also need to support correct and high-quality software by design.

Thus, the envisioned long-term achievements in embedded software will drive the digital industry, while enabling collaborative product-service engineering, and making sure to be inclusive.

For overcoming challenges related to efficient engineering of software, new programming languages and tools for developing large-scale applications for embedded SoS will emerge. Software engineering will address hybrid distributed computing platforms, including efficient software portability, and the development of new software architectures involving edge computing will follow. Model-based testing will contribute to handle uncontrolled SoS.

Short-delivery cycles, maintenance, and extension of software systems are goals that require continuous integration and deployment. Autonomous embedded systems and autonomous processes for IoT & edge embedded HW/SW co-design, and integration & orchestration platforms for IoT and SoS will contribute to achieving those goals. Model-based engineering, based on multi-dimensional, complex and of scale digital twins in the edge, as well as their deployment along with systems, will contribute to a continuous integration. Next generation hybrid digital twins, based on big data-driven and classical physics principles, will be developed and integrated in embedded hardware, while supporting enhanced cognition and intelligence that will demonstrate enhanced capabilities to encapsulate the real word, e.g. power modules, while enabling unseen capabilities for supporting high-level missions as the Green Deal.

As anticipated, software in cyber physical systems must support sustainability: approaches for lifecycle management will enable this by supporting distinction between core systems capabilities and applications and services, and by enabling interplay with legacy subsystems. Interoperability must be built-in and ensured by integration platforms, and will enable features such as easy SW updates, device management, and data management. Composability of systems will be a property supported by properties contracts and orchestration systems, and will be directed towards “write once, run anywhere” for optimal execution on the cloud-for-edge computing continuum.

The modularity of future cyber physical systems, which will dynamically compose in large SoS, will require a high-level of trust, both at the level of the constituent components of SoS and considering how they connect and compose. To this regard, the evolution towards stronger protocols and interfaces (including well-defined pre-compilation connections), supporting security, privacy, and dependability aspects, represents a key factor.

Use of safe, trustworthy & explainable AI will be dominant in autonomous systems and will enable embedded intelligence. AI will play several key unconventional roles in innovation, e.g. as a tool for SW development/ engineering. These innovations will be supported by the European Processor Initiative and its integration in cloud servers, open-source hardware, and software.

Finally, use of quantum computing and IoT digital twin simulation will support software reliability and trust.

4.3.4 System of Systems

System of Systems (SoS) is projected to become an area of exceptional economic growth, both short term and over the coming decades[4]. This will create a strong market pull for the complete ECS value network upstream of the SoS area.

Strategic investments addressing open platforms, engineering, and deployment efficiency, SoS management and control represent key factors to propel Europe towards very large scale of digitalization and automation solutions across integrated and optimised operations of engineering, production, logistics, infrastructures, etc. The inherent heterogeneity of SoS is expanded with the new, emerging computational models that include accelerators, AI/ML subsystems, approximate computing, organic systems, and others, pose significant challenges at all levels. Interoperability and adaptation to diverse physical interfaces and communicated data structures constitute clear examples of challenges. The management of heterogeneity at all levels, including dynamic instantiation of multi-paradigm computing resources considering application requirements and specifications, auto-configuration of distributed resources (locally or globally) to satisfy application functional and non-functional requirements, require significant advances in the field. Success in this direction requires additional activities towards standardization for HW/SW functions as well as scalability specifications to achieve wide and cost-effective use in applications and use case with variable performance requirements.

Large scale usage of SoS technology is further expected to be a significant contributor to the Green Deal through distributed and intelligent solutions that provide significant reduction of environmental footprint in terms of energy consumption, material consumption, waste and, in general, through a more rational and controlled use of all types of resources. This strengthens the ECS value network through energy efficient and robust electronics hardware, connectivity, and embedded software.

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[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.

The future evolution of SoS will further require cooperation between domains, enabling a wider shared understanding of the context and situation, more useful services, richer functionality, better user experience and value proposition. This evolution will introduce the concept of connected and interacting domains (potentially both physical and virtual), where application and services run transversally on top of connected vertical domains.

In the medium/long term, many technologies will allow the evolution of SoS towards the scenarios previously described, including:

- Distributed AI, to control the inherent and quickly increasing complexity of SoS, making them secure, reliable, easier to maintain, etc.
- Connected and interacting domains, supported by:
  - Open and robust integration platforms.
  - AI method adopted to address conflicting functional and non-functional requirements.
- Engineering support for emerging behaviours in complex SoS:
  - Model based engineering.
  - Predictability, controllability, monitoring and diagnoses.
- Automated and autonomous engineering.
- Machine interpretable content.

4.3.5 Edge Computing and embedded artificial intelligence

Artificial intelligence will be the enabling foundation for the digital society, ensuring that the systems that make up its framework function in an effective, efficient, secure, and safe manner. Most of the ambitions that are to be realized in the digital society, such as a zero-emission economy, affordable healthcare for everyone, safe and secure transactions, etc., can be achieved only if an underlying AI infrastructure is in place. This implies that the Internet of Things will gradually transform into the Artificial Intelligence of Things (AIoT), where AI constitutes the interface between the digital world (e.g. edge and cloud computing, cognitive and autonomous cyber-physical systems, embedded systems) and the analogue real world.

Artificial intelligence and machine learning (AI/ML) methods enable efficient and effective automated decision making in domains ranging from system design, design space exploration and manufacturing to application and business processes. As computing models distribute functionality at all systems from the cloud to the edge, AI/ML methods need to be distributed and coordinated, leading to efficient smart systems at all levels of the computing hierarchy. In addition to the ongoing research in AI/ML for applications in increasing application domains, efficient and effective methods for distributed intelligence and federated learning become increasingly important. Advanced AI approaches, like composite AI, require heterogeneous technologies to be addressed altogether, such as vision and natural language processing. The accelerating adoption of AI/ML, in its various approaches, results in high demand of subsystems and accelerators, creating a significant set of challenges analogous only to the growth of the respective market. Importantly, considering the known social questions regarding the adoption of AI, significant effort needs to be spent on certifiable and explainable AI, which will lead to the necessary social acceptance of AI-related technologies at all fronts.

AI technology is becoming increasingly demanding for computational power, especially for the learning phase. As Figure 4.2 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 4.2), which, in turn, lead to dramatic increase of need for computational power to implement these techniques. This will imply new progress in energy efficiency to keep the Cost of Ownership affordable. Mainly the GAFAM and BAITX will be able to afford the computing infrastructure that will require a large number of servers.

