E C S

Strategic Research and Innovation Agenda 2021

ELECTRONIC
COMPONENTS AND SYSTEMS

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ELECTRONIC COMPONENTS AND SYSTEMS

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Strategic Research and Innovation Agenda 2021

INTRODUCTION AND OVERVIEW

GOALS AND PURPOSES OF ECS-SRIA 2021

This is the fourth edition of the ECS Strategic Research and Innovation Agenda (ECS-SRIA), jointly developed by members of three industry associations: AENEAS, ARTEMIS-IA and EPOSS. This year a major revision of the ECS-SRIA was conducted with the goal of improving alignment in the community to help collaboration along the European value chains and value networks. This ECS is as wide-ranging as that of the three communities on micro- and nanoelectronics, smart systems integration, and embedded System of Systems.

Why this ECS-SRIA?

This document describes the major challenges, and the necessary R&D&I efforts to tackle them, in micro- and nanoelectronics for smart systems integration all the way up to embedded systems and System of Systems. Aspects of photonics, flexible and hybrid electronics integration are now also covered by this document to open up new opportunities in Europe. This SRIA is intended to be funding programme agnostic, and can be used as a basis for the various cooperative programmes across Europe.

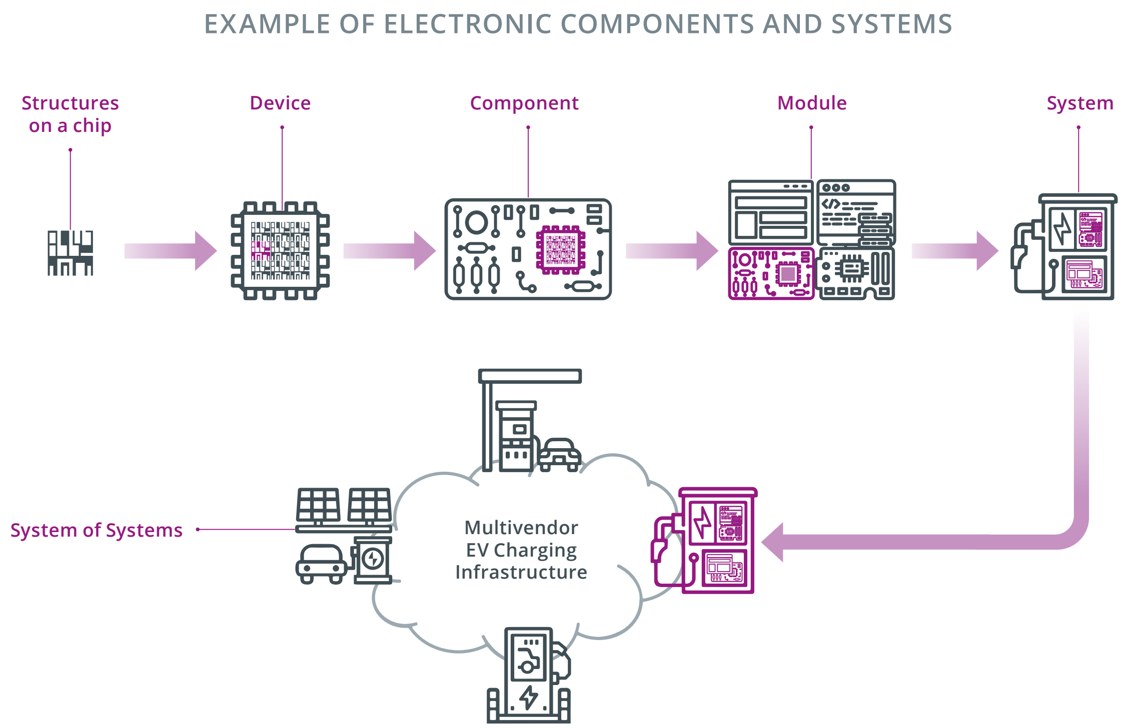
However, the scope of our work, and of this document, is firmly within the ECS domain. For details on developments in the specific application areas further up the value chain, please consult the SRIAs of other associations or public/private partnerships (PPPs) addressing those specific areas.

The range of this ECS-SRIA is very wide, going from transistors within silicon chips acting as individual electrical switches for integration in smart systems up to global System of Systems performing complex cognitive tasks and interacting with numerous humans and machines over a wide geographical spread. A very simplified view of this ECS "stack" is shown in *Figure F.1*.

Designing such artefacts requires a hierarchical approach, whereby various ECS specialists are working at different abstraction levels. As a result, the same term can have different meanings for specialists of different ECS domains: for instance, a "system" designed and implemented within a given development process may be integrated as a "component" into a higher-level "system" within another development process. Nevertheless, to avoid confusion, this year the ECS-SRIA includes a glossary, to be found in Annex *page 421 ff.*, where many of the key terms are defined to avoid inconsistency across the various chapters. It was also felt that developing a common language was important in building a strong and integrated ECS community. In addition, some of the bricks of the ECS "stack" are further detailed below.

- **Device:** In the context of the SRIA, and if it is not further qualified, a device will be defined as a "packaged chip", whether it is a packaged integrated circuit (e.g. system on a chip, memory, processor, microcontroller) or a micro-electromechanical system (MEMS)/micro-opto-electro-mechanical system (MOEMS). A device performs a general electrical, electronic or electrical/electronic/physical transduction role.

- **Component:** A combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case. A component is not self-contained in all its functions, as it requires the close support of



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

other components for operation (e.g. in data processing, power handling, embedded software).

- **Module:** A combination of correctly integrated components in which their assembly embodies a specific functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and software, making it interchangeable between systems, and allowing a higher abstraction level in systems design.

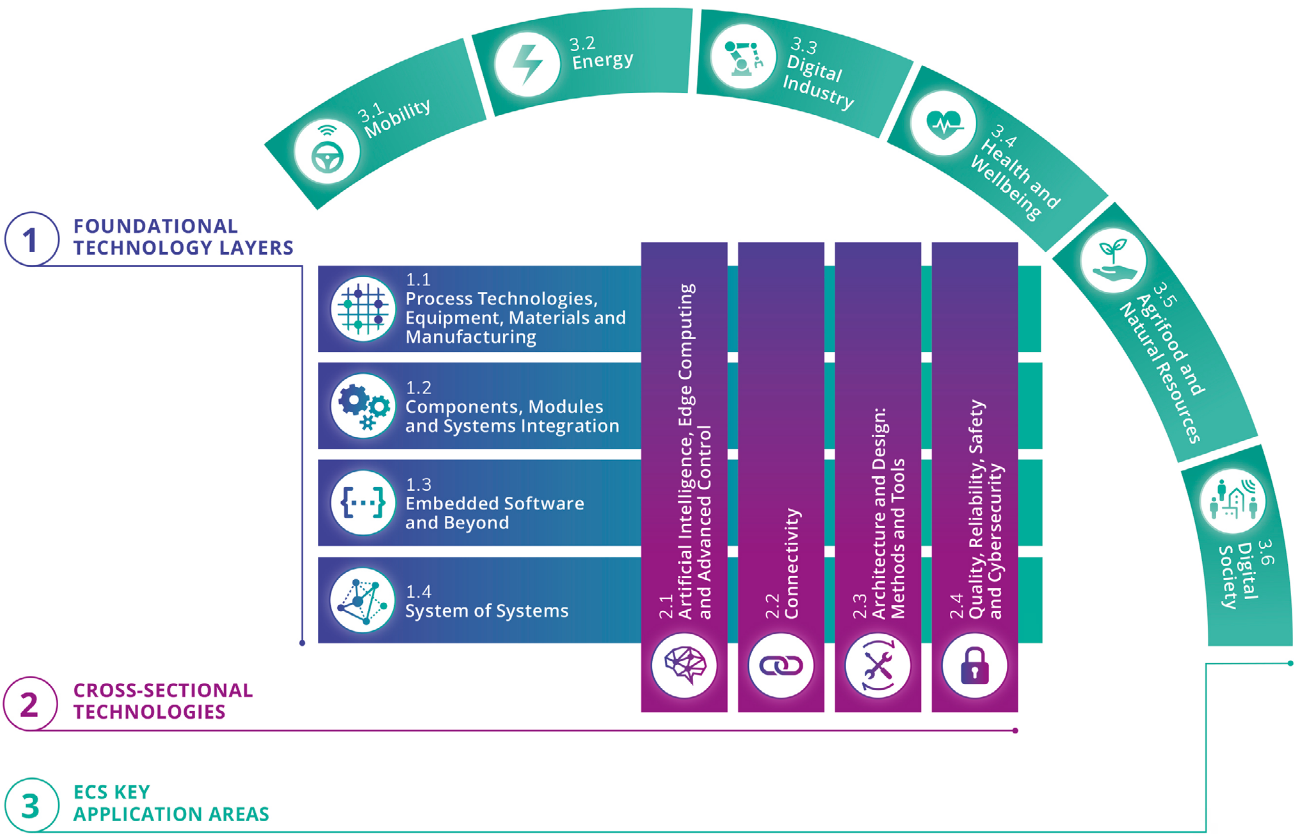
- **System:** For the purpose of this SRIA, a system is a set of electronic-based constituents (subsystems, modules and components, realised in hardware, software, or both) that are integrated in a way that allows the system to perform a desired (set of) function(s). Due to ECS typically being constructed hierarchically, a "module" (e.g. camera or other sensor) being part of the electronic "system" in an autonomous car might itself be referred to as a "system" when being designed (e.g. while integrating lower-level components together to achieve the "camera" function).

1 *Structure on a chip: Elementary building blocks of an integrated circuit, such as a FDSOI or FinFET transistor, or more complex structures such as an embedded memory block.*

- **System of Systems (SoS):** A collection of independent and distributed embedded and cyber-physical systems dynamically composed to generate a new and more complex system, provided with new functionalities and driven by new goals not present in the constituent embedded and cyber-physical systems individually. The difference between a "system" (comprising subsystems, modules and components) and a "System of Systems" (also comprising subsystems) is that the constituents of a system are chosen and integrated during design-time (i.e. completely under the control of the engineers), while in a System of Systems the constituent (sub)systems are physically independent and dynamically form a System of Systems at run-time.

The new structure

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



The new structure of the ECS-SRIA F.2

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

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

Six **Application** sections describe the challenges arising from specific ECS application domains that are key for Europe, and identify the R&D&I efforts required by these application domains as regards ECS. For the first time, we also include a whole section on **Agrifood and Natural Resources**.

Finally, the **Long-Term** chapter illustrates our vision of the ECS beyond the time horizon covered by the other chapters. It seeks to identify the research subjects that must be addressed at low TRL levels as foundation and preparation for the crucial developments in European industry over the next decade. Based on the trends and plans described in the preceding chapters, the long-term industrial requirements are also examined to help research programmes understand which hardware, software and system solutions should be produced most effectively for the continuous improvement of European digital technology.

HOW TO READ IT

As mentioned, the ECS covered by this document is very wide-ranging, and involves many technical disciplines in materials, hardware and software. This means not many will understand all its technical details presented, and most readers will only want to read those sections that cover the disciplines they are working in.

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

A **Glossary** describing the terms used in the document, as well as a List of **Acronyms** used in the document, can be found in the **Appendix**. At the end, you can also find a **List of Contributors** who collectively wrote this ECS-SRIA.

HIGHLIGHTS AND COMMON CHALLENGES FOR THE NEXT FEW YEARS

In this ECS-SRIA for the first time, the Major challenges identified by the different chapter teams were analysed and merged into four Main common objectives for the ECS community. In addition, and also for the first time, three common Roadmaps covering the short term (up to 2025), medium term (until 2030) and the long term (2031 and beyond) provide the key milestones derived by the chapter teams.

Main common objectives

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

Across this document, 65 different Major challenges are identified that that have emerged from the analysis of the foundational technologies, the cross-sectional technologies and the application key areas. The challenges are frequently interdependent – they influence each other, become increasingly demanding, and impact on many areas, including technology innovation, industrial competitiveness, security, safety, business and environmental sustainability, society, etc. From this perspective, the Major challenges represent key factors for the achievement of the four Main common objectives, which are aligned with the European Commission's strategic priorities (see table in *Appendix, page 460 ff)*.

Main common objective 1: Boost industrial competitiveness through interdisciplinary technology innovations

Electronic components and systems, by their inherent nature, are the result of interdisciplinary research and engineering. These require competencies in diverse technology domains, including process technologies, equipment, materials and manufacturing, electronics and telecommunications, as well as cross-sectional technologies such as Artificial Intelligence, high-speed connectivity and cybersecurity.

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

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

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

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

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

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

They will ease the implementation of the European Strategy for Data[2], and ensure security, privacy-by-design and sovereignty all along the industrial and digital value chains. Such technological innovation will also enable the design and development of secure, safe, reliable, dependable, privacy-compliant electronic components and systems, as well as generate new requirements that will drive the development of new technologies, restarting the cycle.

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

- aerospace, defence, security.
- automotive, vehicles.
- machinery, robotics, electrical equipment, energy.
- communications and computing, health and care.

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

←

[2] *https://ec.europa.eu/digital-single-market/en/policies/building-european-data-economy*

** Rethinking Strategic Autonomy in the Digital Age (EPSC – July 2019)*

Main common objective 3: Establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal

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

To reach the main goal of being climate-neutral by 2050, Europe needs to step up its transition. This challenge must be perceived as an opportunity to create a new environment for boosting innovative aspects of industry in terms of business models through achieving the following.

- Relying extensively on ECS-based technologies and digitalisation as key factors for lowering our global energy footprint at all the levels of the economy, and by placing sustainability at the heart of combined digital and green transitions.
- Positioning the European players in hardware as front-runners in sustainability to secure a wider market so they can become world leaders. This will need to take into account the circular economy, new market positioning (by turning small market shares into specialisation areas), the environmental impact of global manufacturing, etc.
- Establishing this carbon-neutrality challenge based on a close link between the digital and green transitions at the core of future funded collaborative research and innovation in ECS. This will help ensure a positive impact for each stage of the value chain, and to achieve carbon neutrality right down to the final application/digital service.

Main common objective 4: Unleash the full potential of intelligent and autonomous ECS-based systems for the European digital era

ECS must be provided with a certain level of intelligence and autonomy to control their complexity more efficiently and more cost-effectively. This will help provide novel advanced functionalities and services, limit human presence to only where it is strictly required, improve the efficiency of vertical applications, etc. Intelligence and autonomy are also required through the role of ECS in the application domains, representing an important factor for the sustainability and resilience of the value chains.

An ECS-based system that provides intelligent energy management, relying on technologies such as AI, represents a key building block – for example, for smart home and energy applications. However, it also improves the resilience required to ensure optimal energy consumption in critical conditions and contributes to the sustainability of the value chain associated with vertical applications since it reduces operational costs, environmental impact, improves the quality of service (QoS), return on investment (ROI), etc, thereby strengthening the global competitiveness of European companies and helping to achieve the objectives of the EU's Green Deal.

The ECS-SRIA 2021 lists a number of milestones to be reached in the short term (2021–2025), medium term (2026–2030) and long term (2031 and beyond) via collaborative research projects across Europe, reflecting the ambition of the ECS industry towards the achievement of the four objectives identified above. The diagram (*pages 21–23*) positions some of the most salient of these milestones onto the European ECS roadmap.

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

As discussed, modern digitalisation systems are complex, and heterogeneous solutions are increasingly based on ECS. Therefore, they cannot be considered as real products without the appropriate engineering support across the entire lifecycle, from requirements analysis to design, development, deployment/

commissioning, operation/management, remote-maintenance repair and overhaul, retirement/recycling and evolution.

Engineering support represents a key factor for achieving the four main objectives as it:

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

The ECS global timeline for Europe

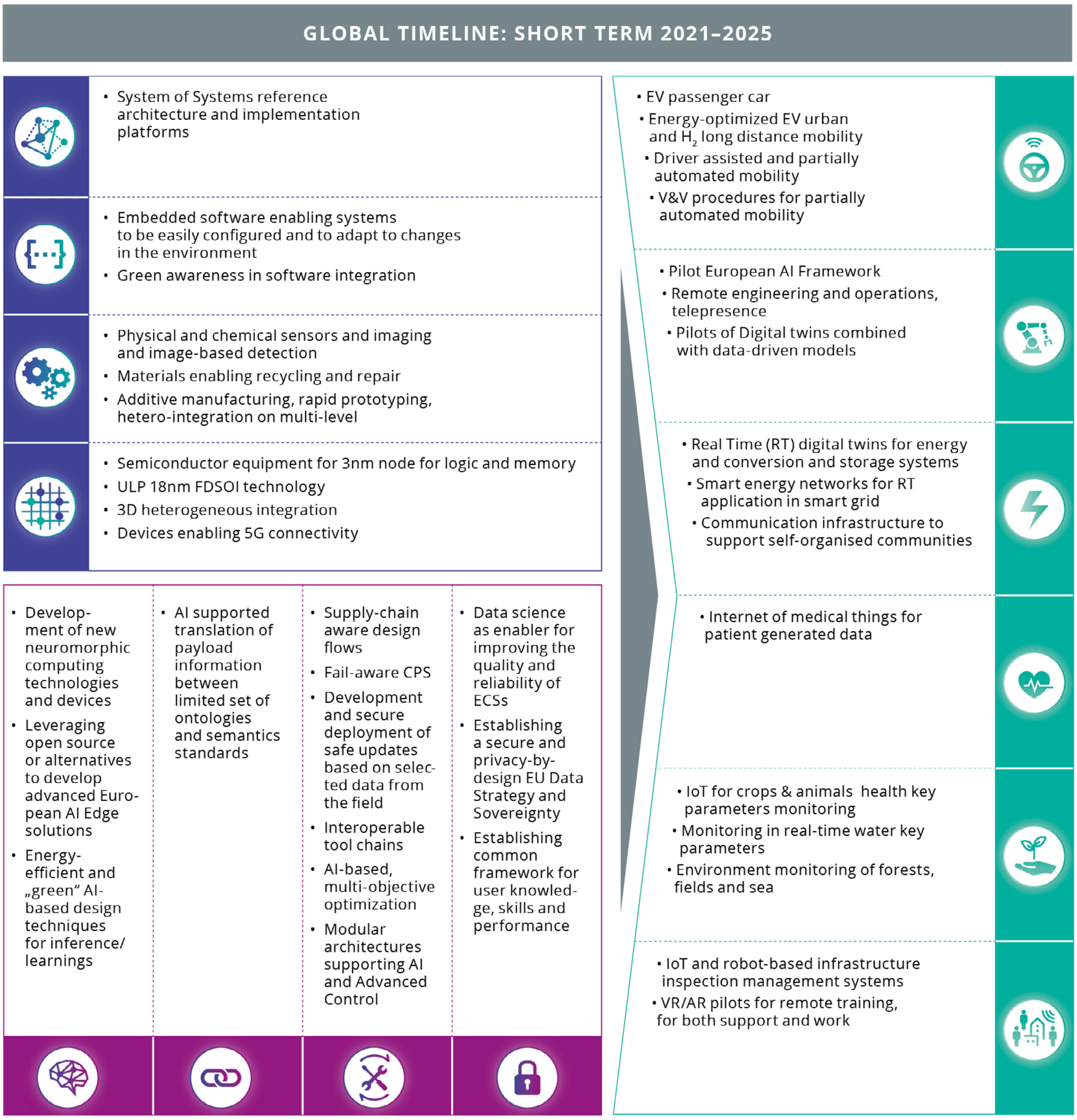
The following figures summarise the main milestones to be reached in the various domains covered by the ECS-SRIA over the three time periods.