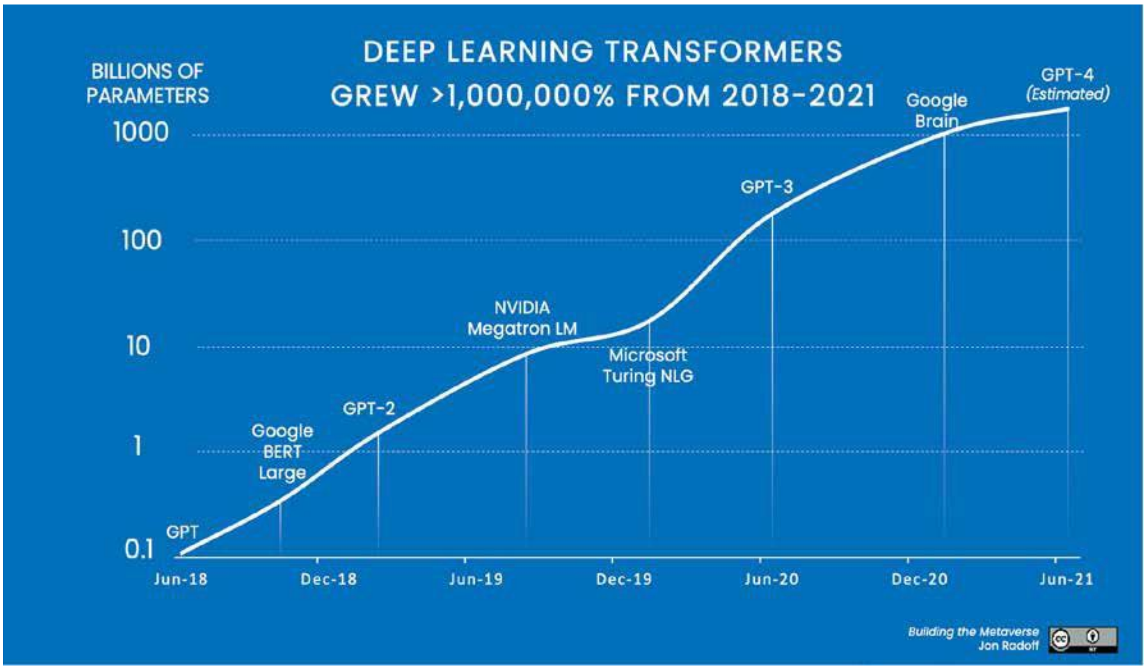

Figure 4.2 - *The increase of parameters employed for deep learning systems (2018-2021)*

IA accelerators will appear in many devices from the deep edge to home servers, allowing to process all kind of data and changing the way we interact with computers. Figure 4.3 demonstrates this, showing the dramatic increase of deep learning chiplets that have been shipped worldwide in the last years. Computing systems will disappear in the environments and will allow natural interactions.

To be able to cope with the diversity of requirements and the Cambrian explosion of designs, AI techniques will be used to select the best architecture (automatic design space exploration) and to generate the code from high-level specifications (no-code) with guarantees of correctness. AI/ML application in the ECS domain include the automated design of SoCs, the respective design space exploration, the integration and orchestration of multiple computing paradigms into embedded systems (including AI-based ones) as well as the design and evaluation of cyber-physical systems overall, which include physical components for operation or computation.

New AI paradigms will emerge, including self-supervised approaches, that can be highly efficient at the edge and decreasing the need for a large database and computing power like for deep learning. Quantum computing, in addition to other computational models, needs to be explored for efficiency and effectiveness in AI methods.

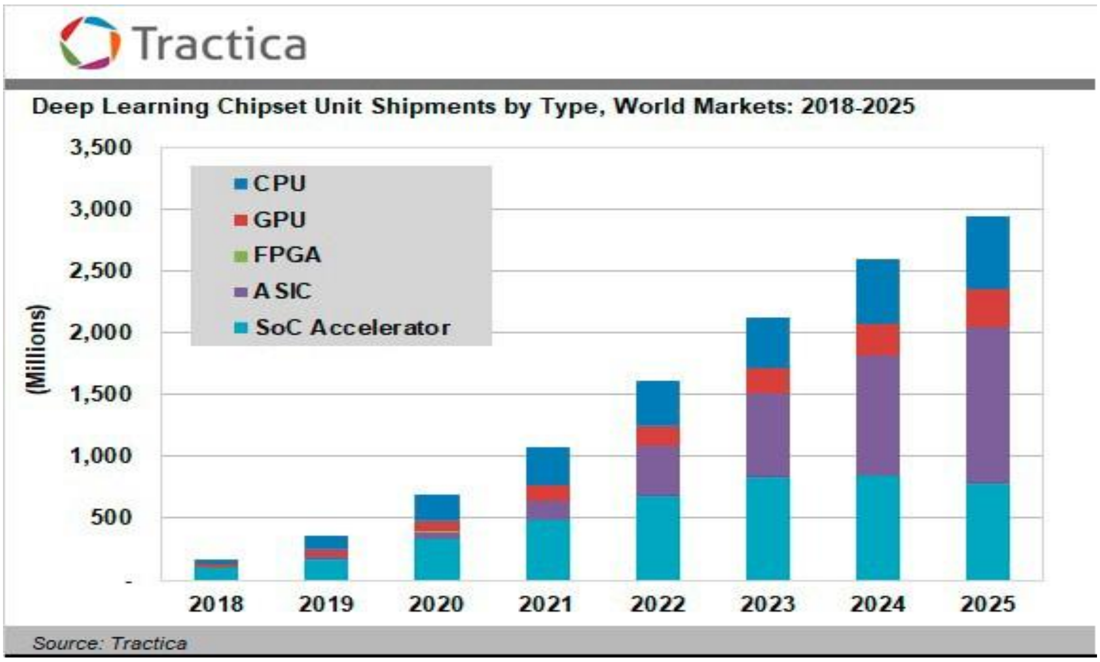

Figure 4.3 - The growth of deep learning chip shipments (2018-2025)

The mass market for smart systems will still be fulfilled by very advanced foundries, but “small” foundries will also appear (assuming that they become sufficiently cheap and efficient) to make the very diversified deep edge devices that most of the time don’t need the latest technology. Some low-cost applications will be made with non-silicon technologies, e.g. using printing or 3D printing technologies[5]. This will allow enterprise level organizations to have their own “device manufacturing” that don’t need high quality clean rooms. AI/ML technologies will play an important role in this direction, towards high automation that leverages AI/ML for the exploration of architectures and code generation.

4.3.6 Connectivity

Today, connectivity is a key enabler to support the development of innovative applications in several markets, such as consumer, automotive, digital manufacturing, network infrastructure (to name a few). This is also pushed by the need of being connected anywhere+anyhow+anytime. The availability of innovative connectivity technologies, both wireless (e.g. low-power wide area networks (LPWAN),

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[5] https://www.nature.com/articles/s41586-021-03625-w

cellular (5/6G)) and wired (e.g. new bus-oriented communication protocols), will enable and enhance a wide range of new business opportunities for the European industry in the context of Systems of Systems (SoS), Cyber-Physical Systems (CPS), and Internet of Things (IoT). Long-term roadmaps for connectivity and interoperability will guide a seamless integration of heterogeneous technologies (hardware and software) for the design and implementation of complex connected systems in effective ways.

Connectivity is a critical asset to any digitalization and automation activity to strengthen Europe's position and enable the European industry to capture new business opportunities associated with the connected world we live in. It is vital to support European technological leadership in connectivity, fostering digitization based on Internet of Things (IoT) and System of Systems (SoS) technologies; for example, this can be achieved by being at the forefront of new standard development for the current 5G initiative, the emerging SoS market, and the upcoming 6G initiative. Furthermore, to bring added value and differentiation with respect to US and Asian competitors, The European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report[6]). For instance, connectivity (e.g. in terms of wireless infrastructure market, led by Ericsson and Nokia) will be supported by the European leadership position in the traditional IT environments as well as the embedded segments, guaranteed by companies such as STMicroelectronics, Infineon and NXP. Connectivity from device, over the edge, and to the cloud will need to be virtualized, relying on run-time design, deployment, and management of integrated edge and cloud network architectures. This will enable the connectivity from cloud to far edge, shifting the perspective from point-to-point connectivity to application-to-application connectivity.

Connectivity engineering and management must be significantly improved to support simplified and inexpensive deployment and integration of new applications into SoS, CPS and IoT solutions.

Connectivity will provide the basis for a data layer supporting instant and seamless data and information exchange between producers (supply below the data layer) and consumers (demand above the data layer) within and between domains. This layer will enable large-scale integration of SoS, CPS and IoT solutions. Targeting systems and applications, we should consider the interconnection between sub-systems and focus on individual component technology development, according to needs identified at system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key. To fully leverage this heterogeneous integration at hardware level, software interoperability is a parallel challenge to provide connectivity that will allow for SoS integration. Thus, an alternative major challenge is to enable SoS integration through nearly lossless interoperability across protocols, encodings, and semantics. To do so, dedicated software tools, reference architecture and standardization are key to supporting SoS integration, thus enabling the provision of a scalable and evolvable SoS. As it remains very difficult to assume that highly customized embedded systems will be built based on a single, unified, high-level modelling principle and toolset, there is a quest for consolidation, or even the standardization of basic

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[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.

runtime frameworks, component libraries and subsystem interfaces that will ease the deployment of interoperable components into generic, domain-specific solutions and architectural frameworks in a bottom- up fashion. Such an approach is also expected to provide for better traceability of requirement validation, and formal verification of distributed system compositions and their emerging functional and non-functional properties.

Finally, data protection must be ensured at an appropriate level for each user and each functionality, regardless of the technology. One major challenge is to ensure security interoperability across any connectivity. This foresees the utilization of different connectivity technologies, and these differences create security incompatibilities leading to increased engineering costs. Therefore, the development of innovative hardware and software security solutions, that will support and provide correctness and safety, is of fundamental importance. Such a solution will have to be linked with the previous challenges to ease SoS engineering, deployment, and operation in a seamless manner. Security assessment is a significant issue here considering the criticality of applications. Standards and directives are required not only for technology transfer and system evaluation, but for legal purposes as well, considering the existing GDPR legal framework and the emerging laws regarding European and national cybersecurity requirements.

Thus, the following major challenges need to be addressed in the connectivity roadmap until 2050:

- Keeping European leadership in connectivity.
- Providing virtualized connectivity.
- Introducing data-oriented connectivity.
- Developing connectivity engineering.
- Meeting future connectivity requirements leveraging heterogeneous technologies.
- Enabling nearly lossless interoperability across protocols, encodings, and semantics.
- Ensuring secure connectivity and interoperability.

4.3.7 Architecture and design: methods and tools

The European ECS industry has been strong in systems engineering, integration, validation and verification, test and simulation, and certification of innovative ECS-based products. The produced systems are characterized by high quality in such terms as functionality, safety, security, reliability, trustworthiness, and certifiability.

Considering the need to maintain and increase this strength, we need to invest in extending existing, and developing new processes, methods and tools that will ensure European leadership in the field. Emerging ECS components and systems are characterized by new functionalities, increased complexity, and diversity on all fronts, ranging from methods and paradigms to modelling and analysis. As the competition by US and Asian ECS companies is fierce, significant effort and investment is necessary to enable European leadership in the technologies for integration, validation, verification, testing and certifiability. A significant parameter in the establishment of leadership and effective technologies is the support of the European Green Deal, by enabling green development and green ECS-based products. Tools and methods for managing the complete ECS lifecycle are necessary, ranging from resource-considerate and climate-neutral design and operation to development, production and maintenance of ECS-based products addressing issues that include even decommissioning and recycling.

To realize this vision and associated goals, the European efforts need to extend existing, and develop new, processes and methods that cover the whole lifecycle of products, from initial requirements elicitation through design, integration, verification, validation, test, certification, production to commissioning, operation, maintenance, and decommissioning. These processes and methods need to support data collection from production as well as from operation and maintenance to be 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 one with a mobile phone to can 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 constant growing trend. We expect that in the next ten years such systems will be increasingly deployed, not only in controlled environments, such as in manufacturing industries, but massively spread in our personal, professional, and social spheres.

ECS of the future will not require an external environment control to work as wished. More generally, the ECS of the future will have to satisfy different constraints on different scientific and social disciplines and ought to meet both the founding principles of European society.

To maintain European leadership in electronic devices and systems we must make our efforts to provide innovative products of the well-known high quality, reliability, safety and cybersecurity to our customers. From this perspective we expected the following challenges to be considered in a long term:

- Development and integration of new materials for advanced packaging and interfaces, new characterization techniques, and new failure modes caused by new use-case scenarios.
- AI/ML methods, including digital twins, to be a cornerstone of keep leadership regarding quality and reliability of ECS made in Europe and be an enabler for new data-driven business models.
- Model-based engineering (incl. standardization of data management and processing) to be a key instrument for virtual release of ECS through the supply chain and shortening time to market.
- Assuring user trust and acceptance of ECS through early inclusion of user requirements, explainability-by-design, and user education and training.
- Model-based engineering (including standardization of data management and processing) to be a key instrument for virtual pre-qualification of ECS and shortening time-to-market.
- Data transmission methods and protocols that are so reliable that they can be used to transmit life-sustaining information over long distances (e.g. for robotic surgery).
- Reliable and certified software that can be kept even if the underlying hardware or hardware architecture is changed, including potential influence of SW updates on HW

reliability.

- Software that can adapt to a degrading underlying hardware to achieve a long-lasting and reliable HW/SW combination.
- Liability of trusted AI-driven systems (it is based on trustworthiness of (AI-driven) systems, included safety and certification of AI-driven CPS, which is a main challenge in 2021).
- Safely manage /design for human interactions in complex systems, SoS and application scenarios
- Ensuring sustainability, cybersecurity, safety, and privacy, for AI-driven and quantum-based systems (based on "ensuring safety, security and privacy and sustainability of (AI-driven) systems").
- The attention to the environment and privacy have increased significantly in the population. This implies that conceiving any safety solutions is not enough. Our vision on 2030 is an integration between disciplines, which have nothing to do with safety or computer science in stricto sensu, such as privacy, social trust, liability, and sustainability.

Importantly, all properties of quality, reliability, trustworthiness and safety are heavily dependent on the integrity of the supply chain that is employed to develop ECS and ECS-based systems. The business models that are employed within Europe and abroad, lead to dependence of organizations on suppliers and contractors for provisioning of hardware as well as software components and systems. Trust among them is not a given. 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 optimization of desired parameters, such as delay, area, power, etc. Heuristic algorithms have been employed extensively to identify appropriate designs, since exhaustive search of design spaces for modern IC's is infeasible. AI/ML methods are increasingly adopted in design space exploration in place or complementing heuristic algorithms at several stages of circuit design, from manufacturing and physical design to RTL design and high-level synthesis. Importantly, AI/ML are increasingly exploited in design testing and verification.

AI/ML methods are used in several approaches to address different problems in the system design process. A comprehensive review of the problems and approaches is given by M. Rapp et al.[7], which classifies the problem types solved with ML with 3 parameters: (i) development of predictions, actions and/or data, (ii) the design stage and (iii) the exploited AI/ML algorithm. In terms of predictions, currently, AI/ML methods are used and proposed for predicting design properties after explored decisions, while for actions, they are used in place of existing techniques at various stages of design, such as RTL design, placement and routing, etc., with the purpose to optimize an appropriate criterion. As most of the employed algorithms are supervised learning ones, data constitute a significant component of effective employment of AI/ML techniques. As such data do not exist or may differ significantly in practice, because of the different existing tool chains, AI/ML methods are used to produce or collect training data within and from the design process itself. Employed algorithms range from regression to neural networks, mostly for supervised learning, based on models that range from graphs to images at the various stages of the design process.

Despite the large and increasing research work in employing AI/ML in embedded system design, there are several challenges that need to be addressed for the penetration of research results in practical design frameworks. The biggest problem is that of appropriate data for training the models; this is a well-known problem in most application domains of AI/ML. The need for large amounts of appropriate data, considering the exponential space of design alternatives that need to be evaluated, will lead to long delays until the appropriate models are built. Alternative methods for generating appropriate date will also need to be developed.

Machine Learning (ML) and, more generally, Artificial Intelligence (AI) algorithms are essential to extract relevant information from massive data amounts. As the computational capabilities of edge- and end-devices (also indicated as “far edge”) is ever increasing, ML-based inference processing is no longer carried out in the cloud, but is distributed across the device-edge-cloud continuum. This requires the identification of a proper architecture to efficiently distribute the computational load, with dynamic methods for model compression or model splitting among the architecture tiers. Edge AI or, more generally, edge intelligence has emerged as crucial in multiple applications. Likewise, the possibility of implementing tiny ML (TinyML) algorithms in constrained devices opens new perspective in the Internet of Things (IoT). Distributed ML will involve several aspects, including latency, bandwidth utilization, data safety, data quantization, privacy, cost.