- **Short term (2021–2025):**
  The industry has a precise idea of what will be achieved during that timeframe.
- **Medium term (2026–2030):**
  There is still reasonably good knowledge of what can possibly be achieved.
- **Long term (2031 and beyond):**
  Expected achievements are more of a prospective nature.

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

The above example also clearly shows that progress in the various domains covered by the ECS-SRIA are deeply interconnected. Innovation in one area is building upon, or being driven by, innovation in other areas. Similar examples could, of course, be developed for the other time horizons, as represented in the *Figures F.3/F.4/F.5*.

More detailed diagrams, including additional milestones, are presented in the individual sections. Summarised achievements, grouped according their contributions to the Main common objectives, can be found in the Executive Summary to this SRIA, showing the clear contribution of the various ECS research and innovation domains to the overall societal and economical goals of Europe.



Global Timeline: Short term 2021–2025

F.3

GLOBAL TIMELINE: MEDIUM TERM 2026–2030

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

- Compilers and link to new hardware
- Interface management to prepare for System-of-systems integration
- Embedded software enabling systems to dynamically (re)-configure after updates or changes in the environment
- Maturity model for robustness of embedded software

- Energy management towards low/zero power
- Heterogeneous integration for harsh environments
- Organic, compostable and biodegradable materials

- In-memory computing
- PCRAM
- 6G connectivity RF & photonics devices
- Smart GaN power devices
- Equipment for 1 nm node nanowire, nanosheet-based logic and memory

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

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

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

- Certification strategy under uncertain & dynamically changing environment
- New self-learning methods to ensure safe operations of complex systems
- SW & HW reliability metrics
- Digital twin as enabler to monitor ECS

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

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

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

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

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

- Improved human–machine interfaces
- Time-critical functions moved to cloud
- Multimodal and multi-sensory interfaces in serious gaming (beyond single games)

F.4 *Global Timeline: Medium term 2026–2030*

GLOBAL TIMELINE: LONG TERM 2031 AND BEYOND

- Policy based autonomous System-of-systems engineering and evolution

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

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

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

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

- Autonomous interoperability: from physical layer to instant information understanding

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

- EU ecosystems for dependable SW
- Digital literacy curricula to achieve high levels of AI knowledge and competences
- AI/ML enable to shorten development cycle and deploy PHM for the ECS's

- Fully automated mobility
- True multimodal mobility
- Approach to CO_2-neutral (from cradle to grave) mobility

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

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

- Organ-on-a-chip developments addressing rare diseases

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

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

Global Timeline: Long term 2031 and beyond

F.5

ECS-SRIA AND ITS POSITION IN THE TECHNOLOGY LANDSCAPE

Electronics components and systems are key digital technologies enabling the development of numerous applications. As such, the ECS research and innovation priorities are significantly driven by application roadmaps and needs. To that effect, the **ECS Key Application Areas chapter** translates application roadmaps into requirements for ECS. Conversely, the **Foundational Technology Layers** chapter maps out future advances and potential new breakthroughs in applications. The ECS-SRIA therefore promotes synergies with many neighbouring application-oriented communities. For example, the **Mobility** section (*Section 3.1*) has strong links with ERTRAC; the **Digital Industry** section (*Section 3.3*) with EFFRA; and the **Agrifood and Natural Resources** section (*Section 3.5*) with the working group of the Alliance for the Internet of Things Innovation (AIOTI) in Smart Farming and Food Security, and with Water Europe[3]. In each case, experts participated in the work of both groups. There are also close interactions and alignments with European PPP initiatives such as 2Zero and CCAM, IHI, etc.

The **Cross-Sectional Technologies chapter** also leverages the links of the ECS community with other technology-oriented domains, such as the European Technology Platform for High Performance Computing (ETP4HPC) and Big Data Value Association (BDVA), with strong relations with the **Artificial Intelligence, Edge Computing and Advance Control** section (*Section 2.1*) and **Connectivity** (*Section 2.2*) and with the 5G Infrastructure Association or euRobotics and European Cyber Security Organisation (ECSO) (*Section 2.4*).

Several contributors of the **Technology** chapters are also actively involved in the elaboration of international roadmaps (e.g. the Heterogeneous Integration Roadmap (HIR)[4] in electronic packaging and integration, and the IEEE International Roadmap for Devices and Systems (IRDS)[5] for the semiconductor industry.

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

↑

3 *https://watereurope.eu/wp-content/uploads/2019/07/Water-Europe-SIRA.pdf*

4 *https://eps.ieee.org/technology/heterogeneous-integration-roadmap/2019-edition.html*

5 *https://irds.ieee.org/*

1.1
PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING

1.2
COMPONENTS, MODULES AND SYSTEMS INTEGRATION

1.3
EMBEDDED SOFTWARE AND BEYOND

1.4
SYSTEM OF SYSTEMS

1

Strategic Research and Innovation Agenda 2021

FOUNDATIONAL TECHNOLOGY LAYERS

1.1

Foundational Technology Layers

PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING

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

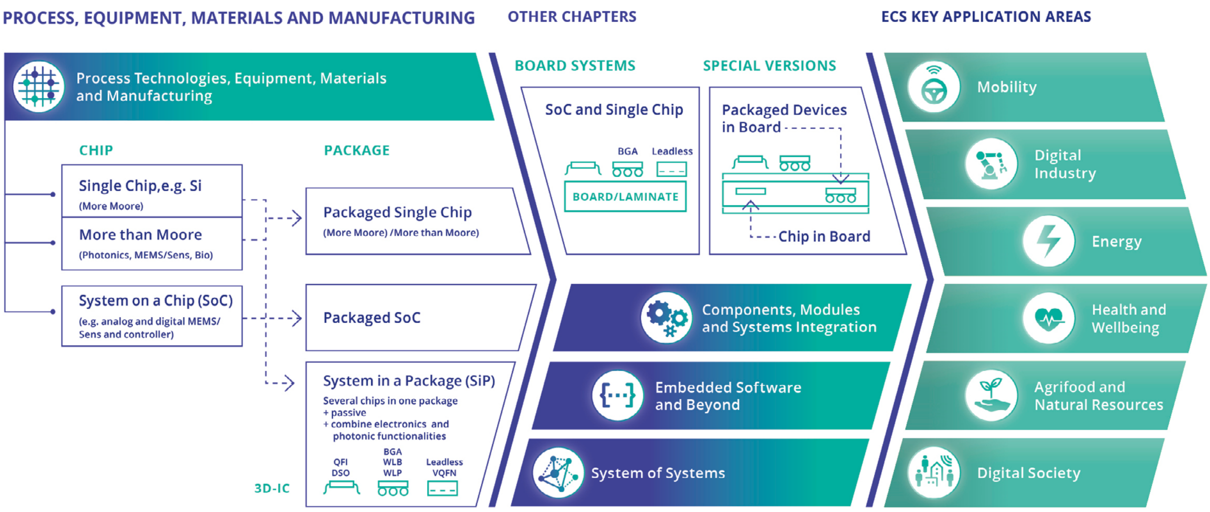
Nano- and microelectronics are key to achieving digital sovereignty in Europe, and offer a range of solutions for a green and sustainable society. If Europe wants to control the development of a digital future fitted to its citizens and their requirements, as well as its social, economic, industrial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

1.1.1 SCOPE

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

- process technologies, equipment and manufacturing technology to advance integrated circuit (IC) functionality and/or systems on chips.
- packaging and integration technologies for chips, chiplets, system on a chip and system in a package (SiP).
- solutions to challenges imposed by other chapters in this SRIA, which include challenges from other technology building blocks, cross-sectional technologies as well as key application areas throughout the value chain.

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



The chip and packaged chip-level building blocks are the starting point for the other ECS-SRIA sections F.6

1.1.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

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

European industry in sectors such as healthcare, automotive, energy, smart cities and manufacturing strongly depends on the timely availability of highly specialised electronics devices enabling added value and new functionalities in their products. Moreover, the advances in chips and packaged chips will strongly contribute to Europe's ambition to become climate-neutral by 2050, as promoted by the European Green Deal [6].

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

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

- device scaling by moving into 3D for sub-3 nm node memory and computing technologies will also drive down energy consumption following the power, performance, area and cost (PPAC) scaling roadmaps.
- new embedded non-volatile memory technologies enable local processing and storage of configuration data, decreasing data transmission and energy needs for a wide range of automotive and IoT applications.
- new power electronics devices, either based on silicon or new (gallium nitride, GaN, silicon carbide, SiC) materials, will increase the energy efficiency of electric powertrains, energy storage, lighting systems, etc.
- improved radio frequency (RF) device technologies based on new materials such as GaN, new switches (complementary metal–oxide–semiconductor (CMOS), silicon-on-insulator (SOI)-based RFCMOS, fully depleted SOI (FDSOI), bipolar CMOS (BiCMOS), etc), and passives enable increased output power and efficiency towards higher frequencies, as well as improved control of the emission and reception channels with more energy efficiency due to finer RF band control and better directionality.
- new hybrid and heterogeneous combinations between photonic ICs and electronics enable microwave photonic modules – for example, for wideband millimeter-wave processing, and high-bandwidth off-chip and on-chip communications RF filtering.
- new sensor technologies and devices enable better control of processes (e.g. industrial processes, lighting), which contributes to energy saving.

Application breakthroughs

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

In 2020, the globally consumed power of data centres alone is expected to be 200 TWh[7] , which represents 1% of the all power consumed around the world. If the average annual increase in the digital consumed power remains constant in the near future, worldwide total energy production will not be sufficient to even support the digital domain by 2040[8].

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

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

The adoption of wide bandgap materials such as GaN and SiC is crucial for allowing higher operating temperatures and reducing the switching losses in power electronics for electric vehicles, as well as to increase their range. GaN/SiC is also important for increasing the power efficiency of 5G RF base stations. In addition, GaN/Si and GaN/SOI can induce the same effect in RF front-end modules when combined with high thermally conductive materials (finite element method, FEM).

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

The exponential increase in internet traffic (which is doubling every three years) sets demanding requirements on data communication technologies. Optical interconnects enable higher bandwidth-distance products, higher bandwidth density, lower electromagnetic

←

6 *https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en*

→

7 *https://www.iea.org/articles/energy-efficiency-and-digitalisation*

8 *Anders et.al. On Global Electricity Usage of Communication Technology: Trends to 2030, Challenges 2015, 6(1), 117–157; https://doi.org/10.3390/challe6010117*

interference, and potentially lower power consumption than electrical interconnects. They are being deployed at increasingly shorter distances – for example, within and between data centres. In the longer term, chip-to-chip and even intra-chip communication may be performed with CMOS-compatible photonics. Beyond these applications, emerging precision applications – including atomic clocks, precision metrology, and transformative applications such as quantum communications and information processing – will also benefit from photonic capabilities integrated with electronics, such as silicon and heterogeneous III/V (membrane) photonics, and potentially disruptive technologies such as nanophotonics and graphene photonics.

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

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

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

Rethinking human activities to take advantage of the innovation opportunities offered by hyper-connectivity and AI solution and new kinds of sensors based on miniaturised technologie will create numerous benefits for every new market, ranging from connected cars and digital health to smart home and smart living, and factories of the future.

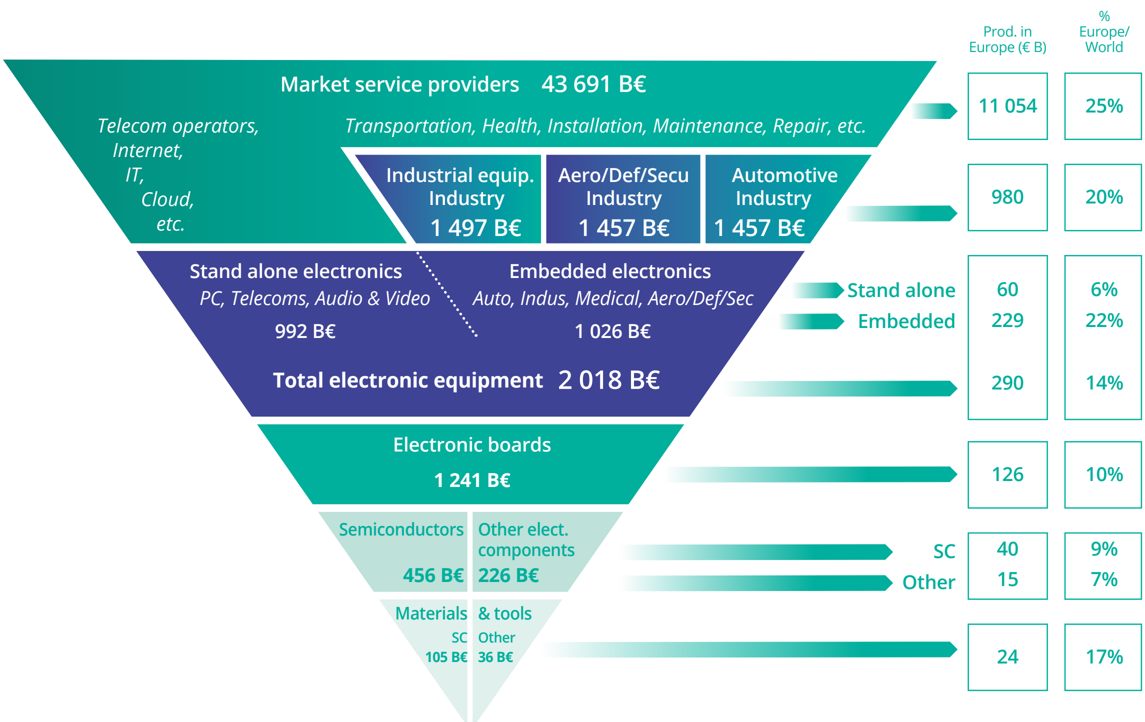
Sensors and biosensors will be an extensively studied discipline since their rapid, low-cost and highly sensitive features contribute to tremendous advances in many domains. Visible light and IR imagers, lidar, radar and ultrasonic sensors, in combination with high-precision inertial sensors, will be essential for the deployment of advanced driver assistance systems (ADAS). Advancements in chemical-sensing technologies also open the door for multiple new markets. Gas sensors are increasingly integrated into IoT ecosystems to monitor air quality indoors and outdoors – for instance, wearable devices, smart city projects, sensor networks for pollution mapping, smart home electronics and automotive technology. Another key trend to utilise advanced gas-sensing technology is breath analysis, which aims at non-invasive diagnostics via detecting biomarkers from exhaled breath. Breathalysers will assist medical practitioners in monitoring patients with chronical illness (e.g. diabetes, paedophilic obsessive-compulsive disorder (POCD)) and the screening of potential upcoming diseases (e.g. infections, cancer).

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

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

1.1.3
STRATEGIC ADVANTAGE FOR THE EU

Independent access to semiconductor technology for the manufacture of function-critical electronics components and systems (ECS), and their development and manufacturing in Europe, are indispensable for meeting the challenges of European society, realising the European Green Deal, increasing sovereignty, and for ensuring Europe remains competitive against foreign markets.



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

F.7

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

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

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

Future and emerging technologies (FET) flagship initiatives, such as those on graphene, have been shown to have significant impact on European leadership in this technology area, raising the bar for the more recent flagship initiative on quantum computing. To ensure European leadership in this highly challenging discipline, early involvement of equipment suppliers will bring these activities to the next level in parallel with identifying the best application areas. Importantly, the functionality of a number of current ECS technologies needs to be updated to respond to the challenges that new materials and QIP are raising. Advanced materials and computational paradigms require not only the development of new scalable platforms, but also non-trivial adaptations and extensions of existing technologies as enablers of such functionalities. For example, any solid state-based quantum computer will need efficient "classical" low-power cryogenic electronics to enable operation of its computing circuit.

The creation of manufacturing pilot lines is key, as already demonstrated by successful European projects to date. Pilot lines are a launching ground for new processes, equipment technologies and materials, allowing for early validation of new concepts in support of industrial introduction, and fostering collaboration between industry, research institutes and academia. In addition, they constitute valuable technology platforms for a wide range of applications. Pilot lines are important drivers to advance an understanding of application needs, cut products' time to market, and showcase European capabilities to potential customers worldwide. Pilot lines provide excellent opportunities for advanced education and training to skilled engineers and scientists. Early availability of innovative semiconductor, sensor and packaging technologies will pave the way to cyber-physical production systems. Having a strong semiconductor portfolio "made in Europe", with early access for lead system suppliers, is a winning competitive asset for Europe. Such semiconductor manufacturing requires access to advanced materials and characterisation equipment, and competitive manufacturing techniques at the current base of the European value chain. In future, the complete value chain must be covered to promote the competitive situation of the European semiconductor process and integration technology, and to ensure European independence in this field.

Regions around the globe have recognised the strategic importance of a local base for key enabling technologies, including electronic components and systems, to reduce the potential disruptive impact of disasters such as pandemics and climate-related effects. Foreign and domestic investments leveraged by government subsidies have enabled many of these regions to take on a leadership role in several areas of semiconductor manufacturing. Despite competition from East Asia and the US, Europe can reinforce its lead in semiconductor processing and packaging, equipment and smart systems based on the priorities set out in this ECS-SRIA. The Important Project of Common European Interest (IPCEI) on microelectronics, for example, was a first successful step towards strengthening European semiconductor manufacturing in strategic areas where large-scale subsidies in other regions have started to threaten the position of European players. There are now also strong arguments for bringing back leading-edge semiconductor manufacturing to Europe – to maintain sovereignty, and to be involved in AI and other key technologies of the digital world.

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

1.1.4 MAJOR CHALLENGES

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

- Materials, process modules and integration technology for novel devices and circuits for advanced computing, memory and in-memory computing concepts based on nano-electronic, photonic or quantum technology.
- Materials, process modules and integration technology for novel devices and circuits that enable advanced functionality (sensing, actuating, power, connectivity, biomedical, etc), including (wafer or flexible) substrate technologies.
- Advanced heterogeneous integration and packaging solutions for system on a chip (SoC), 2.5 and 3D stacking (including chiplet technology), and smart SiP, sensor integration, photonics, power electronics, and other functionalities required for application domains (such as augmented reality/virtual reality (AR/VR), automotive, (bio)chemical, biomedical, aerospace, etc)
- World-leading and sustainable semiconductor manufacturing equipment and technologies for the realisation of sub-3 nm node logic and memory according to PPAC roadmap requirements, chips/chiplets with single and/or multi-node layers, advanced functionality devices and heterogeneous integration technology options, as described under **Major challenges 1–3**.

1.1.4.1 Major challenge 1: Advanced computing, memory and in-memory computing concepts

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

1.1.4.1.1 State of the art

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

3D FinFET transistors provide high current drive, and hence higher speed, low leakage and, most importantly, less wafer area per transistor than 2D metal–oxide–semiconductor field effect transistor (MOSFET) technology. FinFETs are designed and processed to deliver better performance for applications in high-growth markets such as hyperscale data centres, autonomous vehicles and power-efficient SoCs for the most demanding computer applications. Extreme ultraviolet (EUV) lithography has also made its way into high-volume manufacturing. The international industry value chain is pushing production beyond the 5 nm node, and requires solutions in materials and process integration challenges to realise the novel device architectures currently on the roadmap.

FDSOI is a 2D technology based on a thin buried oxide (BOX) layer under the CMOS channel. FDSOI exhibits several advantages, such as reducing the leakage current at standby mode and its higher tolerance against soft errors compared to traditional structures. FDSOI is perfectly suited for ultra-low-power IoT automotive, edge AI and 5G devices. The leading companies produce 18 nm and 22nm FDSOI-based chips.

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

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

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

The large dimensions of TSVs, and difficulties in establishing vertical interconnects between layers, greatly limit the density of TSV 3D devices. Monolithic 3D integration using sequential manufacturing can be used to fabricate 3D devices with ultra-high density vertical cross-layer connections. Such monolithic integration is not currently available in foundries. In-memory computing also uses the intrinsic properties and operational principles of the memory cells and cell arrays, by inducing interactions between cells such that the cells and/or cell arrays can perform computations themselves.

Due to the increasing need for large memory systems by modern applications (big data analytics, AI, etc), dynamic random access memory (DRAM) and Flash memory scaling is being pushed to its practical limits. It is becoming more difficult to increase the density, reduce the latency and decrease the energy consumption of conventional DRAM and Flash memory architectures. New approaches are therefore being developed to overcome these barriers for implementing near- or in-memory computing.

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

The second major innovation is the use of emerging non-volatile memory (NVM) for the main memory subsystem. To avoid DRAM scaling limitations, new memory devices and technologies that can store data at much higher densities than the typical density available in existing DRAM manufacturing process technologies are currently being investigated. The main emerging NVM technologies to augment or replace DRAM at the main memory layer are: (i) phase-change memory (PCM); (ii) magnetic RAM or spin-transfer or spin-orbit torque, or voltage-controlled magnetic anisotropy magnetic RAM (MRAM, STT-MRAM, SOT-MRAM, VCMA-MRAM); (iii) metal-oxide resistive RAM (RRAM or ReRAM) and conductive-bridge RAM (CBRAM) or memristors; and (iv) ferroelectric FET (FeFET). All these NVM types are expected to provide memory access latencies and energy usage that are competitive with, or close enough to, DRAM while enabling much larger capacities per chip and non-volatility in main memory.

1.1.4.1.2 Vision and expected outcome

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

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

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

Expected achievements

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

1.1.4.1.3 Key focus areas

This challenge includes the following key focus areas.

- Explorations of the scaled Si technology roadmaps of the 3 nm node and beyond (including FDSOI, FinFET/Trigate and stacked gate-all-around horizontal or vertical nanowires, Forksheet, complementary FET architectures, 3D integration), and further device and pitch scaling where parallel conduction paths (nanowires, nanosheets, etc) are brought even closer together.
- Exploration and implementation of materials beyond Si (SiGe, SiC, GaN, Ge, InGaAs, functional oxides, 2D material heterostructures, nanowires).
- Novel device, circuit and systems concepts for optimum PPAC specifications, high-energy efficiency and novel paradigms such as for near/in-memory, neuromorphic, optical and quantum computing.
- Long-term challenges such as steep slope switches (tunnel FET, negative capacitance FET, nanoelectromechanical systems, NEMS), spin-based transistors, and alternative high-performance switches.
- Unconventional devices and materials, such as 2D and III-V materials, metamaterials, metasurfaces, nanowires, nanosheets, nanoparticles, quantum dots, spin effects, functional oxides, ferroelectric and magnetic, which are being investigated to overcome the limits of conventional CMOS logic and memories.
- New embedded non-volatile memory (eNVM) technologies to enable local AI processing and storage of configuration data, which decrease data transmission volume, energy needs and allow for more efficient control of electric powertrains and batteries.

1.1.4.2 Major challenge 2: Novel devices and circuits that enable advanced functionality

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

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

1.1.4.2.1 State of the art

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

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

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

In power technologies, recent years have seen the emergence of wide bandgap materials able to reduce the losses of power conversion, namely SiC and GaN. These technologies are making quick inroads into the domain of electric and hybrid vehicles. However, they are still nascent, and the challenge is to develop low-cost (involving larger diameter, good quality and less-expensive substrates) and robust technologies. Today, SiC is produced mainly on 150 mm substrates, while GaN has begun to be produced on silicon substrates, but the technology and epitaxy techniques will need further refinement (and even breakthroughs). Moreover, a transition from sub-200 mm to 300 mm substrates is essential for future integrated logic and power management functions using technologies to combine logic and power transistors. Beside research on wide bandgap materials, the Si-based insulated-gate bipolar transistor (IGBT) technologies have further innovation potential in the area of cost-sensitive applications. Challenges are in the domain of high power and high voltage electronics with high junction temperatures processed on 300 mm substrates – leading to increased power densities and lower costs to support the transformation in the energy systems with Si-based power semiconductors.

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

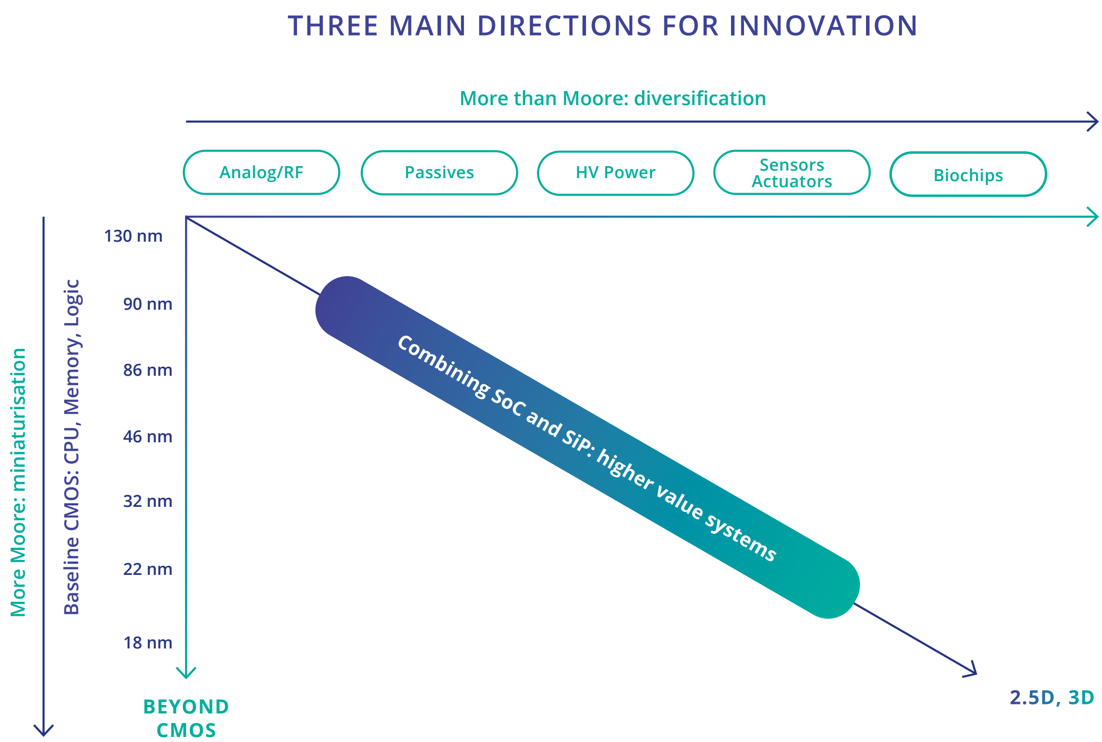
In “traditional” polyimide (PI)-based flexible electronics, the continuing trend is towards more complex designs and large-area processing, especially in displays and sensor arrays. Since the achievement of high-performing flexible electronics by monolithic approaches is limited, hybrid approaches are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

1.1.4.2.2 Vision and expected outcome

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

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

Innovations for these domains require the exploration and functional integration, preferably in CMOS-compatible processing, of novel materials. A non-exhaustive materials list includes wide bandgap materials, III-V, 2D (e.g. graphene, MoS2 and other transition metal dichalcogenides), 1D (e.g. nanowires, carbon nanotubes) and 0D (e.g. nanoparticles, quantum dots) materials, metal oxides, organic, ferro- and piezoelectric, thermoelectric and magnetic thin films materials, metamaterials and metasurfaces. Obviously, safety and environmental aspects should also be taken into consideration.



F.8 *Diversification of applications, continued miniaturisation and integration on chips and in package leads to higher value systems (Source: ST Microelectronics/ITRS)*

Proper packaging is very important to interface the advanced non-conventional devices to the external world, to satisfy requirements such as thermal management, harsh environment or biological compatibility. Thus, there should be a special focus on chip/package interaction – for example, with respect to stress, electromagnetic compatibility (EMC), and temperature- and application-specific environmental integrity.

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

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

Expected achievements

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

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

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

1.1.4.2.3 Key focus areas

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

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

- Tight logic/memory integration for new architectures for neuromorphic computing. Logic integration with power management devices, including compatibility with harsh environments (high temperatures, vibrations, electromagnetic interference (EMI) conditions for industrial, automotive and space technology).
- Logic integration with RF, optical or sensor technologies.
- Ultra-low power (ULP) technology platform and design.

Advanced sensor technologies:

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

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

- Higher power density and frequency, wide-bandgap materials for high temperature electronics, new CMOS/IGBT processes, integrated logic, uni- and bipolar; high voltage classes, lateral to vertical architectures.
- Materials for energy harvesting (e.g. perovskite solar cells, piezoelectric ceramics and thin films) and storage (e.g. perovskites, ferroelectrics and relaxors), micro-batteries, supercapacitors and wireless power transfer.
- Ambient energy generation, storage, battery back-up, dynamic load configuration.
- Energy-efficient components and systems.
- Energy-autonomous multi-sensor nodes and systems for IoT applications.
- Power devices and modules for highly demanding automotive, industrial and energy infrastructure applications.
- Substrates towards larger diameters to serve future greater demand for cost-sensitive power solutions.

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

- New energy-efficient RF and mm-wave integrated device options, including radar (building on e.g. SiGe/BiCMOS, FD SOI, CMOS, PIC).
- Development of new RF cryogenic electronics for QIP.
- Energy-efficient computing and communication, including a focus on developing new technologies, architectures and protocols.
- Bringing MOEMS and micro-optics, nanophotonics, optical interconnections, photonics-enabled device and system options into a CMOS-compatible manufacturing and/or packaging flow.
- Integration of solid-state light emitters such as LED and laser with, or onto, a CMOS-compatible platform.

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

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

1.1.4.3 Major challenge 3: Advanced heterogeneous integration and packaging solutions

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

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

1.1.4.3.1 State of the art

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

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

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

1.1.4.3.2 Vision and expected outcome

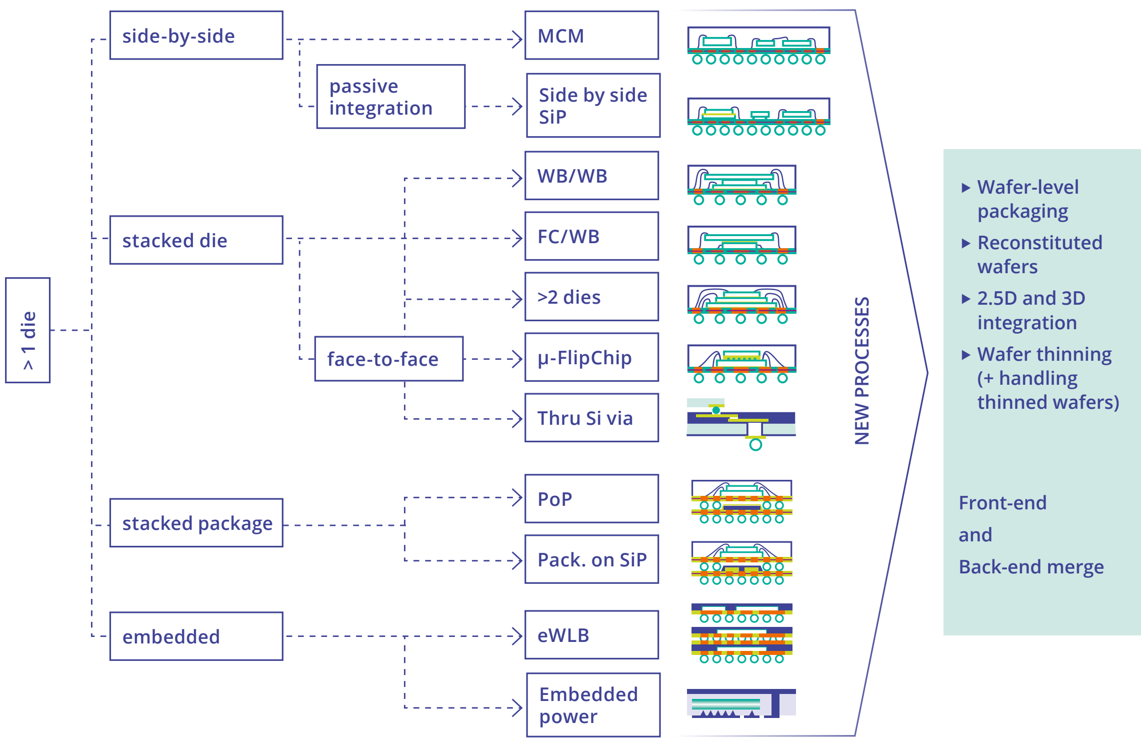
This challenge covers the integration of new chip technologies in advanced low parasitic packages, as well as chips of different functionalities resulting from the previous two challenges – e.g. CMOS logic, NVM, NEMS/MEMS, RF, analogue, sensing, actuating, energy harvesting and storage – into an SiP.

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

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

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

Compared to chip technology, assembly and packaging are becoming increasingly important. In many cases, assembly and packaging costs are becoming higher than the chip cost. To reverse this trend, we must focus



F.9 *System in a package (SiP) examples. With merging of front-end and back-end, almost unlimited possibilities are enabled (Source: Andreas Grassmann – Infineon – 3D Systems Summit)* on dedicated packaging and SiP process technologies that consider all the levels of chip, package and board/ system to identify the optimum trade-offs between function, cost, power, reliability, etc.

To remain economically sustainable and globally competitive, a toolbox must be set up that includes process technologies providing cost-effective and outstanding system integration, such as 3D interconnect technologies (including TSVs, Si-interposers or fan-out wafer-level packaging technology) to combine hardware technologies across multiple fields, and to enable integration of several devices into multifunctional electronic smart systems (ESS).

As for packaging SoCs, due to miniaturisation and the increasing functional density of SiPs, it is important to consider chip/package interaction – such as power, thermal and mechanical stress, EMC, environment, etc. In addition, the interfaces to the system/board need to be considered. For example, photonics or MEMS devices require a carefully designed package for optimum performance.

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

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

Expected achievements

It is of strategic importance to keep assembly and packaging, especially SiP manufacturing, in Europe. This can be achieved through the R&D of proper processes, such as parallel processing (e.g. front-end technologies and wafer-level processing), as well as with increasing automation and logistics. Special care should be given to address reliability, robustness and quality at reasonable cost. Other expected achievements include: process technology for multi-chip embedding on flexible substrates; process technology for heterogeneous chip integration; accurate and automated alignment for integration/combination of photonic chips; and the continuous improvement of materials aspects and thermal management, including high-temperature package characterisation and modelling. In assembly and packaging, dedicated bilateral R&D with equipment and semiconductor suppliers often needs to be supported to meet dedicated package designs (e.g. for sensors and MEMS).

1.1.4.3.3 Key focus areas

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

- **Advanced interconnect, encapsulation and packaging technologies:**
  - Interconnect technologies that allow vertical as well as horizontal integration: This includes process technologies for vertical interconnects, such as TSV, through-encapsulant via (TEV) technologies and microbumps, and copper/copper bonding, as well as process technologies for horizontal interconnects such as thin film technologies for redistribution both on chips and encapsulation materials. A technology base is needed for 3D stacking as well as horizontal interconnecting of dies and chiplets. This also includes interconnects through optical interfaces, most notably off-chip, but also within a package.

- Encapsulation technologies, handling carriers and panels, which on the one hand protect dies and on the other allow optimum electrical and thermal performance. Chip-embedding technologies such as chip embedding in mold material (e.g. fan-out wafer-level packaging (WLP) or embedded wafer-level BGA technologies) and chip embedding in laminate materials, in both of which Europe already has a strong capability, must be sustainably supported to prepare for the next-generation technology.
- Implementation of advanced nanomaterials and metamaterials, including 2D materials, nanowires, nanoparticles and quantum dots with scalable logic and memory device technologies, which will be key for adding new functionalities and developing multifunctional smart systems.
- Packaging and bonding technologies with advanced thermal management capability using materials such as carbon-nanotube reinforced metal matrix composites and liquid crystal polymers.

— Specific power and RF application technologies

- Solutions for high-frequency miniaturisation, such as for mm-wave applications (> 60 GHz) and for > 100 GHz towards THz applications for which no package solutions currently exists.
- Process technologies for integration of additional functionality such as antennas, passive devices and power source in a package (PSiP)/power source on a chip (PwrSoC) embedded micro-generation power sources into an SiP. This additional functionality will be an enabler for new applications.
- Packaging of wide bandgap materials such as SiC and GaN.
- Development of new cryogenic-compatible packaging platforms for QIP.

— 3D integration technologies

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

— Enhanced reliability, robustness and sustainability technologies

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

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

1.1.4.4 Major challenge 4: World-leading and sustainable semiconductor manufacturing equipment and technologies

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

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

1.1.4.4.1 State of the art

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

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

1.1.4.4.2 Vision and expected outcome

The ever-increasing demand for leading-edge logic and memory technology is driving the development of new equipment and material solutions for sub-3 nm node semiconductor technologies. Besides finding equipment solutions for further shrinking minimum feature sizes well below 10 nm, the alignment accuracy of successive layers, called "overlay", needs to move towards (sub)1 nm levels in a process technology roadmap that combines complex materials in 3D structures and architectures. At the same time, productivity demands on the equipment continue to increase to maintain reduced overall production costs. Process yield also continues to be a challenge with shrinking feature size and the increasing impact of defects and contamination.