AI/ML accelerators constitute innovative components in new generation computing systems of all scales, from large and core to edge. Research in this area is continuously growing with accelerators

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[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.

that target application domains, from low-power embedded systems for inference to back-end high-performance accelerators for model training. Several surveys exist presenting methodologies for AI/ML accelerations, especially for neural networks[8,9,10] , while there also exist surveys of commercial accelerators[11]. The wide range of application domains of accelerators poses significant challenges to designs, from performance to power to cost. Especially for embedded systems, accelerators are effectively targeted for edge systems, from automotive to medical, from industry to consumer. From the surveys it becomes alarmingly clear that most technologies are developed and commercialized by organisations outside Europe. European efforts exist, such as AnIA[12] , Axelera AI's AI Edge accelerator, Infineon's Parallel Processing Unit (PPU) AI accelerator[13] and others. However, market penetration, even in the start-up domain, is limited when compared to the US and Asia. Efforts focus on specific application domains, such as computer vision, automotive, etc. Strengthening of these efforts is necessary, to address challenges for cost-effective accelerators in a wide range of domains. The challenges include development of effective architectures and exploration of the trade-offs among memory design, power consumption, high performance and arithmetic calculation precision that dominate AI/ML neural network accelerators, in conjunction with specialized algorithms.

Significant challenges also exist in adopting AI/ML in embedded and cyber-physical application domains. AI/ML methods are already used and are continuously being developed for effective operation of embedded and cyber-physical systems in various environments, through predicting operational parameters, including input, and/or environmental parameters. However, often, the unpredictability of parameters combined with the lack of effective training data leads to suboptimal operation and creates a significant challenge to develop effective solutions that are application dependent.

4.3.10 Quantum Technologies

Quantum technologies are promising to provide effective solutions to a wide range of application domains. Some application-specific systems are at the first steps of 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 fractioning large numbers, optimizations

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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

requiring multiple variables, solving quantum problems as in quantum chemistry and physics, data analysis and sorting, and data encryption.

Quantum systems have been developed exploiting the wave-particle duality at the physics level and their ability to achieve discrete states. Their power originates from the exploitation of their superposition and entanglement properties. Superposition refers to their ability to exist in two or more states at once, while entanglement refers to their ability to create interdependencies among particles even when separated by large distances.

Superposition and entanglement enable powerful operations in terms of computing and communications, considering that entanglement promises high speed and secure communications while superposition coupled with entanglement enables effective parallel processing. Quantum networks and a Quantum Internet are the targets of several research efforts, including a test site in Chicago in the USA. Quantum computers are the focus of several efforts around the world, from large companies, such as IBM, Google and Intel, and small companies, like Rigetti, IonQ and Oxford Quantum Circuits, to universities such as TU Delft in Europe and the University of Science and Technology of China.

Quantum operations in computing and communication systems are based on quantum bits, named qubits, where a qubit constitutes the smallest unit in which quantum information is generated, transduced, processed, stored, and transmitted. A qubit is a superposition of the classical binary states (0,1). Analogously to classical computers, quantum computers perform a series of operations (a quantum algorithm) to modify qubit superpositions (probability of being in a particular state) and entanglements to increase some probabilities and to reduce others. Measurement of a qubit causes its state, and the states of entangled qubits, to collapse to either ‘0’ or ‘1’ with a probability dependent on the state of the qubit at the time of measurement. The goal is to maximize the probability of measuring the correct answer.

There are two main quantum computing models today:

- Analog or adiabatic quantum computing, and
- Gate-based quantum computation.

Analog quantum computing is typically based on quantum annealing, which performs processing by initialization of the system followed by slow, global control of the qubits towards a final state and readout. In this computational model, the energy state of a quantum system encodes or models a problem and the energy landscape, which starts flat, changes slowly and continuously to a final state with the energy peaks and valleys representing the problem to be solved. Analog computers constitute some of the most developed quantum systems to date, but their functionality is limited to simple and very specific problems, because they have limited ability to reduce noise, which impairs qubit quality.

Gate-based quantum computation is analogous to traditional gate-based computers, using a sequence of quantum gates, each composed of a few qubits, that perform logical operations, followed by measurement. Unlike many classical logic gates, quantum logic gates are reversible. A universal set of quantum gates is still needed to achieve the full capability of quantum computation. Gate-based quantum computing is error prone, due to noise. High gate and qubit error rates limit the scalability of quantum systems, leading to the challenging requirement for fault-tolerant quantum computation (FTQC) that would enable system scalability. In this direction, gate error rates as well as qubit and gate fidelity are metrics for the robustness of gate operations; qubit fidelity measures the loss of qubit coherence due to its interaction with its environment and due to shifts of its quantum states over time. These metrics essentially measure how closely actual gate operations match -on average- ideal versions of these operations. Analogously to classical computing error correction methods, quantum error correction (QEC) dramatically lowers effective error rates by encoding the quantum state using redundant "physical" qubits and using a QEC code to emulate stable qubits with very low error rates, often called "fault-tolerant" or "logical" qubits. Importantly, logical qubits currently require a large number of physical qubits and many quantum gates to maintain their state, incurring significant resource overhead in terms of both additional qubits for each "logical" qubit, and additional quantum gates for each logical operation. As an example, for simulating a chemical structure, a FTQC computer based on 111 "logical" qubits would require 10^8 and 10^5 "physical" qubits when the physical qubit error rate decreases from 10^{-3} to 10^{-9} [14]. The development of an accurate and general-purpose quantum computer would need between 10^4-10^6 "logical" qubits (Fig. 1) and a quantum and gate fidelity around ($1-10^{-15}$) for industrial applications[15]. Since QEC leads to considerable overhead with conventional technology, Noisy Intermediate Scale Quantum (NISQ) computers are an intermediate step towards large scale error corrected fault-tolerant quantum computers (FTQC). NISQ computers use qubits without QEC, and although not fully fault-tolerant, they are expected to be practical in the near term for some applications. NISQ computers will require around 10^2 to 10^4 logical qubits (Fig. 1) and a very high qubit fidelity, improving the mean error rate of current quantum computers which reaches 4%. To reduce the impact of environmental noise, and of the unwanted interactions on qubit fidelity, quantum error mitigation (QEM) algorithms are used to mitigate these errors rather than completely remove them.

Quantum computers are expected to find their first use cases in combination with classical computers, so that the QC will serve as an accelerator, that solves the one part of the computation that is computationally expensive for a classical computer, and the classical computer runs other tasks. In this way, even a relatively small and noisy quantum computer can provide benefit in a larger problem.

Figure 4.4 shows the expected evolution of the number of "logical" qubits for both FTQC and NISQ approaches.

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[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)

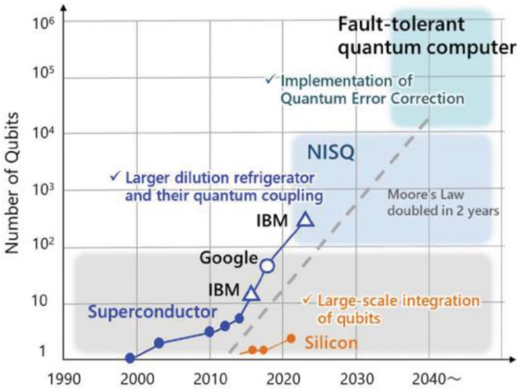


Figure 4.4 - The trend of the number of "logical" qubits and the goal for NISQ and FTQC approaches

The number of qubits, and qubit and quantum gate fidelity in a system are the defining parameter for effective quantum computing. For this reason, significant research and development effort is spent on investigating alternative technologies for qubit manufacturing. Current efforts focus on superconducting qubits, semiconductor gate-defined quantum dots, color centers, trapped ions, cold atoms, photons and topologically protected Majorana modes. These alternative qubit technologies differ significantly in physical aspects, operational and miniaturization challenges. Neutral atoms in vacuum are entirely different from superconducting and electron spin qubits, and photon-based qubits, also named "flying qubits", are also quite different from other types of qubits which are static in location; in contrast to solid-state qubits, photons do not have significant decoherence problems but are harder to generate, control and detect in a deterministic way. Figure 4.5 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.