The overarching goal of equipment development is to lead the world in miniaturisation techniques by providing appropriate products two years ahead of the shrink roadmap of world's leading semiconductor device and components manufacturers[9]. Internationally developed roadmaps such as the International Roadmap for Devices and Systems (IRDS) will also be taken into consideration[10]. Currently, leading integrated device manufacturers (IDMs) are forecasting a continuation of the technology roadmap following Moore's law at least until 2029[11], which corresponds to at least four new generations after the current technology node.

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

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

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

Today's equipment was typically designed for the high-volume continuous production of advanced logic and memory devices, which requires major modifications or re-design when used as production tools for heterogeneous integration. Extending the life of installed equipment to match requirements of this domain via proactive lifecycle

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9 *https://www.tsmc.com/uploadfile/ir/quarterly/2020/1OLf2/E/TSMC%201Q20%20transcript.pdf*

10 *https://irds.ieee.org/*

11 *https://www.anandtech.com/show/15217/intels-manufacturing-roadmap-from-2019-to-2029*

management (refurbishment) of these products will provide cost-effective solutions for specific applications. The performance must be enhanced for smaller batch production providing high flexibility and productivity at low cost of ownership.

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

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

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

Expected outcome

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

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

1.1.4.4.3 Key focus areas

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

— **Wafer fabrication equipment:**
- Advanced patterning equipment for sub-3 nm node wafer processing using deep ultraviolet (DUV) and EUV lithography, and corresponding subsystems and infrastructure (e.g. pellicles, masks and resist).
- Mask manufacturing equipment for sub-3 nm node mask patterning and tuning, defect inspection and repair, metrology and cleaning.

- Advanced holistic lithography using DUV, EUV and next-generation lithography techniques, such as e-beam and mask-less lithography, directed self-assembly (DSA) and nano-imprinting.
- Multi-dimensional metrology (MDM) and inspection for sub-3 nm node devices that combine holistic, hybrid, standalone set-ups (of optical, fast atomic force microscopy (AFM), electron-beam processing, scatterometry, x-ray and science, technology, engineering and mathematics (STEM) technologies) for mapping the device material, electrical, magnetic composition, dimensional properties and defects, with productivity-aware design (PAD) techniques such as: recipe automation; fleet management; "close-to-process" monitoring; and supporting big data management with predictive methodologies.
- Thin film processes including thin film deposition, such as plasma-enhanced atomic layer deposition (PEALD) and plasma-immersion ion implantation (PIII) for doping and material modification, and corresponding equipment and materials. Future solutions could lie in proximity doping and surface functionalisation.
- Equipment and manufacturing technology for wet and dry processing, wet and dry etching, including (atomic layer) selective etch processing, thermal treatment, laser annealing and wafer preparation.
- Technologies and tools for the manufacturing and integration of semiconductor components made with advanced nanomaterials and metamaterials (2D materials, nanowires, nanoparticles, quantum dots, etc) with logic and memory technologies.
- High-volume manufacturing tools for the production of III-V, SiC or other exotic material substrates of up to 200 mm, or 300 mm in the future.
- Dedicated equipment for manufacturing of electronics on flexible, structural and/or bio-compatible substrates.

— **Assembly equipment:**

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

— **Test equipment:**

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

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

- Enable flexible line management for high-mix and distributed manufacturing lines, including lines for fabrication and deposition of advanced functional (nano) materials.
- Enhance equipment optimised for high-volume manufacturing of large batches of the same chip into efficient reconfigurable equipment for the manufacturing of different chips in smaller batches.
- Enable productivity enhancements (e.g. wafer diameter conversions) for heterogeneous integration technologies to significantly improve cost-competitiveness.
- New manufacturing techniques combining chip and packaging technologies (e.g. chip embedding) will also require new manufacturing logistics and technologies (e.g. panel moulding).
- Adopt factory integration and control systems to address the digital industry challenge of the ECS-SRIA, and to apply fast (and deep) learning as well as semi-automated AI-based decision-making to control processes, to enhance quality, increase reliability, shorten time to stable yield, and preserve knowledge and master complexity in these innovative machine-to-machine domains.
- Apply PAD approaches with a focus on predictive maintenance, virtual metrology, factory simulation and scheduling, wafer-handling automation and the digitisation of the value chain for AI-based decision management. In addition, attention should be given to control system architecture based on machine learning: viz. predictive yield modelling, and holistic risk and decision-mastering (integrate control methods and tools and knowledge systems).
- Future innovations should also address new environmentally friendly solutions for manufacturing (e.g. in terms of energy consumption, chemical usage) and environmentally friendly new materials (e.g. in terms of quality, functionality, defects) in parallel with addressing the continued cost of ownership challenges. This will entail, for example, new precursors, chemicals for deposition and other wafer-processing materials, as well as gas delivery, gas handling, pumps and abatement systems.

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

- In parallel with the new manufacturing/equipment technologies to suit the specific needs of integrated photonics, novel characterisation equipment and methodologies will need to be developed. These may be partly based on available technologies from electronic chip manufacturing and packaging. In addition, completely new and innovative techniques are required. Nanophotonic technologies for enhanced light–matter interaction will require the development of multi-scale fabrication and characterisation techniques suitable for dimensions ranging from a few nanometers to several centimetres. Specific equipment and processes need to be developed to enable industrial-scale fabrication of photonic ICs, such as DUV lithography and epitaxial growth of III-Vs. The hybrid combination of chips from different platforms and technology areas will also be essential to further increase functionality in the modules, and cost-effective volume packaging should therefore be a priority.
- The development of quantum computing technology will require new types of equipment, materials and manufacturing technologies. Advanced implementation options for QIP (superconducting circuits, Majorana states, etc) often require cryogenic environments and processing. Advanced industrial characterisation equipment tailored to operating in highly challenging environments will be key enablers for such developments to reach market applications. This includes new metrology equipment for mapping electrical and magnetic properties with high spatial and temporal resolution.

1.1.5
TIMELINE

All leading European industry and research actors should align their activities with international roadmaps and timelines. Roadmap exercises are being conducted in various projects and communities, including NEREID[12] and the IEEE's IRDS[13], in which European academia, RTOs and industry are participating. For system integration, the International Electronics Manufacturing Initiative (iNEMI)[14] and the new Heterogeneous Integration Roadmap activities are also considered. The European R&D priorities are planned in synchronisation with global timeframes and developments that are under continuous adaptation. The timelines below are high-level derivatives from these global evolutions, and follow the structure of the four **Major challenges** described above.

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

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

First, the development of sub-5 nm solutions in terms of equipment and materials as part of **Major challenge 4** needs to be two-to-three years ahead of mass adoption, and is of critical importance to maintaining European leadership. Second, new equipment and materials solutions should be developed in line with the needs defined in the roadmaps of **Major challenges 1–3**. Lastly, improving manufacturing efficiency and enhancing yield and reliability are ongoing tasks that need to be performed in accordance with the needs of the "more-Moore" and "more-than-Moore" domains. Fundamentals of "manufacturing science"

12 *https://www.nereid-h2020.eu/*

13 *https://irds.ieee.org/*

14 *https://www.inemi.org/ https://eps.ieee.org/technology/heterogeneous-integration-roadmap/2019-edition.html*

will concern projects at rather low TRLs (typically 3–5), whereas implementation in pilot lines and full-scale manufacturing lines will contemplate higher TRL projects (typically 7–8). For most of the manufacturing science projects, the execution will take place in the medium- to long-term timespan, although shorter-term impact, such as improving the uptime of equipment due to PAD or the improvement of robustness of the manufacturing processes, will get due attention to enhance competitiveness.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Advanced computing, memory and in-memory computing concepts	**Topic 1.1:** Extensions of the scaled Si technology roadmaps High-performance Ultra-low power 3D integration	• N3 - N2 R&D • 2nd generation gate-all-around devices, forksheet integration • 18 nm FDSOI at technology platform integration level
	Topic 1.2: Exploration and implementation of unconventional devices based on materials beyond Si	• SiGe (high Ge) channel • Cu alternative solutions
	Topic 1.3: Novel device, circuit and systems concepts, such as for near/in-memory, neuromorphic, optical and quantum computing neuromorphic, optical and quantum computing	• Near/in-memory computing • 3D heterogeneous integration (logic/memory)
	Topic 1.4: Long-term challenges such as steep-slope switches, spin-based transistors and alternatives	
	Topic 1.5: New eNVM technologies	• PCRAM • STT-MRAM • FDSOI embedded MRAM
Major challenge 2: Novel devices and circuits that enable advanced functionality	**Topic 2.1:** Application-specific logic integration	• ULP 18 nm FDSOI technology integration
	Topic 2.2: Advanced sensor technologies	• Continuous improvement of sensitivity (imagers, IMU, etc), range (lidar), and reduction of sensor area and energy consumption • Development of miniaturised low power chemical sensors • Development of biomedical sensors integrated with micro/ nanofluidics • Heterogeneous integration of sensor technologies with (ULP) logic/memory technologies • 22 nm FDSOI for the IoT
	Topic 2.3: Advanced power electronics technologies	• Silicon, BCD, SiC and GaN-based technologies and substrate materials • Energy-efficient systems, including energy harvesting

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• N1,5 R&D - 3rd generation of Gate-All-Around devices • CFET introduction • 12/10 nm FDSOI at technology platform integration level • 3D monolithic integration	• Sub-1 nm node logic and memory technology (nanowires, nanosheets) at process and device research level • Vertically stacked nanosheets • 3D monolithic integration • Beyond 10 nm FDSOI at technology platform integration level
• Ge channel • Optical interconnects • 2D materials exploration	• III-V channel • 2D materials device integration
• In-memory computing • Neuromorphic computing (spiking) • 3D monolithic integration • Photonic SOI	• Quantum computing • Optical computing
• TFET • CNTFET • 2D material FET	• NCFET • NEMS switch • Topologic insulator electronic devices • Spin wave devices • Mott FET (VO_2, HfO_2, etc)
• PCRAM • VCMA-MRAM • ReRAM • FeRAM	• ReRAM (MLC) • Hi-density ReRAM
• 12 nm FDSOI technology integration • New architectures for neuromorphic computing • 3D stacking for monolithic integration	• 3D monolithic integration
• Quantum sensors • Ultra-low power chemical sensor systems for pollution monitoring • Energy autonomous sensor systems • Multi-sensor systems for IoT • Integrated biomedical sensor system • Heterogeneous integration of sensor technologies with novel device, circuit and systems memory and computing concepts • 12nm FD-SOI for IoT	• Nanoelectronic sensor devices with individual molecule sensitivity and selectivity • Nanoelectronic biomedical sensor systems • Monolithic integration of sensor technologies with novel devices, circuit and systems memory and computing concepts • Beyond 10 nm FDSOI for IoT
• New CMOS and IGBT processes • Smart GaN devices (combining logic and power devices) • Vertical GaN power devices • Towards 300 mm GaN and 200 mm SiC substrates • Energy-autonomous systems • Energy harvesting and energy storage systems	• B-Ga_2O_3 • Diamond

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 2: Novel devices and circuits that enable advanced functionality	**Topic 2.4:** Advanced RF and photonics communication technologies	• Enable 5G connectivity • RF and mm-wave integrated device options building on, for example, SiGe/BiCMOS (increase of ft), RF and FDSOI, CMOS, PIC • GaN/Si and GaN/SiC technologies • Next-generation RFSOI • 300 mm photonic SOI • 200 mm POI
	Topic 2.5: Flexible and structural substrate electronics	• Increased reliability of materials and process techniques, reduction of pattern size • Development for displays, textiles and wearables (sensors) • Integration of conformable electronics on 3D surfaces
Major challenge 3: Advanced heterogeneous integration and packaging solutions	**Topic 3.1:** Advanced interconnect, encapsulation and packaging technologies	• Vertical as well as horizontal integration via TSV, TEV, microbumps • Fan-out WLP or embedded wafer-level BGAs and chip-embedding in laminate materials • Advanced wafer-stacking technologies • Packaging & bonding technologies with advanced thermal management capability
	Topic 3.2: Specific power and RF application technologies	• RF miniaturisation for mm-wave applications • Package integration of additional functionality such as antennas, passive devices and power sources
	Topic 3.3: 3D integration technologies	• Chip I/O-pad level 3D-SiC • Chip-package-board co-design
	Topic 3.4: Enhanced reliability, robustness and sustainability technologies	• Enable testing of separate components, before assembly via concepts such as BIST and self-repair
Major challenge 4: World-leading and sustainable semiconductor manufacturing equipment and technologies	**Topic 4.1:** Wafer fabrication equipment for nanoscale patterning, layer deposition, metrology, and inspection for advanced logic and memory technologies	• Manufacturing equipment for 3 nm node logic and memory
	Topic 4.2: Wafer fabrication equipment for new transistor front end of line (FEOL) and new interconnect back end of line (BEOL) concepts	• Manufacturing equipment for 3 nm node transistor and 3D heterogeneous integration interconnect concepts
	Topic 4.3: Wafer fabrication equipment for new materials and processes	• Manufacturing equipment for 3 nm node materials and processes • Equipment for manufacturing of components with advanced nanomaterials • Production tools for III-V, GaN, SiC or other exotic material substrates
	Topic 4.4: Assembly and test equipment enabling advanced packaging of single and/or multi-node chips/chiplets	• Assembly and test equipment for chip-to-wafer stacking, fan-out WLP, multi-die packaging, "2.5D" interposers and TSVs • 300 mm photonic SOI • 200 mm POI

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Enable 6G connectivity? • MOEMS and micro-optics, optical interconnections and light emitters • Photonic SOI next generation • Advanced RF filter materials and technologies	• RF cryogenic electronics for QIP
• Stretchable devices and displays • Flexible photonic components • Compostable electronics	• Seamless integration of μ-electronics, flexible electronic and photonics
• 3D stacking/horizontal connecting of dies/chiplets • Advanced nanomaterials (including 2D materials, nanowires, nanoparticles, etc) • Critical raw materials elimination from packaging bill of materials such as W, Co, Mo, Be, BeO • Chip level hermetization	
• RF miniaturisation for THz applications • Packaging of wide bandgap materials (GaN, SiC, etc)	• New cryogenic compatible packaging platforms for QIP
• 3D SoC • System technology co-optimisation • 3D stacking for monolithic integration	• Ultimate transistor-level 3D ICs
• Novel material solutions for high reliability, robustness and high quality	
• Manufacturing equipment for 1 nm node logic and memory • Equipment to enable novel switches, transistors and alternatives based on, for example, 2D materials, topologic insulator and spin-wave devices	• Manufacturing equipment for sub-1 nm node logic and memory
• Manufacturing equipment for 1 nm node transistor and 3D monolithic integrated and optical interconnect concepts	• Manufacturing equipment for sub 1 nm node transistor and 3D monolithic and optical interconnect concepts
• Manufacturing equipment for 1 nm node materials and processes • Equipment for materials and processes for new eNVM types such as (high-density) ReRAM • Production tools for 300mm wafer substrates based on selected exotic materials	• Manufacturing equipment for sub 1 nm node materials and processes
• Assembly and test equipment to enable next-generation autonomous sensors, power electronics and RF/optical communication packaged ICs	

1.1.6
SYNERGY WITH OTHER THEMES

Europe needs leadership throughout the value chain – from the development of processes, materials and equipment to the production of devices, systems and solutions – and the deployment of services to leverage its strong differentiation potential and drive its competitiveness. The impact of technology choices on applications, and vice versa, is becoming very large and decisive regarding successful market adoption. This is true for all application fields, but especially where the communication, computing and sensing technology is key to delivering the expected (quality of) service or function (e.g. industry, automotive, health).

System technology co-optimisation is key to all leading-edge innovations. Specific actions include: the specification of technology and product roadmaps for the planning of future products; the creation of technology platforms and pilot lines; advanced access to new technologies for prototyping; cooperation on the development of dedicated technologies; and advanced access to test beds and markets. Designing embedded software for specific ECS architectures requires verifying that it functions correctly with the hardware, but also that the performance is optimised for the architecture subsystem in which it is running. Ideally, all of this should be done very early in the design cycle before hardware prototypes have been created.

Collaboration with the design community

While there is traditionally a close link between the technology and design communities (design/technology co-optimisation is a well-known trend), these ties need to be further reinforced and strategically aligned. The number of technology options, each with its own challenges, is exploding. Early and quantitative assessment of the gains, applications, issues and risks is key to maximising the value of a technology for a given application. Likewise, technology development faces the same challenges to deliver a technology that suits the purposes of designers. Specific focal areas include: building, sharing and incorporating physical models of components; device's electrical characteristics; models of degradation effects; and data on parameter variability and dispersion. In response, there will be design solutions generated for process variability and process reliability, as well as for in-package device integration with the modelling of thermal, mechanical and EMI effects. The use of advanced multimodal and predictive software tools with well-calibrated physical parameters of electro-thermal models for the identification of critical issues at the device and system level, and for the generation of new devices with optimised properties, is key to targeting cost-effective, sustainable and energy-efficient development.

These process technology and integration developments will be closely synergised with design efforts, and as such offer opportunities for building unique European IP to establish leadership in applications for global markets. This responds to the growing need for co-design efforts for security, energy efficiency, data management, distributed computing, etc.

Specific links between design and technology will have to be established to take advantage of the advancements in AI and ensure that Europe is well positioned to add this dimension to its existing strong base in sensors and actuators. The combination of new technologies (new memories, 3D, etc) with AI-embedded architectures and a combination of sensors is fundamental to maintaining Europe leadership in this domain.

Connection with digital industry

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

Connection with photonics community

In the photonics domain, the Integrated Photonic Systems Roadmap (IPSR)[15] is defining the way forward, and this roadmap is aligned with the activities being exploited by AIM Photonics in the US. In this roadmap, we increasingly see a trend towards multi-PIC application modules. Similar to the IC industry, the PIC-based developments also do not rely on just silicon photonics for their functionality. Hybrid and heterogeneous integration of functionality from different platforms is essential to enable the currently required and new functionality. This trend also spreads further to integration with electronic ICs, which is becoming a commercial reality. The combination of electronics and photonics at an increasingly intimate scale will be a requirement to keeping Europe at the forefront of this – strategic – foundational technology development. The focus should therefore be to maintain both the manufacturing foundries of chips and the packaging in Europe.