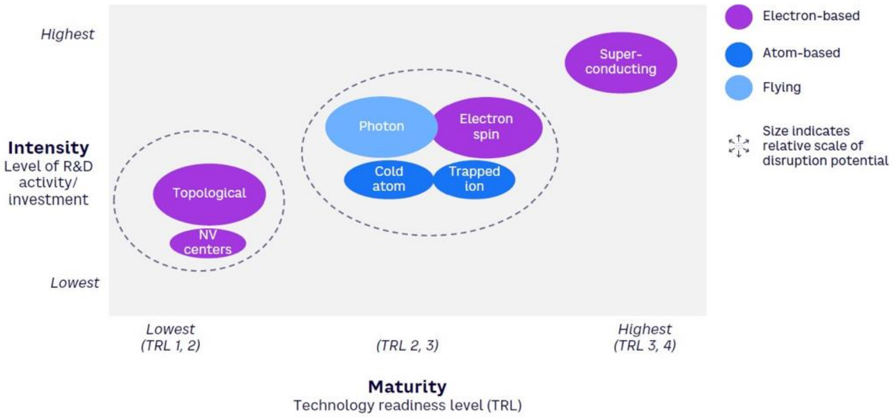


Figure 4.5 - Core qubit technologies mapped by maturity, intensity, and disruption potential

Table 1: Properties of various qubit manufacturing technologies for quantum computing

Qubit technology	Superconductor	Trapped ion	Si e^- spin	Cold atom	Photon	Color centers
Qubit size	$100\mu m^2$	$1mm^2$	$100nm^2$	$1\text{-}10\mu m^2$	$5\text{-}25\mu m^2$	$100nm^2$
Quantum gate	Microwave Magnetic field	Laser Microwave	Magnetic field	Laser Microwave	Interference	Microwave
1-qubit fidelity	99.96%	99.999%	99.93%	99.9%		99.9952%
2-qubit fidelity	99.3%	99.9%	> 99%	99.5%	98%	99.2%
Gate speed	12-400ns	100µs	1µs	0.4-2µs	1ns	20-50ns
Coherence time T_2	150µs	50s	20ms	40s	150µs	0.6s
Variability	3%	0.01%	0.1-0.5%	-	0.5%	large
Operation Temperature	15mK	10K	1K	4K	4-10K	≈ 273K
Entangled qubits	433	32	6	256	≈ 20	5

The different quantum computing approaches lead to challenges in problem-solving aspects of quantum computers, in addition to the manufacturing issues. Quantum algorithms and software for quantum computing are in their first steps and present significant challenges. The goals of user-friendly quantum computers that are programmed effectively and efficiently require significant advances in terms of algorithms and software tools. Recent advances in specialized application domains such as localization, optimization and machine learning exploit quantum computers effectively but require very specialized 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

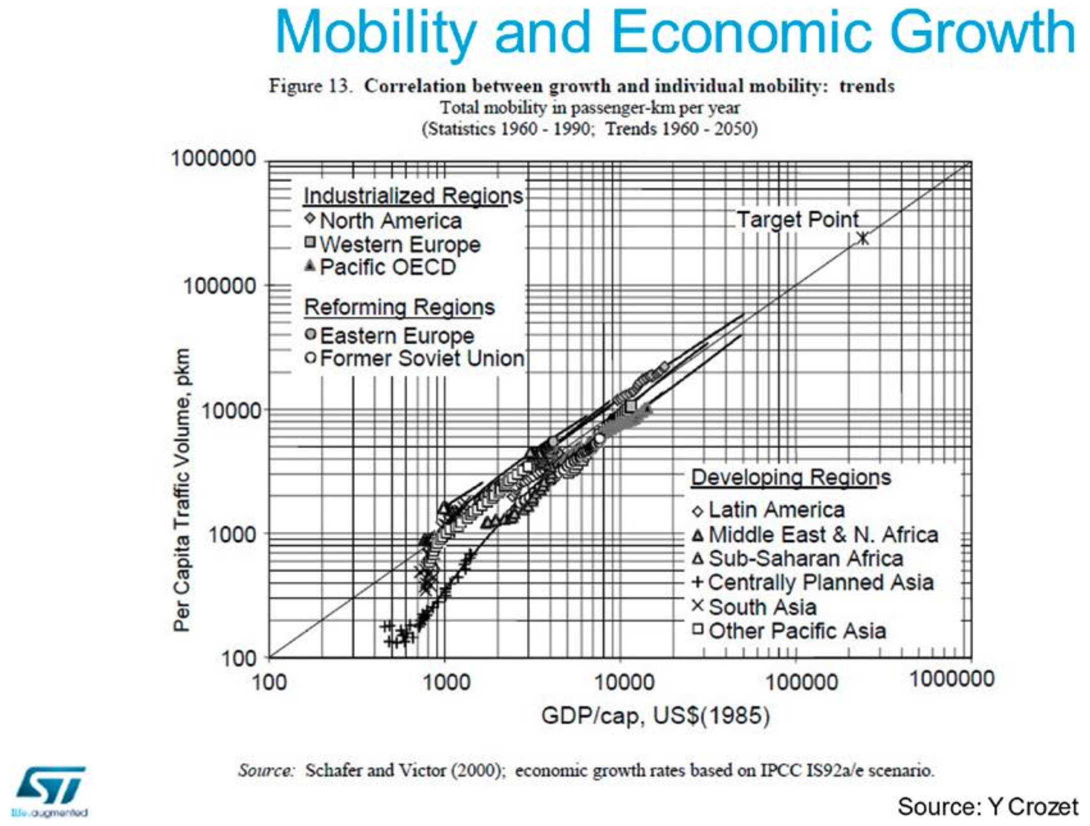
4.4.1 Mobility

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 realize this vision, possible scenarios include the projection that mainly autonomous and electrically driven vehicles (FEVs) will be on the road, and that all road users will be connected. It is envisaged that other road users (bicycles, pedestrians, public transport) will also participate in this connected, autonomous model, in addition to transportation network infrastructure (tolls, signals, etc.), creating an augmented Internet of Vehicles. Key networking technologies, such as the emerging 5G cellular connections with their very low latency (ms range) and the powerful edge nodes (Mobile Edge Computing, MEC), will enable highly effective vehicular communications for traffic management and safety applications. Railways and maritime transport will also become more autonomous. Fully integrated multimodal traffic will be applied, in which air, railways and maritime are fully integrated with road transport.

Until now, the rule was simple: more income equals more travel distance as *Figure 4.7* indicates. Will this very simple equation still work in the future?



Mobility and Economic Growth

Figure 13. Correlation between growth and individual mobility: trends
Total mobility in passenger-km per year
(Statistics 1960 - 1990; Trends 1960 - 2050)

Source: Schafer and Victor (2000); economic growth rates based on IPCC IS92a/e scenario.

Source: Y Crozet

Figure 4.6 - The correlation between growth and individual mobility

Many attempts have been made in the past to move people from individual to public transport. Huge investments have been made into infrastructure, fast trains have been deployed massively, bus lines installed. Nevertheless, this did not change the distribution of shares in the transport between planes, trains and cars. It could just allow to keep pace in an ever-increasing mobility. The most important means of transport is still, and will also very probably be in the next decade, the individual car.

If we want to reduce emissions and energy waste, then we need to focus on this means of transport and make it more ecologically friendly. It must use less space and energy.

The global mobility is undergoing a significant change triggered by the increasing thread of global warming. The European Union started the Green Deal, which is radically changing the way mobility works. Classical fossil fuel-based transport and mobility will be completely replaced by CO_2 neutral mobility. As all the alternative mobility systems, be it battery-based, H_2 based or synthetic-fuel-based, have their individual challenges, all of them have in common that CO_2 neutrality is only possible in using a connected, shared and energy-usage minimized mobility network. To reduce the space needed by cars, the best solution would be to use them better during the day by sharing their usage.

Owning cars should thus be replaced by shared mobility and intermodal transportation offering the most convenient and CO_2 neutral way to move goods or persons from point A to point B. This will be only possible by a stable, everywhere available, user-friendly, secure, fast communication system connecting people, traffic operations, cars, trucks, busses, airplanes, ships, busses, etc. across the globe.

Today's vehicles contain more software than any other embedded system and most compute applications. Tomorrow's vehicles will multiply the software lines of code by a factor 6. Semiconductor value in the car will more than double through the next 10 years (from 600$ to 1200$). Some already talk about ''software- enabled vehicles" or "data-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 the aging society will be supported by more and more automated transport means at all mobility variants taking the best advantage of the available resources as roads, parking space, airspace, and water space, and serving best the needs for mobility of the society. This will be supported by sensors combining different sensor principles in one sensor with significantly less power consumption, as well as new AI optimized edge computers in the transport vehicles. These systems will be part of completely new HW/SW systems spanning from sensors via embedded edge computers via predictable, fast, clean (also for the user), safe, secure, and failsafe communication to globally interconnected cloud systems.

4.4.2 Energy

Power electronics is the enabling technology for the efficient generation, conversion, distribution, and usage of electrical energy. It is a cross-functional technology covering very high gigawatt (GW) power (e.g. in energy transmission lines) down to the very low milliwatt (mW) power needed to operate a mobile phone, and even to microwatt (μW) to power autonomous sensor nodes. Many market segments, such as domestic and office appliances, computers and communication, ventilation, air conditioning and lighting, factory automation and drives, traction, automotive and renewable energy, can potentially benefit from the application of power electronics technology. The ambitious goals of the EU to reduce energy consumption and CO_2 emissions can only be achieved through extensive application and use of power electronics, as this is the basic prerequisite for:

- Efficiently feeding wind and solar energy into the power grids.
- The stabilization of the power grids with an increased share of fluctuating renewable energy sources.
- Highly efficient, variable speed, motor drives.
- Energy-efficient and low-emission mobility with hybrid and full electric vehicles.
- Energy-saving lighting technology.
- Efficient recovery of braking energy.
- Energy management of batteries.
- Control appliances and building management systems via the grid interface (smart grids).

The estimated energy savings that can be achieved by introducing state-of-the-art and future power electronics components into systems is enormous, estimated at more than 25% of current electricity consumption in the EU. Since power electronics is a key technology in achieving a sustainable energy society, the demand for power electronics solutions will show significant growth over the coming decades. The European industry holds a strong position in the field of silicon-based power semiconductors and modules and is establishing a robust foundation for future progress in wide bandgap semiconductor technology. Europe also has high-quality power electronics research groups at universities and research institutes with well-established networks and associations across Europe to provide platforms for discussion, cooperation, and joint research.

A long-term roadmap for power technology needs to cover different sectors.

- New, highly efficient power devices based on wide-bandgap semiconductor materials such as SiC and GaN-on-silicon, and possibly Ga_2O_3, AlN, diamond, diamond-on-silicon, or nanowire-based materials.
- New, cost-efficient, Si-based power devices to enable high efficiencies for mass-market applications such as super-junction MOSFETs.
- Power management for very low-power applications as required for IoT, including the development of energy harvesting technologies, covering the full range from GW to μW levels.
- High temperature-capable packages serving new materials and 3D technologies that offer the highest requirements and integration capabilities.

In the energy roadmap towards 2050, five major challenges were identified:

- Smart & Efficient – Managing Energy Generation, Conversion and Storage Systems, trying to fulfil the vision of loss-free energy conversion and generation.
- Energy management from On-Site to Distribution Systems.
- Transmission grids with the goal to achieve in 2020 solutions to cope with rising grid loads as a base for the carbon-free energy transition of Europe.
- Efficient Community and Regional Energy management.
- Cross-Sectional Tasks for Energy System Monitoring & Control, so that highly integrated monitoring and control of energy systems and grids, are achieved utilizing innovative ECS-based solutions.

These challenges need to be addressed to achieve the current EU policy target of 30% savings by 2030 by utilizing innovative ECS-based solutions, as well as the milestones of (a) -55% GHG emissions until 2030 (getting closer to zero emissions due in 2050) and (b) grid integration. To realize this vision, we need to target the decentralization of energy sources, opportunities with networked systems, limitations in peak electricity supply, oversupply times, new demand for electric energy supply for urban mobility, and the introduction of storage systems. This will lead to new challenges in energy management providing flexibility, stability and reliability in the grids and distribution for communities and cities. Furthermore, we need to develop components for HV transmission, of 1.2 MV or even higher voltages, to roll out an efficient energy transmission over Europe. Also, we need to combine local generation & demand site management with transmission & distribution grid operation & control technologies from sub-MW to GW scale, and we need to develop resilient solutions coping with adverse conditions resulting from the advancing climate change.

Additional technical solutions are needed to increasing share of renewable energy generation, self-consumption (mainly heating/cooling and EV) and building optimization, as well as introducing and managing new types of renewable energy carriers like hydrogen.

Relevant promising technologies, already under use and extension, include (a) artificial intelligence & advanced communication techniques for cyber-security increasing resilient energy system control, and (b) optimal control of distributed generation and dispersed energy-storage devices as well as robust, high power control devices.

4.4.3 Digital industry

Digital Industry is a must of European productive and commercial evolution on the next decade, following and empowering the EU policy related to digitalization. Digital capabilities and functions will be the enabler for safer, greener, sustainable, lower cost and more productive, autonomous, and competitive EU industrial ecosystem.

EU planned, mostly after the Covid experience and lesson learnt, strategic investments addressing digitalization including industrial productive arena, edge technological engineering studies, developments and deployment efficiency and services, addressing, in addition to industrial production, logistics, transportation, health, critical EU infrastructure etc.

The future evolution of EU Industry into Digital Industry will further require cooperation between multiple domains enabling a wider shared understanding of the context and situation, filling the gap towards EU industrial strategic autonomy and more useful services, richer functionalities, better user experience and value proposition introducing the concept of connected and interacting domains.

The manufacturing industry can essentially be classified into two main categories: process industry and discrete product manufacturing. The process industry transforms material resources (raw materials, feedstock) during a (typical) (semi)continuous conversion into a new material that has significantly different physical and chemical properties than the starting substance. Discrete manufacturing refers to the production of distinct items. Automobiles, furniture, toys, smartphones, and airplanes are examples of discrete manufacturing products. The resulting products are easily identifiable and differ greatly from process manufacturing where the products are undifferentiated, for example oil, natural gas, and salt. Another meaningful way to distinguish between manufacturing industries is by dissecting the domain by the end-product categories, such as energy industry, chemical industry, petrochemical (oil & gas), food industry, pharmaceutical industry, pulp & paper industry, steel industry (process industries), and furthermore car manufacturing, machine industry, robotics, and the semiconductor industry. Also, these subdomains constitute significant industrial domains for Europe. These industries are ever more demanding and voluminous consumers of ECS technologies such as sensors, big data, artificial intelligence, real-time system, digital twins, safety & security, computing systems, lifecycle engineering, human-system integration etc. ECS technologies are essential parts of most of the advances in these domains.