Connection with flexible electronics community

Semiconductor process technologies, manufacturing methods, equipment and materials can also be used to produce electronics on flexible and other structural substrates. Examples here are structural, wearable, flexible, biodegradable and disposable electronics, where electronics are integrated on various materials for a wide range of automotive, aviation and consumer electronics applications. These technologies and their applications are well described in *Section 1.2* of this ECS-SRIA on **Components, Modules and System Integration**.

Connection with quantum computing

The current status is that quantum computing technologies and their applications are expected to break through over the next two decades. These technologies are addressed with projects from 1/1/2019 onwards in the "Quantum Technologies Flagship" (budget €1 billion) of the "Future Emerging Technologies" programme of Horizon 2020 and its successor Horizon Europe. The results of this Flagship and the related Strategic Research Agenda[16] are likely to influence the ECS-SRIA from now on. Scalability is seen as a key in the medium term (6–10 years). Systems integration will require a stronger ecosystem that is able to deliver components, including assembly and package technology, device and systems development, as well as integration.

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15 *https://aimphotonics.academy/roadmap*

16 *https://ec.europa.eu/digital-single-market/en/news/new-strategic-research-agenda-quantum-technologies*

1.2

Foundational Technology Layers

COMPONENTS, MODULES AND SYSTEMS INTEGRATION

1.2.1
SCOPE

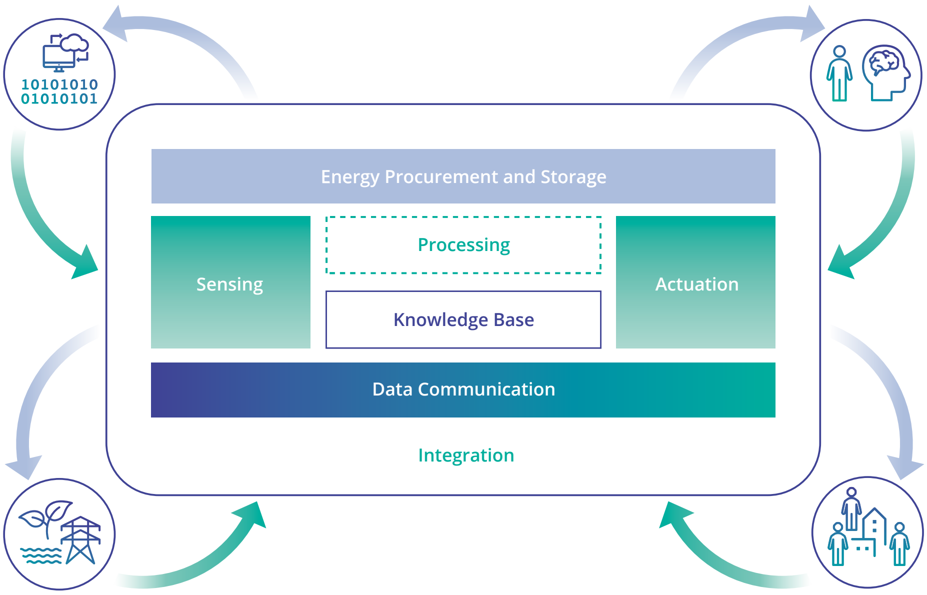
Physical and functional integration (PFI) on the component, module and system level targets application-independent methodologies and technologies to develop and produce smart electronic components and systems (ECS). Although in practice PFI is often geared towards specific applications, the materials, technologies, manufacturing and development processes that form these domains are generic, and should be standardised and interoperable where possible. Therefore, PFI is one of the essential capabilities required to maintain and improve the competitiveness of European industry in the application domains of smart systems. PFI is an enabling technology of smart systems integration (SSI) for ECS, and for efficiency reasons research on PFI is treated generally. This section deals with approaches beyond the semiconductor technologies, material families and compact system on a chip (SoC) integration that the **Process Technologies, Equipment, Materials and Manufacturing** (PTEMM) section covers, thus tapping into alternative technologies (such as additive manufacturing), complementary materials (both at the functional and substrate level) and hybrid approaches to assembly and integration.

Mastering integration technologies at the components, modules and systems level, and extending them to cope with the new requirements imposed by modern and future smart systems, is a highly significant capability of European industries to ensure their leading position in smart systems engineering, as well as to move innovations into real-life products, services and markets.

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

In addition to the usual silicon-based semiconductor technologies, smart components, modules and systems require the following.

- A combination of device architectures: sensors (including all kinds of image sensors), actuators, energy generators, storage devices, MEMS/NEMS, MOEMS, MNBS, LAE and communication interfaces.
- Heterogeneous integration technologies on the component, module and system level, utilising multi-physics/multi-domain approaches, e.g. nano-electronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, quantum effect, micro-fluidic, acoustic, radiation, RF, and bio- and chemical principles.
- A multitude of processes: micro- and nanotechnologies, additive manufacturing, printing, lamination and other joining and assembling technologies, as well as hybrid combinations.
- Methods, processes and schemes for design, production, assembly and testing of the various components, modules and systems and multi-scale fabrication to ensure appropriate unit cost, quality, reliability and sustainability (circular economy, CO_2 footprint, resources).



F.10 *Smart systems are integrated with the (natural, man-made and social) environment, networks of power, natural resources and data. Smart systems provide (and use) cognitive support to (and from) their surroundings (Source: EPoSS)*

Figure F.10 defines an integrated smart system showing its components and modules, while interacting with the natural, man-made and societal environment. Smart systems integrate sensing and/or actuation as well as signal processing to enable actions. Such systems utilise multifunctional perception, and are predictive, contextual and adaptive. Smart systems perform human-like perception and actions, and can even generate energy when required.

1.2.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

Societal benefits of smart components, modules and systems stem from the applications that they are enabling, as described in the **Application** chapters. Improved integration technologies and miniaturisation, together with cost-, energy- and resource-efficient and eco-friendly manufacturing, will make future applications affordable for the broader public, and support sustainability of products and production technologies, enabling responsible use of resources (e.g. by means of assisting in the development of a circular economy).

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

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

Another major application is in digital industry. Smart systems harness data, extract information, distil knowledge and convert to actions and/or provision of improved decision support. This is achieved by integrating components and modules for data acquisition and context-based actions, signal conditioning and data analysis, and also by communicating elements to organise collaborative networks. In offering alternative access via the cloud to data processing and knowledge extraction engines, smart components, modules and systems enable the deployment of edge computing, thus reducing the demands on communication bandwidth and system-level power consumption. However, this also creates challenges for the sustained self-powering of edge devices of increasing complexity, and the need for such power demands to be carefully managed and limited, using ambient energies where possible. To resolve this challenge requires not just technology advances, but also close coordination and collaboration between all the "power IoT" stakeholders based on realistic targets and expectations.

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

- Embedded intelligence (typically realised by a combination of hardware and software components) in the ECS – higher functionality, less or changed requirements for interfaces, improved interoperability, haptic interfaces, and lower demand for power and power resources.
- Greater performance and digital configurability of sensors, analogue and RF devices, while at the same time reducing energy consumption, which impacts component, module and system integration, transmission of RF waves and interconnects, without decreasing component performance (e.g. in the detection limit of MEMS/NEMS sensors).
- Greater performance in power devices through an impact on the thermal characteristics and electromagnetic interference (EMI) performance of components, modules and systems, in addition to higher integration levels due to more effective switching capabilities.
- Energy savings, efficiency and harvesting through smart and intelligent battery management, combination of functions and/or digital interfacing with sensors, transceivers and microcontrollers to minimise system-level power consumption, multi-source energy harvesting and high density, low leakage storage devices to avoid battery replacement, integration of new power-saving techniques (e.g. GaN-based switching) in combination with energy-efficient packaging technologies.
- Features such as reliability, security, safety, self-monitoring, faultlessness and trustability will become more crucial. Properly used, PFI technologies can greatly ease the assurance of these qualities.
- Wearable and/or disposable sensors, opening a new area for sensors in, for instance, healthcare and wellness applications, and materials and substrates for printed circuits and hybrid integration of traditional integrated circuits with printed electronics.
- Structural electronics, opening up a new form of electronics integration on/in various different materials (plastics, laminates, glass, textile, etc), enabling novel smart systems in automotive, aviation, consumer electronics, healthcare, etc.
- Flexible and stretchable electronics, and biodegradable materials for electronics (if there are going to be countless IoT devices in operation, lifecycle considerations will be significant, including for ingestible devices for healthcare).

- Technology integration through electronics, photonics, chemical/biochemical (in the case of sensors), fluidics and additive manufacturing for multi-domain smart systems.
- Quantum technologies, where components that harness quantum superposition and entanglement for quantum computing, communication and sensing (e.g. superconducting or Si qubits, or ion traps), interfacing components and modules for quantum system integration, from cryogenic temperature (e.g. cryo-CMOS, superconducting circuitry) to room temperature.

1.2.2.1 Application breakthroughs

The future structures of smart components, modules and systems will not only show a strong increase in functional and structural complexity, but also in diversity. They will demonstrate even smaller form factors with more features and materials integrated within a given volume. It is not just higher complexity, but also higher integration that is a goal of the PFI of components, modules and systems – for instance, it could bring low-cost disposable sensors for point-of-care (PoC) diagnostics or sensors for measuring environmental parameters in aqua/agriculture. However, new structural and fabrication concepts will be needed to reliably suppress any unwanted interactions and parasitic effects that may threaten the safe and dependable function of the new components, modules and systems.

Technology advances on the component, module and system level will have a key impact on the applications in a multi-application and technology-oriented approach.

Applications are another driver for such approaches:

- Communication landscape with 5G, 6G, high bandwidth, time-sensitive network (TSN) operations and near-field communication, as well as navigation and localisation.
- Autonomous systems, including energy autonomy – in mobility, transport, logistic, manufacturing or control of buildings and micro-grids, etc (ensuring faster time response and decreasing the impact of human error).
- For low data rate communications, lower power consumption devices and supporting architectures are needed, particularly to support the autonomy of IoT edge devices.
- Healthcare landscape with applications towards assisted care, PoC devices and telemedicine, including for the disabled.
- Adaptive lighting systems with high-speed interfaces, thermal and optical arrangements, and the reduction of light contamination by intelligent illumination.
- Energy systems for high-power charging and/or highly variable and changing conditions.
- Industry 4.0 manufacturing landscape to enable agility and autonomy, as well as energy and resource efficiency.
- Overall transition from stable controlled environments to harsh environments with longer operational lifetime and variable conditions.
- The transition in mobility towards zero-emission power trains, with their significant cost and energy efficiency challenges.
- Sensing of environmental parameters in agriculture or aquaculture, in manufacturing and working places, at home and in urban areas.
- Imaging applications for security, healthcare, digital industry, (precision) agriculture, digital society (television, social media) and perception.
- Optical Integration for higher data transfer rates, and more energy efficient cloud and edge computing solutions.

1.2.3
STRATEGIC ADVANTAGE FOR THE EU

Components, modules and systems are versatile in terms of design, size, material and composition, and thus the network of stakeholders involved in the production process of smart systems is equally complex. Europe's supply chain for smart systems production consists of more than 6,000 large companies and SMEs[17]. New models that will bring greater efficiency and more agile production processes need to be developed to ensure they can immediately react to sudden market shocks, as well as flexible manufacturing to accommodate the short lifecycles of products and fabrication-on-demand. The current Covid-19 pandemic has revealed the vulnerability of global, distributed value chains. Emphasising and supporting ECS manufacturing and subcontracting can lead to increasing smart systems activity for European industry. In the ECS sector, this means about nine million jobs across Europe.[18]

These are important issues, in addition to the increased demand for smart technologies working to improve issues around size (miniaturisation), performance, quality, durability, deployability, energy-efficiency, compliance with data security, integrity and safety. Last, but not least, issues regarding materials (from polymer parts to rare earth metals) will gain in importance and be regulated progressively.

At this particular level, the required technologies deal with the productive integration of this heterogeneous set of elements. At the component and module level, however, apart from the more-Moore information processing devices and communication elements, it is more-than-Moore devices that are more akin to the components and modules level. Hence, the parallel development and use of more-Moore and more-than-Moore technology is leading the way to a new level of system integration. These more-than-Moore devices are at the forefront of the physical digital intimacy mentioned earlier: devices that physically (mechanically, optically, etc), chemically and biologically interact with their environment, translating real-world quantities and phenomena into data and/or energy after some electrical transduction, and vice versa. In short, they comprise the sensing and actuating elements, and the devices needed to power them. According to Yole Développement[19] the global MEMS and sensor market (excluding RF filter modules) will almost double from US$48 billion in 2018 to US$93 billion in 2024. Assuming the same annual growth rate, the market should reach US$180 billion by 2030, with Europe supplying at least one-third to one-half of this market,

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17 *Prognos AG: Analyse zur ökonomischen Bedeutung der Mikrosystemtechnik, Studies about the Smart Systems economy in Baden-Württemberg and Germany; European Competitiveness Report; EU Industrial Structure 2011; Figures provided by major industry associations*

18 *EU Commissioner Gabriel at the ECSEL JU Symposium 2020 (https://www.ecsel.eu/media/2081)*

19 *Yole Développement: Status of the MEMS Industry 2019, Market and Technology Report, 2019 edition*

with hopefully the same success in other microsystems' markets. To summarise, the strategic advantages for Europe are:

- strengthening the European economy regarding future technologies.
- maintaining Europe's leading position in electronic components and systems, and key digital technologies.
- establishing and/or maintaining European sovereignty in electronic components and systems, and key digital technologies, by strengthening European enabling technologies.
- ensuring a stronger economy through the generation of high-tech jobs and more value-added across Europe.

1.2.4
MAJOR CHALLENGES

The following four major challenges are identified:

- **Major challenge 1:** Physical and functional integration.
- **Major challenge 2:** Materials.
- **Major challenge 3:** Technologies, manufacturing and integration processes.
- **Major challenge 4:** Decarbonisation and recyclability.

1.2.4.1 Major challenge 1: Physical and functional integration

1.2.4.1.1 State of the art

Smart components, modules and systems utilise a combination of features based on nanoelectronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, micro-fluidic, acoustic, radiation, RF, biological, chemical and quantum principles, as well as a combination of such technologies for smart devices (e.g. sensors, actuators, semiconductors, energy generators/batteries, storage devices, microcontrollers/data processing devices, transceivers, MNBS, MEMS/NEMS, MOEMS and LAE). Such integration goes beyond the compact monolithic SoC approaches supported by the semiconductor technologies covered in the **Process Technologies, Equipment, Materials and Manufacturing** section. Previously, the integration of functions in the same module was achieved by using hybrid integrated circuits or multi-chip modules (MCM). The current trend is a focus on the system in a package (SiP), where all functions are designed together to improve performance and compactness, something that also enables the heterogeneous integration of separate devices with different fabrication processes and methods (see the section on **Process Technologies, Equipment, Materials and Manufacturing**, and the section on **Architecture and Design: Methods and Tools**).

1.2.4.1.2 Vision and expected outcome

Given the broad range of physical scenarios they face, smart components, modules and systems need to interact with many environments – from well-controlled laboratory conditions (in vitro: lab-on-chip, organ-on-chip, etc) to real-life scenarios (also in vivo: in the body (implants), temporarily inside the body (ingestibles), on the body (wearables)) and harsh environments (also electrical, e.g. EMC). There are a multitude of operational issues affecting smart components, modules and systems regarding energy, performance and size. There is a need in low-power operation/(portable)energy autonomy (self-powered devices, devices for providing short-/medium-/long-term autonomy depending on the application) on the one hand, and dealing with high-power density and thermal stress on the other. The optimal "minimum" size has to be achieved, which means that fast response/latency/real-time issues, adequate operation time/cycling (from real-time continuous monitoring to event-triggered operation) and multi-parameter performance have to be ensured.

Heterogeneous integration technologies are strongly driven by consumer applications, such as the various types of handheld devices. The manufacturer and associated supply chain for these high-volume applications are based in Asia, and so for PFI Europe needs to reinforce its supply chain of packaging solutions. One example of this lies in the convergence between sensing and imaging domains for consumer applications, in particular for face recognition and AR based on consumer lidar solutions.

One of the key application drivers for the PFI of smart components, modules and systems is the IoT and its sensor nodes, which require a wide range of sensor and actuator functionalities, combined with data processing and wireless communication, with power autonomy provided by energy storage and harvesting devices. In many cases, power autonomy is the limiting factor in such applications, and improvements are especially required to improve energy storage and harvesting in low-power components and modules, as well as in low-power techniques at the system level. In particular, this means the development of low-power solutions for sensors and actuators, as well as radio communication components and other functional devices.

Components to provide power efficient computational resources (i.e. low-power microprocessors) are needed, as are low-power computational methods, including distributed and low-power AI solutions in hardware and software, and in-sensor data processing. In addition, reliable, energy-efficient, low-loss interconnection and packaging solutions are a necessity. Furthermore, new and improved energy storage, especially low-leakage rechargeable storage devices need to be developed, as well as universally deployable harvesting solutions to improve the case-specific devices used today.

Although silicon is an impressive enabling material (and technology), and silicon micromachining (as in Si MEMS) has opened the door to applications other than in electronics (e.g. in sensing and actuating), the PFI of a broader set of materials and technologies are crucial for covering all envisaged application scenarios. This complementarity is particularly addressed in the challenges below, which go beyond semiconductor technology.

1.2.4.1.3 Key focus areas of physical and functional integration

- Selective sensing components and selective detection of gas and volatiles, allergens, residues in food/water, atmospheric particles and disease monitoring.
- Sensors and actuators for biological and medical applications.
- Imaging systems (image capture, multi-modal and hyperspectral, e.g. spectrally resolved).
- Sensing devices and power sources compliant with integration in wearables.
- Low-power/low-loss modules for low-power sensing, actuation, processing and communication, including efficient power transfer, harvesters and storage devices.
- MOEMS and micro-optics.
- Photonics features such as optical sources, waveguides and connectors integrated into photonic integrated circuits or photonic systems in a package on silicon, PCB or other substrate.
- Module-level high-speed communication features (dependent on frequencies, filters, multimode capability, acoustically decoupled frontend components, etc).
- Component-level features for self-diagnosis (PHM detectors) and module-level signal processing and control features for self-diagnosis and self-learning.
- Data analysis embedded on different levels for smarter devices, including AI on the sensor level.

- Hardware solutions for security and privacy.
- Machine learning and artificial intelligence on the sensor, module and systems level, i.e. on the edge.
- High-performance signal quality in harsh environmental conditions.
- Advanced and active cooling systems and thermal management.
- EMI-optimised components, modules and systems – TRL dependent on switching frequencies, introduction of wide bandgap materials.
- Highly efficient smart power modules using novel power devices with integrated functionalities (e.g. sensors).
- 3D component, module and system design and simulation; also for flexible and stretchable electronics – TRL dependent on materials, components, etc.

1.2.4.2 Major challenge 2: Materials

1.2.4.2.1 State of the art

Smart components, modules and systems leverage a multitude of materials, such as silicon and non-silicon, (precious) metals, ceramics, polymers, glass, inks and functional materials for sensing, actuation and energy harvesting, as well as hybrid combinations on substrates (e.g. Si, ceramic, polymer, glass), in package and in systems. In this sense, the scope considered in this section extends the coverage of the usual semiconductor materials. Indeed, non-silicon materials, even non-silicon-compatible materials, are needed to interact wholly and efficiently with the physical world by benefiting from different transduction principles, and new substrates may be considered to better serve all types of application scenarios.

The main idea of heterogeneous integration, from components up to the systems level, is the requirement for co-engineering (power, signal integrity, EMC, thermal, thermo-mechanical). All such domains have to be designed together to ensure a high level of performance and the necessary integration. The challenge here is to simulate and design the manufacturing process, and operations based on advanced material information (which links to the section on **Architecture and Design: Methods and Tools** on this issue).

1.2.4.2.2 Vision and expected outcome

The broad range of the physical scenarios of smart components, modules and systems require exploring and solving the materials and device architecture issues posed by these different scenarios. For widespread applications, such materials need to be performant but also abundant, recyclable and non-toxic. In some cases, it will be critical that they are compatible with the operating environment – e.g. bio-compatible, self-cleaning and parts of devices that are self-healing, and in some cases self-powered. The nano-modification of less exotic materials will also boost performance.

For instance, MEMS/NEMS development focuses on sensors and actuators. The former rely on new generations of inertial measurement units (accelerometers and gyroscopes) with increased performance, with or without AI support, magnetometers, pressure sensors, microphones, as well as particle sensors; the latter rely on piezoelectric micro-mirrors, print heads, oscillators (membranes and cantilevers), tunable lenses, loudspeakers and piezoelectric micromachined ultrasound transducers (PMUTs). New materials are being evaluated and selected to fabricate some of these MEMS/NEMS, such as lead zirconate titanate (PZT), aluminium nitride (AlN) and scandium aluminium nitride (ScAlN) and, more generally, lead-free piezoelectric thin films for actuation or sensing functions.

In addition to active electronic or functional materials, carrier or substrate materials also have to be further developed. Future RF modules, operating in the mmWave and THz range and beyond, will also entail new carrier and substrate materials (such as glass). Flexible electronics necessitate novel stretchable substrates (such as thermoplastic polyurethane (TPU) and polydimethylsiloxane (PDMS)). Biocompatible and even biodegradable substrates and packaging materials are required to reduce the environmental impact of the electronics industry, in addition to opening new applications in areas such as wearable and implantable electronics. All these new materials have to be well-characterised to enable the first-time-right design of these electronic systems.

In addition to the new materials themselves, the materials' property data are significant. They are fundamental in, for example, simulations and for reliability investigations. Here, close links to the section on **Quality, Reliability, Safety and Cybersecurity** and the section on **Architecture and Design: Methods and Tools** are critical. Europe has a very strong academic network and an advanced position in material characterisation and simulation techniques. Nevertheless, it is important to highlight that the majority of organic materials used in composite, moulding adhesive materials comes from Asia.

1.2.4.2.3 Key focus areas of materials

- Surface coatings for multifunctionality on the same base structures, including self-cleaning materials.
- Protective housing and coating features (e.g. to protect against aggressive environments).
- New/alternative organic and biocompatible materials, housings and coating features (implants, ingestibles, wearables, biosensors, etc)
- Non-fossil/recycled bioplastics, compostable/biodegradable materials.
- Functional materials for printing, coating, potting, thermal forming, lamination and over/injection-molding (TRL dependent on temperature levels, etc)
- Materials improving integrated photonics performance (efficient modulation, higher bandwidth, modulation/detection).
- Materials for affordable infrared imaging, integrated with Si (readout and image processing) electronics.
- New materials and features for sensing and actuation (metal nanowires, carbon nanotubes (CNTs), graphene, cellulose nanofibres, biocarbons, metal–organic frameworks (MOFs), nitrogen voids in diamond, metamaterials, etc)
- Topological insulators for low-loss electronics.
- Low quiescent/leakage power materials/devices for miniaturised sensors and energy storage.
- Metamaterials for sensors.
- Materials for low-power, fast-responding gas sensors and occupancy sensors.
- Non-toxic, scalable, high-density feature materials for energy-harvesting sources (thermoelectric, piezoelectric, tribo-electricity, etc), and higher performing electrodes and electrolytes for improved capacity and conductivity of energy storage devices.
- High-performance materials for passives.
- Transducer materials (e.g. CMOS-compatible piezo or flexible solar panels) that can be integrated into SiPs.
- RF > 10 GHz: CMOS or GaN-compatible thin film piezoelectric materials, materials for high-efficiency acoustic transduction, conductive materials.
- Rare earths replacement (e.g. for magnetics).
- Functional materials for flexible and stretchable devices, flexible "board/stripe", hydrophobic barriers, agent reservoirs, additive technologies, etc.
- New thermal interface materials (dependent on temperature capabilities, etc)
- New substrate materials – rigid, flexible or stretchable – TRL-dependent on power, frequencies, applications, single-use, multi-use, long lifetime, etc.

- Replacement materials to comply with Restriction of Hazardous Substances Directive (ROHS) regulations.
- Recycling and repair of components, modules and systems, especially for composites and other complex systems with many closely integrated materials.
- Materials for cryo-electronics.
- Material properties database for simulation and reliability.
- Advanced packaging materials, e.g. carbon-reinforced metal matrix composites (CrMMC) and liquid crystal polymers (LPC).

1.2.4.3 Major challenge 3: Technologies, manufacturing and integration processes

1.2.4.3.1 State of the art

Smart components, modules and systems require a multitude of processes: silicon and non-silicon micro-nano, additive manufacturing, lamination and other joining and assembling technologies, as well as hybrid combinations. To increase the package density and combine the above-mentioned features, many different packaging technologies are available, such as thin film processes, embedding, classic assembly and joining methods, right up to novel additive manufacturing techniques.

Flexible electronics is an enabler to reduce the weight, volume and complexity of integrated systems and products, to create novel form factors and 3D design features. Flexible electronics has already broadly penetrated the markets, and can be found in a wide range of products such as smartphones, flat-panel displays, smart cards, medical imaging sensors, photovoltaic sheets and electronic paper. Currently, the majority of flexible electronics products are based on polyimide (PI, Kapton), copper laminate substrates, etching of copper to pattern the circuitry, and conventional SnAgCu (SAC) soldering or anisotropic conductive adhesives (ACA) bonding processes for the assembly of discrete components on the flex. The more complex the design of flexible electronic circuits, the more difficult it is to achieve high yield during production and reliability during operation.

The critical requirements for any of these techniques to enable new advanced applications are to ensure sustainable and cost-efficient manufacturing while providing high performance and reliability. One example would be an IC connection to flexible substrates with low cost and high reliability for flexible devices, used in wearable and disposable sensors for health and wellbeing. Further important developments include hybrid integration of different silicon IC components into miniaturised multifunctional modules in different SiP technologies, combining technologies such as flip chip, bonding, lamination and substrate materials from silicon, glass and ceramics to polymers. Multifunctional integration also requires the development of multi-domain integration – e.g. the integration of photonic and RF functionalities into smaller form factors.

1.2.4.3.2 Vision and expected outcome

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

The complexity and diversity of heterogeneous components, modules and systems substantially exceed that of mere microelectronic components due to their multi-physics and multiple domain nature. Environmental and sustainability issues (production, disposal, re-use, lifecycle and circular economy) also need to be taken into account.

This development will include greater integration on every level to respond to the need for miniaturisation and functional integration in a sustainable, cost-effective and scalable way. Components, modules and systems will include more integrated functionalities (see **Major challenge 1**). In addition, more components will be integrated into single modules, and even integration substrates and module packaging will include integrated components and functionalities, rendering them a functional part of the modules and systems rather than "passive" boards and frames. In this multifunctional and multimodal integration on the component, module and system level, the development of manufacturing methods that meet the accuracy and repeatability criteria of high-quality and high-reliability products are a necessity. These methods will enable zero-defect manufacturing starting at lot one. Furthermore, design and simulation methods that enable and support such multi-physics and multimodal manufacturing must be addressed.

Additive manufacturing can provide structural solutions for smart components, modules and systems integration that are not feasible based on traditional methods. Although additive manufacturing also improves manufacturing flexibility, solutions for the cost-efficient scaling of these fabrication methods have to be addressed. 3D component, module and system integration methods will need to be developed to provide greater functionality and miniaturisation in a cost-effective and scalable way (e.g. in RF front-ends), especially for high millimetre wave frequencies, enabling novel beyond-5G telecom solutions and photonics packaging.

Flexible electronics are moving towards structural electronics and stretchable electronics. Structural electronics consists of electronics manufactured on flexible substrates, embedded in a material matrix (plastics, glass or high-pressure laminates), resulting in a self-supporting functional element. Structural electronics are introducing new integration technologies that can produce functional systems within irregular shaped surfaces and 3D architectures. Use cases will broaden from current touch panels to RF antennas, control electronics, embedded lighting, sensors and energy harvesting. Stretchable electronics are already being demonstrated in wearable electronics as body-worn skin patchable devices and in smart textiles (integration of various sensors and electronics on textile). To achieve their full potential, wearable electronics (hardware) must become soft, lightweight, thin and conformable to the body, innovation that is dependent on significant development activities. Another vision is the integration of optics and photonics into flexible or even stretchable devices. However, this also creates large technical hurdles since optical performance relies on geometric key figures that are not fixed in flexible/stretchable electronics. These concepts are limited by a lack of fundamental understanding of material and component interfaces (i.e. rigid-stretchable and flexible-stretchable) and very limited reliability data available globally. In addition, piloting and fabrication facilities and capacities need to be developed.

1.2.4.3.3 Key focus areas of technologies, manufacturing and integration processes

- Robust heterogeneous 3D integration of sensors, actuators, electronics, communication, RF front-end components, energy supply (including fluidics and photonics), low vertical form factor (<100 μm) and the miniaturisation of external matching networks through integration.
- Rapid prototyping and manufacturing technologies (additive manufacturing, etching, coating, 2D and 3D additive technologies, lamination, etc) and direct manufacturing.
- Use of flexible Si-substrates to form random bodies.
- Submicron LAE processes (nanoimprinting, reverse offset printing, etc)

- Additive transfer of heterogeneous components on various substrates (e.g. 3D additive manufacturing of ICs on top of PCBs).
- Chips, passives and other components embedded in substrates (e.g. SoC, SiP).
- Embedding of power sources (batteries, energy harvesting transducers, supercaps, etc) into a package (PwrSiP) and on a chip (PwrSoC).
- Quantum components, sensors and technologies for quantum system integration (e.g. superconducting, photonics).
- Highly miniaturised engineering and computer technologies with biochemical processes and bio-mimicking (bio-hybrids, fluidics, etc).
- Flexible and stretchable devices, substrates (e.g. PDMS, TPU) and interconnections, and associated hybrid integration methods and structural electronics (in glass, plastics, laminates, etc).
- Transfer, assembly and bonding/soldering of heterogeneous components on flexible and stretchable substrates.
- Photonic system integration based on silicon photonics (and other substrates), hybrid integration to photonic systems, including RF, MEMS/NEMS, sensors, etc.
- Enabling electronic-photonic systems by heterogeneous integration (III-V, ferroelectrics, ultra-low-loss waveguide materials).
- Automation and customisation (towards Industry 4.0) in component, module and system manufacturing.
- Manufacturing and health monitoring tools (including tests, inspection and self-diagnosis) for components, modules and systems, enabling zero-defect manufacturing.
- Automated manufacturing equipment for flexible substrates (e.g. roll-to-roll manufacturing) and testing tools for electrical and non-electrical properties.

1.2.4.4 Major challenge 4: Decarbonisation and recyclability

1.2.4.4.1 State of the art

As increased integration will cause the borders between components, modules and systems to become blurred, and more diverse and complex materials are used at each level, the dismantling of systems into their constituent components at the end of their useful life will become increasingly difficult. Design for repair, re-use and recycling is required, as well as other technologies that should be considered to produce smart systems not only as an enabler for, but also an element of, the circular economy. ECS-boosted smart sustainability leads to reduced emissions for transport and manufacturing industries and general decarbonisation, mostly by electrification and the use of CO_2-neutral fuels. Designing higher performing and longer-lasting materials and devices will also result in less material usage and a lower lifecycle carbon footprint.

1.2.4.4.2 Vision and expected outcome

Future ECS products must be environmentally friendly, which means that production and dismantling have to follow future regulations. Activities must start by ensuring recyclability (eco-design, environmentally friendly materials and manufacturing), employing a low CO_2 footprint over the whole lifecycle to facilitate the move to a circular economy, wherever possible. Activities will be on:

- upstream considerations for dismantling, materials separation and recycling.
- compostable and biodegradable materials.
- lifetime extension and system health monitoring.
- (predictive) maintenance, repair, upgrading, reconfiguring, recharging, retrofitting and re-use.

- decarbonisation of the production of raw materials, transport of goods and manufacturing processes (such as through electrification and the use of CO_2-neutral fuels).

The concept of decarbonisation and recyclability (carbon dioxide removal, CDR) is rapidly becoming an adequate solution for overcoming the enormous number of diverse compounds resulting from an integrated system. Incineration is currently the only "recovery" strategy used to dispose of an integrated system once it is broken. The development of integration processes based on new design tools will allow the dismantling of compounds, and the recycling of materials (urban mining) is essential. Therefore, system design techniques need rethinking to use multifunctional components and modules. Recycling technologies, as well as new approaches to second life and re-use, have to be advanced.

Another idea is to develop new approaches in terms of lifecycle assessment (LCA), lifetime assessment or advanced diagnostic methods to properly address second life and re-use. However, this protocol should also be made available to consumers, which will help them feel part of the CDR. This will also have an influence on our economy since industry and the consumer will be forced to cooperate with each other.

The use of new environmentally friendly materials (or compostable/biodegradable materials) has to be seriously considered to replace existing materials with low recyclability in the near future. The use of these materials can easily be extended to other parts of the system, and the development of biodegradable materials can also contribute to solving the problems of recyclability.

1.2.4.4.3 Key focus areas of decarbonisation and recyclability

- Designing and developing integration processes that allow dismantling and material recycling (urban mining).
- Recycling technologies (e.g. for precious metals), second-life scenarios, repair, re-purposing and re-use approaches.
- Design tools for optimised use and recycling strategies for materials, multifunctional components and modules, concept of modularity and re-use of components.
- New environmentally friendly, biodegradable or compostable materials (biodegradable materials may even be required in specific cases, such as in medical implants).
- Condition monitoring (usage as well as health) for repair, maintenance and updating of systems is required, as new business models based on servitisation and pay-per-use schemes for consumer and capital goods.
- Advanced diagnosis methodologies (LCA, lifetime assessment) to enable second life, re-purpose and re-use.

1.2.5 TIMELINE

The following table illustrates the roadmaps for **Components, Modules and Systems Integration**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Physical and functional integration	**Topic 1.1:** Sensing, imaging and actuation	• MEMS/NEMS • Micro-optics, MOEMS • Photonic sensing • Imaging systems • Lidar/radar • Selective gas-sensing fluidics • Disease monitoring and diagnostics platforms (in vitro, wearables) • Quantum principles (also at room temperature)
	Topic 1.2: Communications	• Real-time, low-latency • Photonics • EMI • 5G, 6G
	Topic 1.3: Energy and thermal management	• Advanced and active cooling systems • Energy harvesters • Energy storage • Low/zero power
	Topic 1.4: Information processing	• Security and privacy • Explainable AI, edge computing • Hybrid modelling (physical and data-driven)
Major challenge 2: Materials	**Topic 2.1:** Bulk materials	• Functional materials (piezo, ceramics, polymers, glass, meta-materials) • Organic and bio-compatible materials • Compostable and biodegradable materials • Materials enabling recycling and repair • Replacement materials to comply with RoHS
	Topic 2.2: Surface materials	• Protective coatings • Multifunctional coatings • Self-cleaning • Replacement materials to comply with RoHS
	Topic 2.3: Material properties	• Database for simulation and reliability

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• MEMS/NEMS • Micro-optics, MOEMS • Photonic sensing • Hyperspectral imaging • Selective detection of allergens, residues • Fluidics • Disease monitoring and diagnostic platforms (in vitro, wearables) • Drug delivery • Quantum principles (also at room temperature)	• Advanced MEMS/NEMS • Advanced photonics • Convergence of sensing principles (e.g. thermal, optical cameras with lidar/radar) • Advanced fluidics • Multifunctional healthcare support systems (wearables, implants) • Quantum principles (also at room temperature)
• Real-time, low latency • Advanced photonics • EMI • 6G and beyond • THz communication	• Quantum internet and cryptography • Advanced photonics • Beyond 6G • THz communication
• Energy harvesters • Energy storage • Low/zero power	• CO_2-neutrality and circular economy for ECS
• Integration of information processing close to data acquisition • Hardware solutions for security and privacy • AI, edge computing • Quantum computing • Quantum simulation	• Low-power AI • Neuromorphic computing • Quantum computing • Quantum simulation
• Functional materials (piezo, ceramics, polymers, glass, meta-materials) • Organic and bio-compatible materials • Compostable and biodegradable materials • Photonic materials • Materials for quantum principles	• Materials for advanced MEMS, NEMS (including wearables and implants) • Materials for advanced photonics • Materials for quantum principles
• Protective coatings • Multifunctional coatings • Self-cleaning	• Materials for advanced photonics • Materials for quantum principles
• Database for simulation and reliability	• Database for simulation and reliability

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 3: Technologies, manufacturing and integration processes	**Topic 3.1:** Technologies	• Embedding of components into several types of substrate • System health monitoring • Self-diagnosis • Fluidics • Photonics • Flexible electronics
	Topic 3.2: Manufacturing	• I4.0 • Printing, lamination • Additive manufaturing
	Topic 3.3: Integration processes	• Heterogeneous integration • Rapid prototyping • Automation • Customisation
Major challenge 4: Decarbonisation and recyclability	**Topic 4.1:** Decarbonisation	• Electrification, use of CO_2-neutral fuels • CO_2-neutral production
	Topic 4.2: Recyclability	• Materials for recycling • Dismantling • Separation • Lifecycle analysis • Designs for re-use

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Bio-hybrid • Fluidics • Photonics • Flexible electronics • Quantum technologies	• Advanced photonics • Stretchable electronics • Quantum technologies
• I4.0 • Scalable and flexible manufacturing (lot one) • Zero-defect manufacturing	• Scalable and flexible manufacturing (lot one) • Zero-defect manufacturing
• Heterogeneous integration • Integration for harsh environments	• Maximum functional integration in minimum volume/footprint
• Decarbonisation in mining and processing of raw materials	• CO_2-neutral economy
• Use of compostable and biodegradable materials	• Circular economy

1.2.6
SYNERGY WITH OTHER THEMES

Smart components, modules and systems are key elements in a wide range of activities in all **Application** sections. Conversely, the new and advanced applications described there will also give rise to new functionalities and further advances in integration technologies. Most components, modules and systems integration is based on process technologies, equipment, materials and manufacturing; furthermore, simultaneous development and co-design is necessary with embedded software and SoS technologies, as well as close cross-links to the inter-sectional technologies: **AI, Connectivity, Architecture and Design and Quality, Reliability, Safety and Cybersecurity**. Thus, the field of PFI draws upon key enabling technologies and integrates knowledge from many disciplines. In addition, PFI bridges the gap between components, modules and functional, complex systems. As the development of smart components, modules and systems will benefit from progress in all other technological disciplines, the synergies should not only be in the multidisciplinary development of the technologies, but also in the building of ecosystems (people and infrastructure). This is where all stakeholders can guide and influence each other, and collaborate to assist in the development of optimised system- and application-oriented solutions.