The perspective of industry is reflected in several efforts. The major ones are described in the following:

- The SPIRE[16] 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.

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[16] https://www.spire2030.eu/what/walking-the-spire-roadmap/spire-Roadmap

- New resource efficient applications that require completely new designed processes.
- Complete redesign of industrial parks to realize industrial symbiosis.
- The Factories of the Future (EFFRA[17]) roadmap summarizes its vision as follows:
    - Agile value networks: lot-size one – distributed manufacturing.
    - Excellence in manufacturing: advanced manufacturing processes and services for zero- defect and innovative processes and products.
    - The human factor: developing human competences in synergy with technological progress.
    - Sustainable value networks: manufacturing driving the circular economy.
    - Interoperable digital manufacturing platforms: supporting an eco-system of manufacturing services.
- The Connected Factories[18] project forecasts the emergence of new manufacturing concepts, such as:
    - Hyperconnected factories.
    - Autonomous factories.
    - Collaborative product-service factories.

Recently, a federation was set up of the three electronics ecosystems in Europe in nanoelectronics, electronic smart systems and flexible, organic & printed electronics (https://5e-project.eu/). Combinations of nanoelectronics and flexible organic & printed electronics that provide functionalities to electronic smart systems lead to novel solutions. This trend to functional electronics is characterized by the following aspects:

- A shift from physical to functional integration.
- The use of novel substrates and structural systems.
- Eco-design approaches at product, process, and business model levels.
- Real time capture & management of multi-physics data and contextual information.
- Networked, autonomous operations complemented by software solutions (incl. AI).
- Seamless integration in everyday objects in a broad spectrum of new applications.

All these efforts provide high-level targets, which translate into diverse and much more concrete targets in each domain, ending up also in a number of technology challenges in this ECS-SRIA, such as distributed AI along the edge-to-cloud continuum, computation and simulation capabilities, communications and interacting domains, engineering support for emerging behaviours in complex SoS, model-based engineering, predictability, controllability, monitoring and diagnosis, automation, autonomy and robotics, teleoperation, telepresence, simulation and training.

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[17] https://www.effra.eu/factories-future-roadmap

[18] https://www.effra.eu/connectedfactories

Clearly, ECS technologies that enable distributed Industrial IoT (IIoT) systems to monitor and control manufacturing systems and processes will enable disruptive industrial innovations and realise the vision of Industry 4.0 and the Industrial Internet that will lead manufacturing worldwide. Overall, these long-term trends translate into the need to invest in technology research and innovation projects in the following areas:

- The rise of artificial intelligence (AI), a powerful edge, and cloud computing networks; methods and algorithms need to evolve to more complex, reliable and explainable AI.
- Collection of measurement data, including image, video, and 3D animation, and, in general, large volumes of heterogeneous and unstructured data.
- New production schemes such as:
  - Modular factories, i.e., smaller standard units to be assembled according to needs, also mobile units.
  - More end-user -driven agile production, i.e. end-users more connected to production and logistics chains.
  - Hyper-connected factories.
- New production technologies, e.g. 3D printing, and other novel emerging methods, leading to production that is closer to customers.
- Methods to extend closed-loop production lines to closed-loop regions (extensive recycling, net energy, zero-emission and waste, close to end-users).
- Autonomous to human-machine co-work, to enable flexibility and reduce excessive complexity.

Recyclable electronics, since the digital industry will increasingly become a producer and enabler of “green electronics over the next decade”, leading to the need to recycle as many electronic components and systems as possible.

4.4.4 Health and wellbeing

The rising cost of healthcare, caused by an aging population, is one of the major challenges that present-day society must deal with. To keep healthcare accessible and affordable for everyone, it will change radically in the coming decades. Healthcare will become increasingly decentralized and personalized, as medical care will move from the hospital to people's homes as much as possible. This transition in healthcare can only be achieved through the massive development of digital healthcare devices that can provide personalized monitoring, mentoring and treatment.

ECS will keep on being key enablers to realize the continuum of healthcare, notably in linking well-being, diagnostics, therapeutic approaches and rehabilitation issues. In addition to providing the tools for personal management of individual health and monitoring of health condition, ECS and smart systems will play an active role in assistive technologies with the goal to reduce inequalities linked to impairments originating in loss of physiological or anatomical structure or function after a disease or an accident. Ambient Assisted Living (AAL) is a high-priority direction for Europe, to support its increasing aging population.

In the long term, personalized and patient-tailored healthcare will be at the forefront of technology advancement. Further miniaturization of biomedical devices and integration of smart integrated systems (e.g. smart catheters, electroceuticals) will have significant impact on point of care diagnosis and treatment. Real-time localized detection of disease and minimally invasive targeted drug delivery will be a key priority. Achieving enhanced reliability and building stakeholder confidence in these technology advancements will be key to successful implementation. Data integrity and security around the use and storage of personal information will require new methods of application development and a robust system of operation, especially if moving towards a more connected healthcare approach with more focus on tailored patient diagnosis and treatment.

Beyond those technological challenges, aspects such as reliability, safety and privacy issues in terms of regulation and uptake by practitioners, especially when dealing with procurement policies, 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 digitization has an important impact on the way healthcare is addressed. In ten years from now “digital medicine” will be deployed, and will complement, not necessarily replace, the tools offered to medicine to improve the benefits for patients and medical professionals.

These tools may include, for instance, human models also known as the “digital twin”. Here, ECS will have a crucial role in ensuring the necessary link between the digital and the real twins. Real time acquisition and processing of data and vital parameters collected from on-body IoT sensors, is a key technology that will advance existing wearables and will enable identification and prediction of a person’s condition. The use of AI technologies, based on extended measurement data, will enable significant advances in this area.

Finally, progress in interfacing electronics components and systems with biological systems will offer seamless connection to the body for continuous monitoring but also for electrostimulation purposes. Results from the human brain flagship project will provide input for improved deep brain stimulation. Electroceuticals and nerve stimulation will enhance treatments of diseases and partially replace pharmaceutic treatments, thus avoiding side effects.

Some additional developments are presented in the following:

- Fully personalized medicine will be enabled by smart monitoring of health parameters, including factors from the molecular to the environmental levels. Developments in healthcare will benefit from the concept of “digital twins”, so that prediction of health evolution and preventive treatment will become reality and standard procedures. Fully personalized and accurate health data will be available anywhere, anytime.
- Drug development will be assisted by emerging methodologies such as ‘organ-on-chip’.
- 3D-bioprinting. Medicine is highly benefiting from advancement in other disciplines such as genomics or 3D printing. Combining 3D printing of living material and of electronic systems will develop a bottom-up approach to medicine, with advanced and personalized prosthetics and implants increasing biocompatibility, solving the problem of powering, and increasing quality of life.
- Cyborgisation. Future Brain-Computer Interface (BCI) technology will enable new ways of communication, e.g. for people with severe disabilities. By the 2040s wearable or implantable BCI technology will probably make smartphones obsolete. Due to the massive exposition of the physical and biological world in cyberspace, BCI systems will have to incorporate new means of protection of technology, data, and consciousness – like heartbeat, venous system, fMRI or 'Brainprints' as the top measures of security.

These innovations in the medical domain can be accelerated by the creation of an ECS-based technology platform for medical applications. The Health.E Lighthouse[19] initiative has compiled a list of emerging medical domains where further technical developments are required:

- Bioelectronic medicines.
- Organ-on-Chip.
- Personal ultrasound.
- X-ray free interventions.
- Smart minimally invasive instruments.
- Smart drug delivery.
- Intelligent wound care.
- Ambulatory monitoring.
- Point-of-care diagnostics.
- Remote sensing and monitoring.
- E-health.