1.3

Foundational Technology Layers

EMBEDDED SOFTWARE AND BEYOND

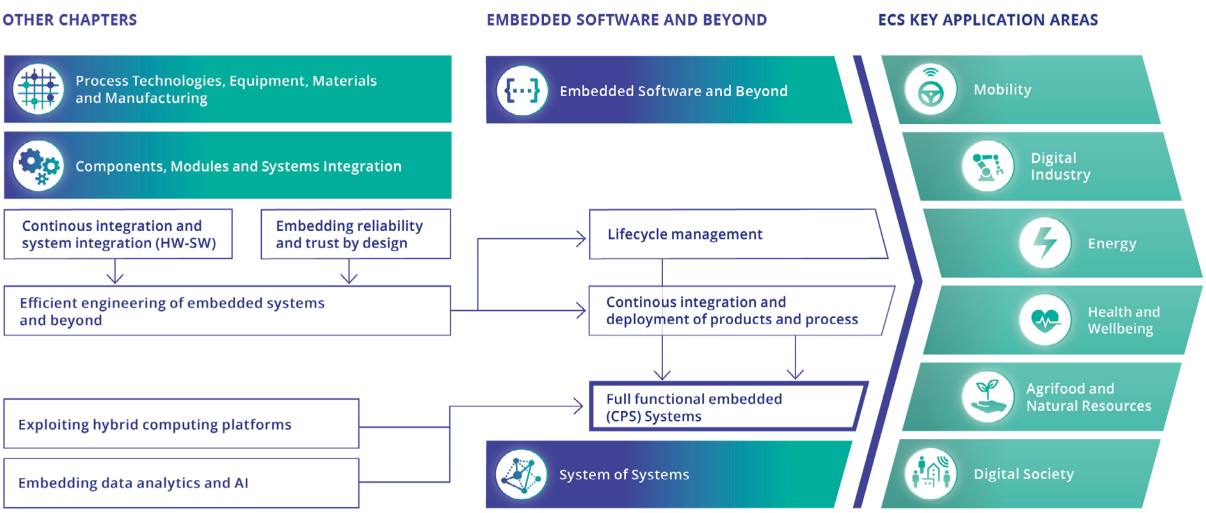
1.3.1
SCOPE

Introduction

According to the Artemis/Advancy report (Advancy, 2019), embedded software technology and software engineering tools are part of the six technology domains for embedded intelligence. Embedded software enables embedded and cyber-physical systems (ECPS) to play a key role in current and future solutions for digitalisation almost in every vertical domain. The reason for this section being entitled **Embedded Software and Beyond** is to stress that embedded software is not only for a system's internal intelligence, but also so it can communicate with other systems and to act on external events. Embedded intelligence is the ability of a system or component to reflect on its own state (e.g. operational performance, usage load, environment), and as such is a necessary step towards the level of digitalisation that is aimed for.

Figure F.11 illustrates the role and positioning of the **Embedded Software and Beyond** section in the ECS-SRIA. The section on **Components Modules and System Integration** focused on functional hardware components and systems that compose embedded and cyber-physical systems (CPS) considered in this section. While the **System of Systems** (SoS) section is based on independent, fully functional systems, products and services (which are also discussed in this section), they are also the constituents of SOS solutions. This section is also linked to the **Architecture and Design: Methods and Tools** section, which examines engineering processes, methods and tools, while this section focuses more on the engineering aspects of **Embedded Software and Beyond**.

From a functional perspective, ECPS role in complex systems is becoming increasingly dominant (in cars, trains, airplanes, health equipment, etc) because of the new functionalities they provide (including autonomy) and the quality properties (safety, security, reliability, dependability, and, ultimately, trustworthiness) they need to exhibit. They are also required for the interconnection and interoperability of SoS (smart cities, air traffic management, etc). Due to their close integration with



Positioning of the Embedded Software and Beyond section in the ECS-SRIA **F.11** the physical world, ECPS must take into account the dynamic and evolving aspect of their environment to provide deterministic, high-performance and low-power computing, as well as efficient processing of intelligent algorithms. Increasingly, software applications will run as services on distributed SOS involving heterogeneous devices (servers, edge devices, etc) and networks, with a diversity of resource restrictions. In addition, ECPS require the capability to evolve and adapt during their lifecycle – e.g. through updates of software or hardware in the field and/or by learning. Building these systems and guaranteeing their safety, security, reliability, long lifetime and certification requires innovative technologies in the areas of modelling, software engineering, model-based design, verification and validation (V&V) technologies, and virtual engineering for high-quality, certifiable ECPS that can be produced (cost-)effectively (cf. *Section 2.3*, **Architecture and Design: Methods and Tools**). Owing to all these factors, ECPS are an irreplaceable part of the strive towards digitalisation.

Scope

Software engineering processes are of increasing importance to enable new and emerging embedded and cyber-physical systems. To enable ECPS functionalities and their level of interoperability, the engineering process will be progressively automated and needs to be integrated in advanced SoS engineering covering the whole product during its lifetime covering functional and non-functional requirements like security, safety, evolution, maintenance, etc. This requires innovative technologies can be adapted to the specific requirements of ECPS and, subsequently, SoS.

Further complexity will be imposed by the introduction of Artificial Intelligence (AI), machine-to-machine (M2M) interaction, new business models and monetisation at the edge. Here, ECPS engineering processes (methods and tools, quality assurance, testing, V&V techniques and methods on all levels of individual IoT and in the SoS domain) solely depend on software technologies and software engineering tools.

Producing industrial software, and embedded software in particular, is not merely a matter of writing code: to be of sufficient quality, it also requires a strong scientific foundation. Modern software used in products such as cars, airplanes, operation robots, banks, healthcare systems and the public sector comprises millions of lines of code. To produce this level of software, many challenges have to be overcome. How do we develop this software and simultaneously manage its complexity? Also, how do we ensure the correctness and security of this software, as human wellbeing, economic prosperity and the environment depend on it? How can we guarantee that software is maintainable and usable for decades to come? Finally, how can we construct the software efficiently, effectively and sustainably?

Despite the fact that such software impacts everyone everywhere, the effort required to make it reliable, maintainable and usable for longer periods is routinely underestimated. As a result, every day there are news articles about expensive software bugs (Jones, 1997; Leveson and Turner, 1993) and over budget or failed software development projects. Difficulties further increase when legacy systems are considered: information and communications technology (ICT) systems contain crucial legacy components at least 30 years old, which makes maintenance difficult, expensive and sometimes even impossible.
The scope of this section is research that facilitates engineering of ECPS, enabling digitalisation through the feasible and economically accountable building of SoS of the desired quality. It considers:

- challenges that arise as new applications of ECPS emerge.
- continuous integration and deployment of products and processes.
- engineering and management of ECPS during their entire lifecycle.

1.3.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

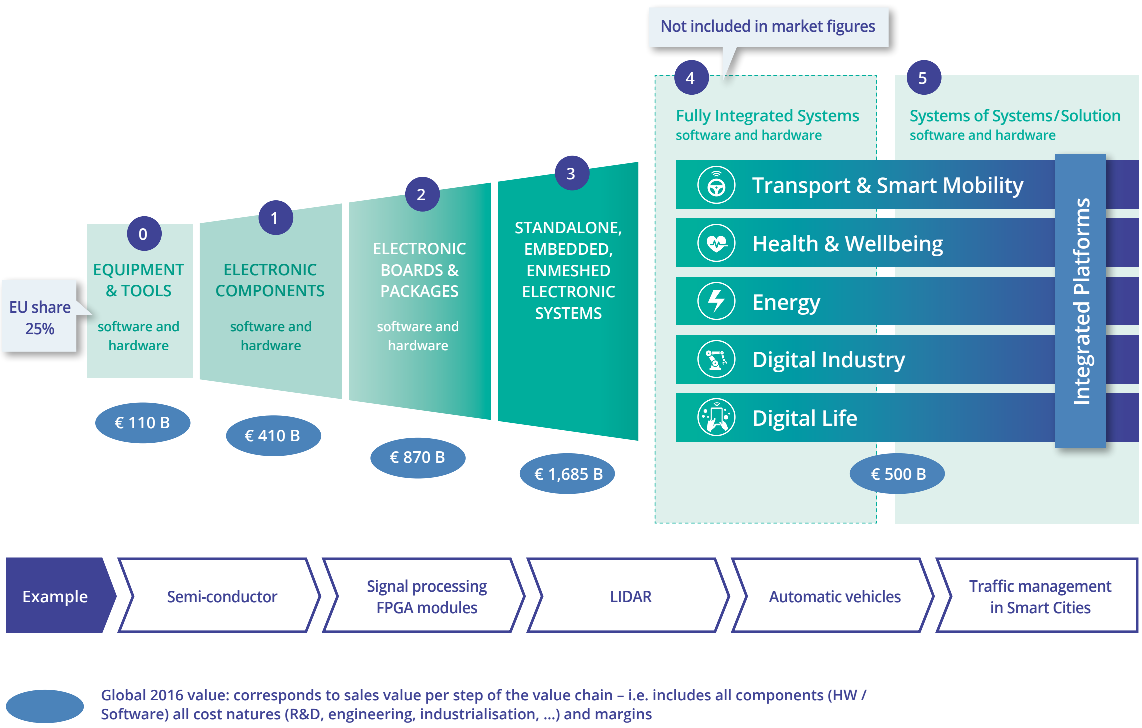
Computing systems are increasingly pervasive and embedded in almost all objects we use in our daily lives. These systems are often connected to (inter)networks, making them part of SoS. ECPS bring intelligence everywhere, allowing data processing on the site/edge, improving security and privacy and,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

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

Application breakthroughs

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

Following a similar approach, it has been possible to extend the functionalities of mobile phones and smart watches, which today can count your steps, keep track of your route, of your health, inform you about nearby restaurants, etc, all based on a few extra hardware sensors and a myriad of embedded applications. Indeed, the trend is to replace specialised hardware application with software running on



F.12 *Advancy (2019) report: value creation.*

generic computing hardware and supported by application-specific hardware, such as AI accelerators, neural chips, etc. This trend is also contributing to the differentiation of the value creation downstream and upstream, as observed in the Advancy report (see *Figure F.12*).

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

- Improved multidisciplinary embedded software architecting and design.
- Increased efficiency and an effective product innovation process.
- Enabled adaptable systems by adaptable embedded software.
- Improved system integration and testing.
- Embedded software, and embedded data analytics and AI, to enable system health monitoring, diagnostics and preventive maintenance.
- Data privacy and data integrity.
- Model-based embedded software design and engineering as the basis for managing complexity in SoS.
- Embedded software architecting/design for (systems) qualities, including reliability, trust, safety, security, performance, installable, diagnosable, sustainability, re-use (cf. *Section 2.3* **Architecture and Design: Methods and Tools**).
- Upgradability and extending useful life.

1.3.3
STRATEGIC ADVANTAGE FOR THE EU

The ambition of growing competences by researching pervasive embedded software in almost all devices and equipment is to strengthen the digitalisation advance in the EU and the European position in embedded intelligence and ECPS, ensuring the achievement of world-class leadership in this area through the creation of an ecosystem that supports innovation, stimulates the implementation of the latest achievements of cyber-physical and embedded systems on a European scale, and avoids the fragmentation of investments in research and development and innovation (R&D&I) (Itea Artemis-IA, 2013).

European industry that is focused on ECS applications spends about 20% of its R&D efforts in the domain of embedded digital technologies, resulting in a cumulative total R&D&I investment of €150 billion for the period 2013–20. The trend in product and solutions perspective estimates a growth from €500 billion to €3.100–11.100 billion (Advancy, 2019), which will be greatly determined by embedded software (30%).

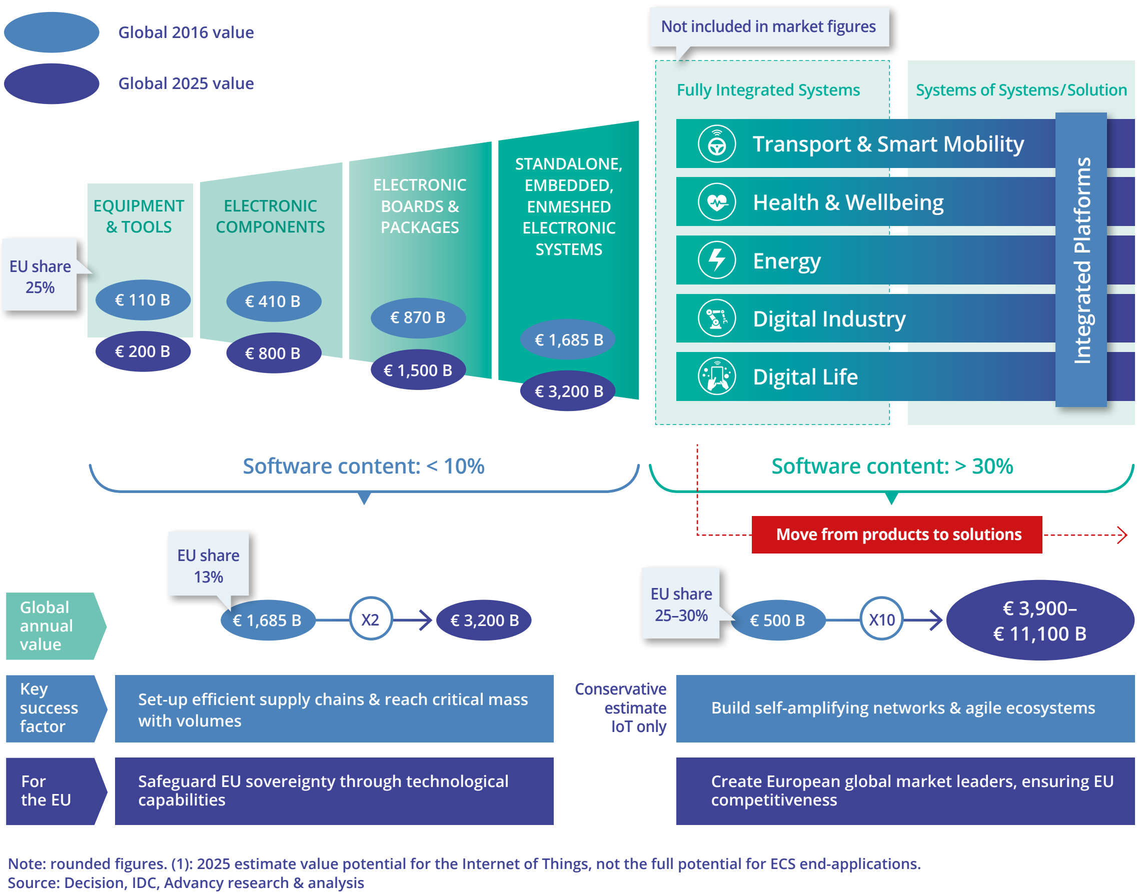
About 60% of all product features will depend on embedded digital technologies, with an estimated impact on the European employment of about 800,000 jobs in the application industries directly resulting from its development.

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

1.3.4
MAJOR CHALLENGES

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

- **Major challenge 1:** Efficient engineering of software.
- **Major challenge 2:** Continuous integration and deployment.
- **Major challenge 3:** Lifecycle management.
- **Major challenge 4:** Green Deal.
- **Major challenge 5:** Embedding data analytics/AI.
- **Major challenge 6:** Software reliability and trust.



F.13 *Global and European value chain 2016–25 (Source: Embedded Intelligence : Trends and Challenges, A Study by Advancy, Commissioned by ARTEMIS Industry Association, March 2019).*

1.3.4.1 Major challenge 1: Efficient engineering of embedded software

1.3.4.1.1 State of the art

Embedded software engineering is frequently more a craft than an engineering discipline, which results in inefficient ways of developing embedded software. This is visible, for instance, in the time required for the integration, verification, validation and releasing of embedded software, which is estimated to exceed 50% of the total R&D&I expenses (Advancy, 2019). Embedded software can be classified in two major categories.

- Hardware(-related) software: Embedded software that is allowed to "use" hardware functionalities (e.g. the battery management software in a car, or the image-capturing algorithms of an x-ray source). This category of software often follows the design flow of the hardware, and needs to adapt to imperfect specifications or realisations.
- Embedded software determining ECPS functionalities: Such as in medical image processing, right up to completely embedded applications or autonomous driving software.

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

1.3.4.1.2 Vision and expected outcome

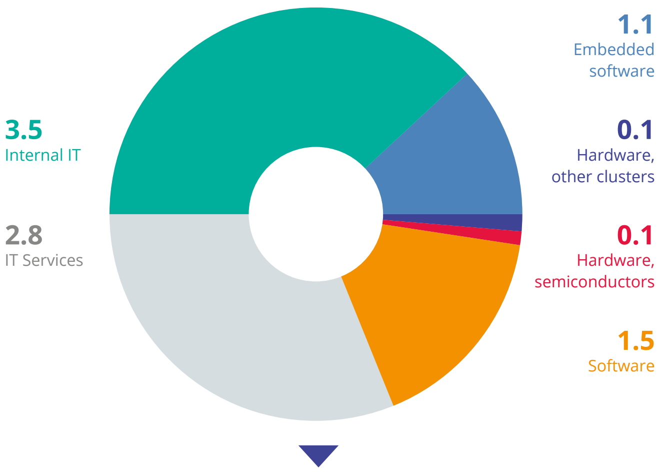
The demands of embedded software is higher than we can humanly address and deliver, exceeding human scale in terms of evolution speed, volume and variety, as well as in managing complexity. The field of embedded software engineering needs to mature and evolve to address these challenges and satisfy market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

(A) From embedded software engineering to embedded systems engineering

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

Instead of focusing just on the efficiency of embedded software engineering, we envision the field evolving into a system engineering mindset of which software is one element. Rather then silos and handovers at the discipline's borders, we expect tools to support the integration of different engineering artefacts and enable better development of quality requirements – such as performance, interoperability, security and reliability – from a system level. New methods and tools will need to be developed to be able to reason and work with the specific software in a system engineering context.