Despite this urgent need and the enormous resources that are being invested in research, true innovation in terms of products reaching the market has been slow. One of the root causes identified is the lack of open technology platforms. This will release the power of Moore’s Law, that has been the driving force in electronics for more than fifty years, to the healthcare domain: “Moore for Medical”. It is the vision of the Health.E Lighthouse that innovation can be accelerated by stimulating the development of truly open technology platforms.

The list of challenges that ECS will face in the next decade is changing and new issues, linked to the developments described above, will have to be addressed. Security and reliability remain major issues to guarantee safety and integrity of medicine. Regulation will have to be developed to address these concerns. Furthermore, ethical issues may become more and more critical in the uptake of patients and may lead to fundamental decisions in the way medicine will evolve.

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[19] https://www.health-lighthouse.eu/emerging-medical-domains

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 optimized. Crops are supplied with nutrients via a monitored system under artificial lighting and can thus be grown year-round. This method makes it possible to grow plants without soil and natural sunlight, with optimal growth conditions being created artificially. The full potential of this approach can only be achieved with the help of information technology (IT) and IoT components and paradigms such as AI and Industry 4.0, which all still need to be adopted for this purpose. With these digital farming approaches, it will be possible to secure food supply autonomy and food safety for large parts of the EU. Furthermore, investigation into the provision of corresponding technologies and approaches will enhance the strategic autonomy of Europe.

The European Green Deal is a response to these challenges, considering the huge negative impact by the climate change. It includes two main programs "From farm to fork" and "Biodiversity 2030" having a strong impact in the goals of this Chapter, which should contribute to reach the targets defined by these two programs by the introduction of the adequate ECS technologies and solutions.

From Farm to Fork

European food is already a global standard for food that is safe, plentiful, nutritious and of high quality. Now European food should also become the global standard for sustainability. EU agriculture, the manufacturing, processing, retailing, packaging, and transportation of food make a major contribution to air, soil and water pollution and GHG emissions, and has a profound impact on biodiversity. As such, food systems remain one of the key drivers of climate change and environmental degradation. For this reason, the From Farm to Fork action targets to reduce dependency on pesticides and antimicrobials, reduce excess 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[20], putting our food security and nutrition at risk. Biodiversity also underpins healthy and nutritious diets and improves rural livelihoods and agricultural productivity[21]. For instance, more than 75% of global food crop types rely on animal pollination.

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[20] World Economic Forum (2020), The Global Risks Report 2020.

[21] 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/)

A sustainable food system will be essential to achieve the climate and environmental objectives of the Green Deal, while improving the incomes of primary producers and reinforcing EU's competitiveness.

To contribute to reach the targets of these two programs, the long-term vision of this Chapter includes the following challenges:

- Food security:
  - Intelligent and adaptive food production should take advantage of smart (bio) sensing for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
  - Precision farming systems should require robots with advanced sensing and perception capabilities and drones with intelligent computer vision devices to provide a higher level of detail and on-demand images.
  - Farming Systems should have machine-to-machine interoperable communication (sensors, advanced farming machines and robotic collaborative systems) for cost-effectiveness.
- Food safety:
  - Plants and Animals control; AI should allow to monitor, quantify, and understand individual plants and animals and their variability to control the bio-physical processes (like growing conditions) and understand the biological environment (with plants and animals) to ensure food safety.
  - Plant precision breeding and plant phenotyping should apply large-scale and high-precision measurements of plant growth, architecture, and composition to optimize plant breeding.
  - Integrated pest management should provide smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts. They should include insect traps.
  - Livestock welfare and health should require smart sensor systems to monitor animal activity to provide useful information for the early detection of diseases and to increase animal wellbeing. They should be also needed for rapid verification of bacterial infection and behavioural observations to control disease spread.
  - Intelligent logistic systems for food chains should require sensing and monitoring of food quality during transport and storage. They should be efficient and interoperable among the logistics chain.
  - End-to-end food traceability should integrate blockchain into current technology to prevent fraud and counterfeiting and provide direct access to end-consumers.
- Environmental protection and sustainable production:
  - In-situ, real-time monitoring of soil nutrients and herbicides should be carried out through intelligent and miniaturized sensors with appropriate packaging. Furthermore, this type of systems should detect weeds, preserve the "good ones" and eradicate the ones that are competing with the crop in question.
  - Air quality monitoring (indoor, urban, and rural) should require the development and

    deployment of real-time intelligent multi-sensor technologies with high selectivity and embedded (re-)calibration techniques. Focus should be put in the GHG emission from animals by performing the analysis of the gathered data to support decision making for mitigation of main issues.
  - Smart waste management should provide smart monitoring, controlling waste treatment units in real time as well as gas emissions in landfills and anaerobic digestion monitoring. Data analytics including gamification for behavioural triggers.
- Water resource management:
  - Smart healthy water systems should provide secure drinking water distribution by detecting –in real-time– compounds and contaminants through data analysis capabilities to take the adequate measures to mitigate these issues to secure water quality and its distribution over the network. This requires online information on the status of water sources at larger scales than before. For this, healthy water systems should require connected high-integrated multi-parameter diagnostic sensors for real-time chemical analysis to ensure freshwater.
  - Efficient and intelligent water distribution should require novel smart metering solutions based on various technologies, including electrochemical multi-parameter sensors with high stability, anti-fouling, high accuracy capabilities, and be cost effective. Furthermore, optical sensors based on different principles integrated into miniaturized systems, at a low cost, are also required.
- Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation:
  - Biodiversity restoration for Forestry Ecosystem should provide precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests as well as early detection and prevention of threats to the forests (wildfires, pests, diseases, etc.). Furthermore, smart systems are required for environment monitoring of forests and fields, as well as CO_2 footprint monitoring. Remotely monitor wildlife behaviour and habitat changes, and provide timely warning upon illegal poaching activity, are also needed.

4.4.6 Digital society

Ubiquitous connectivity (“everywhere and always on(line)”) drive people to rely on intelligent applications and the services they use and offer. Public and private infrastructures will increasingly be connected, monitored, and controlled via digital infrastructures (“always measuring”) and devices.

Furthermore, the trend of combining of working at the office and from home (or other remote locations), which has been triggered by the Covid-19 pandemic, will continue, and people will 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 as well as in cities. These networks will be open and secure and will support intelligent control management of critical infrastructures, such as water supply, street lighting and traffic. Edge/cloud solutions will arise which will enable increased multimodal situational awareness and ubiquitous localization.

Social inclusion and collective safety and privacy will be enhanced by improved access to public services and communities (as healthcare, education, friends, family, and colleagues), supported by technological innovations in several directions, such as tele-presence, serious gaming, chatbots, virtual reality, robots, and personal and social assistants.

More and more, these solutions will be human-centered, will have cognitive abilities, apply nudging techniques, and support personal development, health, and well-being.

4.5

CONCLUSIONS

The European ECS community, from academia to industry, is a world leader in research, development, and innovation for the past decades. The competition of US and Asian communities is strong and requires significant European effort and investment, so that Europe remains a leader in the coming years, considering the dramatic increase in need for ECS systems due to the emergence of IoT and the corresponding embedded and cyber-physical systems.

In this Chapter, we have presented research and innovation directions for ECS in the long-term, considering the European priorities, such as the Green Deal, and the main objectives of the European ECS community. Considering the interdependence of emerging technologies, application domains and policies that drive innovation, and considering the corresponding trends of European industry in the next few years, we identified long-term challenges for technologies and applications, to provide direction for the community to meet the expected needs of the future. Clearly, the list of challenges and directions that we provide is neither complete nor restricting. Innovation is a continuous process that adapts to new technological capabilities – as they progress–, application needs and, even, new application domains that are not foreseen. However, the current review indicates a clear path to establishing European leadership considering current trends and constraints.