DIRECT JOB CREATION – EUROPE (2012, M JOBS)



Number of jobs in European Digital Technology: 9.1 m

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

F.14

(B) Integration of embedded software

To ensure software development is more effective and efficient, it is necessary to place greater focus on integrating embedded software into a fully functional system. First, innovation in continuous and system integration must include more effective ways of integrating legacy components into new systems (see also D). Second, for the integration of data and software, the embedded software running in the field has to generate data (such as on performance, system health, quality of output, compliance to regulations, etc) that can be re-used to improve its quality and performance. By improving this, the data and software integration can not only improve the efficiency of embedded software itself, but also the internal coordination and orchestration between components of the system by ensuring a rapid feedback cycle. Third, with regard to the integration of views, as mentioned in (A) above, a system engineering approach also requires these in models, but also in aspects such as safety, security and performance.

(C) Using abstraction and virtualisation

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

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

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

(D) Resolving legacy

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

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

1.3.4.1.3 Key focus areas

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

— **Model-based software engineering:**

- Model-based software engineering enabling systems to become part of SoS.
- Model inference to enable re-use of existing subsystems in SOS.
- Model-based testing that takes the re-use of uncontrolled systems into account.
- Embedded software architectures to enable SoS.

— **Constraint environments:**

- Knowledge-based leadership in design and engineering.
- Resource planning and scheduling (including multi-criticality, heterogeneous platforms, multicore, software portability).
- Simulating and the impact of using open source.
- Design for software evolution over time, while catering for distinct phases.
- Exploiting hybrid compute platforms, including efficient software portability.

— **Software technology:**

- Virtualisation as tool for efficient engineering.
- Interface management enabling systems to become part of SoS.
- Technology for safe and dependable software ecosystems.

— **SW engineering tools:**

- Middleware controlling embedded (mobile) hardware compilers, with links to new hardware.
- Added value of, and embedding AI in, software architecture and design.
- Programming languages for developing large-scale applications for embedded systems.

1.3.4.2 Major challenge 2: Continuous integration of embedded software

1.3.4.2.1 State of the art

It is fair to assume that most future software applications will be developed to function as a part of a certain platform, and not as standalone components. In some embedded system domains, this idea has been a reality for a decade (e.g. in the AUTomotive Open System ARchitecture (AUTOSAR) partnership, which was formed in 2003). However, guaranteeing quality properties of the software system (e.g. in safety and security) is a challenging task, and one that only becomes more complex as the size of software applications grows. Although we are aiming towards integration on the level of SoS, we are still struggling with the integration of code changes from multiple contributors into a single software project.

One aspect of the problem relates to the design of SoS (Kazman et al, 2013), which are assumed to be composed of independent subsystems but over time have become dependent. The second aspect relates to the certification of such systems, for which it is necessary to develop a set of standards. The most obvious example of how the software industry is too immature to embrace and integrate with new fields is the integration of AI into software systems. Although AI is a software-enabled technology, there are still many issues on the system level when it comes to its integration into software systems – for instance, it is particularly challenging to certify such systems. Some of the existing initiatives that are moving towards certification include SAE J3016, which recommends a taxonomy and definitions for terms related to automated driving.

Finally, it is also necessary to adopt integration practices in engineering processes. Although methodologies already exist to achieve this (such as DevSecOps and ChatOps), these mostly relate to software production. It is necessary for them to be scaled, and complemented with architectural approaches to manage the complexity of ECPS. System architecting must become a regular engineering activity.

1.3.4.2.2 Vision and expected outcome

Europe is facing a great challenge in the lack of platforms that are able to adopt embedded applications developed by individual providers into an ecosystem (cf. Reference Architectures and Platforms in *Section 2.3*). As software systems evolve towards distributed computing and microservice-based architectural paradigms, it becomes even more important to tackle the challenges of integration at the design level. The main challenges here are to ensure the adequate functionality of integrated systems (which is partially solved by the microservices approach), while ensuring key quality properties such are safety and security (which is becoming increasingly complex and neglected as we adopt approaches that facilitate integration on the functional level).

Therefore, it is essential to tackle these challenges by: (i) providing sets of recommended design patterns; (ii) avoiding anti-patterns; and (iii) ensuring there is methodology support for the integration from which the engineers of such systems can benefit. The first goal implies resolving and pre-empting as many of the integration challenges on the design level as possible. The second goal is facilitating communication between different stakeholders to emphasise the need for quality properties of such systems, and to enable mechanisms that raise concerns sufficiently early to be prevented while minimising potential losses.

On the development level, it is key to enhance the existing software systems development methodologies to support automatic V&V processes for new features as they are being introduced into the system. At this level, it is also necessary to enable continuous use of software system architecture to manage the complexity that arises from such integration efforts.

1.3.4.2.3 Key focus areas

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

— **Continuous integration of embedded software:**
  - System integration (HW/SW) and HW/SW co-development (increasingly new technologies have to be integrated).
  - Virtualisation as a tool for managing efficient integration and validation of configurations, especially for shared resources.

— **Verification and validation of embedded software:**
  - (Model) test automation to ensure efficient and continuous integration of CPSs.
  - Enabling secure updates and extending useful life (DevOps).
  - Continuous integration, verification and validation (with and without AI).
  - Continuous certification with automated testing (especially the focus on privacy and security influencing the innovation in certification).

— **Evolvability of embedded software:**
  - Technology for keeping systems maintainable and adaptable considering embedded constraints with respect to resources, timing and cost.
  - Certification of safety-critical software in CPSs.

1.3.4.3 Major challenge 3: Lifecycle management of embedded software

1.3.4.3.1 State of the art

Complex systems such as airplanes, cars and medical equipment are increasingly having a long lifetime, often up to 30 years. The cost of keeping these embedded systems up to date and relevant is often time-consuming and costly. This is becoming more complex due to most of these systems becoming cyber-physical systems, meaning that they link the physical world with the digital world, and are often interconnected with each other or to the internet.

Embedded software has to be maintained and adapted over time. If this is not effectively achieved, the software becomes overly complex, with prohibitively expensive maintenance and evolution, until they are no longer sustainable. We must break this vicious cycle and find new ways to create software that is long-lasting and which can be cost-efficiently evolved and migrated to new technologies. Practical challenges that require significant research in software sustainability include: (i) organisations losing control over software; (ii) difficulty in coping with modern software's continuous and unpredictable changes; and (iii) dependency of software sustainability on factors that are not purely technical.

1.3.4.3.2 Vision and expected outcome

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

How can the software facilitate change by design? There are several socio-technical aspects that can help, or hinder, software change. Many software maintenance problems are not actually technical but people problems. We need to be able to organise the development team (group, community, etc) in such a way that it embraces change and facilitates maintenance and evolution, not only immediately after the deployment of the software but for the decades that follow to ensure continuity.

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

1.3.4.3.3 Key focus areas

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

— **Rejuvenation of systems:**
- Software legacy and software rejuvenation (technical debt).
- Design for X (test, evolvability, diagnostics, adaptability, etc).
- End-of-life and evolving off-the-shelve/open source (hardware/software).

— **Digital twinning:**
- Virtualisation as a tool for dealing with legacy systems.
- Approaches to reduce re-release/re-certification time.
- Distinct core system versus applications and services.
- Design for X (test, evolvability, diagnostics, adaptability, etc).

— **Managing complexity over time:**
  - Interplay between legacy software and new development approaches.
  - Vulnerability of connected systems.
  - Continuous certification of updates in the field (reduce throughput time).
  - Diagnostics of systems in the field.

1.3.4.4 Major challenge 4: Embedding data analytics and Artificial Intelligence

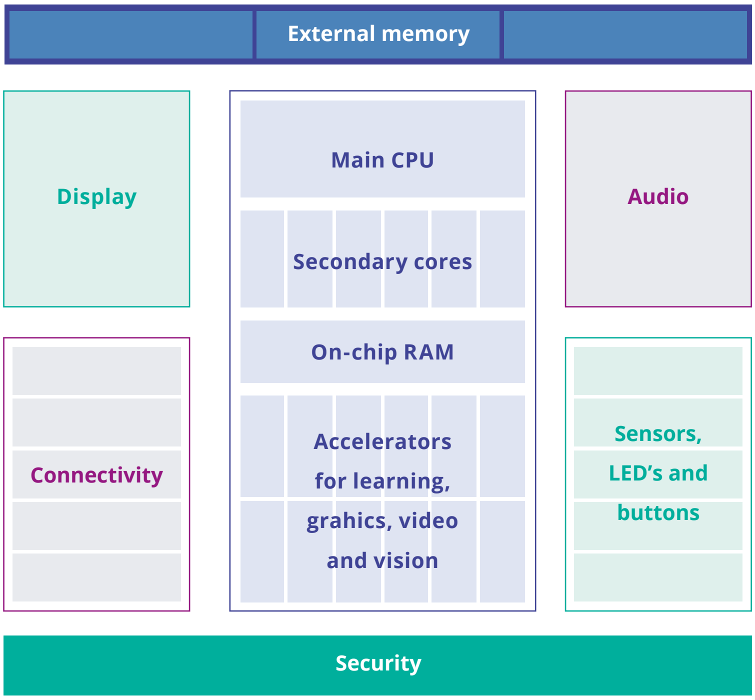
1.3.4.4.1 State of the art

For various reasons – including privacy, energy efficiency, latency and embedded intelligence – processing is moving towards the edge, and the software stacks of embedded systems need to support more and more analysis of data captured by the local sensors and to perform AI-related tasks. As detailed in the section **Artificial Intelligence, Edge computing and Advanced Control**, non-functional constraints of embedded systems, such as timing, energy consumption, low memory and computing footprint, being tamperproof, etc, need to be taken into account compared to software with similar functionalities when migrating these from cloud to edge. For efficiency reasons, very intensive computing tasks (such as those based on deep neural networks, DNNs) are being carried out by various accelerators embedded in systems on a chip (SoCs). Although the "learning" phase of a DNN is still mainly done on big servers using graphics processing units (GPUs), local adaptation is moving to edge devices. Alternative approaches, such as federated learning, allow for several edge devices to collaborate in a more global learning task. Therefore, the need for computing and storage is ever-increasing, and is reliant on efficient software support.

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

Once developed (on servers), a neural network has to be tuned for its embedded target by pruning the network topology using less precision for operations (from floating point down to 1-bit coding) while preserving accuracy. This was not a concern for the "big" AI development environment providers (e.g. Tensorflow, PyTorch, Caffe2, Cognitive Toolkit) until recently. This has led to the development of environments designed to optimise neural networks for embedded architectures[20], but Google, Apple, Facebook, Amazon and Microsoft (GAFAM) and Baidu, Alibaba, Tencent, Xiaomi (BATX) are now increasingly aware of the move towards the edge. For example, Google's Tensorflow Lite is now dedicated for targeting embedded devices. The Google Assistant will also work locally on smartphones due to a "completely new speech recognition and language understanding models, bringing 100GB of models in the cloud down to less than half a gigabyte[21]", allowing real-time performance, lower latency and the ability to work even without a connection. NVIDIA's TensorRT has the same goal of optimising the inference phase for running on embedded GPUs.

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



Data analytics and Artificial Intelligence require dedicated embedded hardware architectures **F.15**

1.3.4.4.2 Vision and expected outcome

European semiconductor providers lead a consolidated market of microcontroller and low-end microprocessor for embedded systems, but are increasing the performance of their hardware, mainly driven by the automotive market and the increasing demand for more performing AI for advanced driver-assistance systems (ADAS) and self-driving vehicles. They are also moving towards greater heterogeneity by adding specialised accelerators.

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

←

[20] *Such as N2D2, https://github.com/CEA-LIST/N2D2*

[21] *https://www.blog.google/products/assistant/next-generation-google-assistant-io/*

1.3.4.4.3 Key focus areas

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

— **Federated learning:**
- Create federated learning at the edge in heterogeneous distributed systems (analysis, modelling and information gathering based on local available information).
- Federated intelligence at the edge (provide context information and dependability based on federated knowledge).

— **Data streaming in constraint environments:**
- Feed streaming data into low-latency analysis and knowledge generation (using context data to generate relevant context information).

— **Embedding AI accelerators:**
- Accelerators and hardware/software co-design to speed up analysis and learning (patter analysis, detection of moves (2D and 3D) and trends, lighting conditions, shadows, etc).
- Actual usage-based learning applied to accelerators and hardware/software co-design (automatic adaptation of parameters, adaptation of dispatch strategies, or use for new accelerators for future system upgrades).

1.3.4.5 Major challenge 5: Green Deal and embedded software

1.3.4.5.1 State of the art

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

1.3.4.5.2 Vision and expected outcome

It is evident that energy/power management has to be analysed with reference to the context, underlying hardware and overall system functionalities. The coordinated and concentrated efforts of a system architect, hardware architect and software architect alone should help introduce energy-efficient systems. The tight interplay between energy-oriented hardware and energy-aware software calls for innovative structural, functional and mathematical models for analysis and design. Model-based software engineering practices, supported by appropriate tools, will definitely accelerate the development of modern complex very large-scale integration (VLSI) systems operating under severe energy constraints.

1.3.4.5.3 Key focus areas

The following key focus areas have been identified for this challenge.
- Green-aware systems.
- Management of computation power on embedded hardware.
- Management of energy awareness of embedded hardware, embedded software with respect to embedded high-performance computing (HPC).
- Enabling technologies for the second life of (legacy) cyber-physical systems.

1.3.4.6 Major challenge 6: Embedding reliability and trust

1.3.4.6.1 State of the art

Two emerging challenges for reliability and trust in ECPS relate to computing architectures and the dynamic environment in which ECPS exist. The first challenge is closely related to the end of Dennard scaling (Hennessy and Patterson, 2019). In the current computing era, concurrent execution of software tasks is the main driving force behind the performance of processors, leading to rise of multicore computing architectures. As the number of transistors on a chip continues to increase (Moore's law is still alive), industry has turned to heavier coupling of software with adequate computing hardware, leading to heterogeneous architectures. The reasons for this coupling are the effect of dark silicon (Esmaeilzadeh et al, 2011) and better performance-to-power ratio than computing hardware specialised for specific tasks achieves. The main challenges for using concurrent computing systems in embedded systems remain: (i) hard-to-predict, worst-case execution time; and (ii) testing of concurrent software against concurrency bugs (Bianchi et al, 2018).

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

On the level of systems composed from embedded devices, the most important topics are the security, safety and privacy of sensitive data. Security challenges involve: (i) security of communication protocols between embedded nodes, and the security aspects on the lower abstraction layers; (ii) security vulnerabilities introduced by a compiler (D'Silva, 2015); and (iii) hardware-related security issues (Lipp et al, 2020). It is necessary to observe security, privacy and reliability as quality properties of systems, and to resolve these issues on a higher abstraction level by design (Sobhy et al, 2020).

1.3.4.6.2 Vision and expected outcome

European industry today relies on developed frameworks that facilitate production of highly complex embedded systems (for example, AUTOSAR in the automotive industry). However, such frameworks are exclusive to big companies that can afford to invest heavily into their systems, ensuring system quality properties such as safety, security and reliability.

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

Besides frameworks and platforms that enable easy and quick development of future products, the key enabler of embedded software systems is their interconnectivity. In this regard, the goal is to develop and make available to a wider audience software libraries, software frameworks and reference architectures that enable interconnectivity and integration of products developed on distributed computing architectures. These need to ensure, by design, the potential for monitoring, verification, testing and auto-recovery of embedded systems. One of the emerging trends to achieve this is the use of digital twins. Digital twins are particularly suitable for the verification of safety-critical software systems that operate in dynamic environments. However, development of models of digital twins remains an expensive and complex process, which has to be either improved or integrated as part of the standard engineering processes.

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

Apart from techniques that enable the testing and verification of developed systems and their parts, it is necessary to provide technologies that ensure reliability and correctness of system development. These activities consider providing tools and means for collaboration when developing such complex software systems – especially modelling approaches for capturing correctness criteria for dynamic System of Systems, against which it is then necessary to perform testing and verification.

1.3.4.6.3 Key focus areas

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

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

However, all these techniques are not very helpful if the systems are not secure and reliable by design. Therefore, it is necessary to investigate patterns and anti-patterns that influence reliability, security and privacy of embedded software systems.

- **Reliable software on new hardware (multi-core systems, GPUs, heterogeneous computing, field-programmable gate arrays (FPGAs), distributed computing architectures, including edge, fog and cloud processing):**
  - Code coverage of reliability tooling and porting.
  - Simulation and mock-up based approaches for handling concurrency.
  - Embedding reliability on a software system architecture level.

- **Robustness against unexpected uses:**
  - Trustworthy, secure, safe, privacy-aware.
  - Testing self-adapting systems using simulation.

- **Security and privacy as a service:**
  - To become part of the software architecture.
  - Means and techniques for continuous system monitoring and self-monitoring.

1.3.5
TIMELINE

The following table illustrates the roadmaps for **Embedded Software and Beyond**. The assumption is that topic in the cell means that technology should be ready (TRL 9–10) in that timeframe.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Efficient engineering of embedded software	**Topic 1.1:** Modelling-based software engineering	• Model-based software engineering enabling systems to become part of SoS
	Topic 1.2: Constraint environments	• Resource planning and scheduling • Design for software evolution over time
	Topic 1.3: Software technology	• Virtualisation as tool for efficient engineering • Technology for safe and dependable software ecosystems
	Topic 1.4: Software engineering tools	
Major challenge 2: Continuous integration of embedded software	**Topic 2.1:** Continuous integration	• DevOps modelling • Virtualisation
	Topic 2.2: Verification and validation	• Virtualisation of test platform
	Topic 2.3: Evolvability of embedded software	• Adaptable embedded software
Major challenge 3: Lifecycle management of embedded software	**Topic 3.1:** Rejuvenation of existing systems	• Software legacy and software rejuvenation • Design for rejuvenating systems in a later phase
	Topic 3.2: Digital twinning	• Virtualisation as tool for dealing with legacy systems
	Topic 3.3: Managing complexity over time	• Diagnostics of systems in the field
Major challenge 4: Embedding data analytics and AI	**Topic 4.1:** Federated learning	• Create federated learning at the edge in heterogeneous distributed systems
	Topic 4.2: Data streaming in constraint environments	• Feed streaming data into low-latency analysis and knowledge generation
	Topic 4.3: Embedding AI accelerators	• Accelerators and hardware/software co-design to speed up analysis and learning
Major challenge 5: Green Deal and embedded software	**Topic 5.1:** Green-aware software	
	Topic 5.2: Green-aware hardware	• Integration of green-aware in software integration
	Topic 5.3: Extending lifetime of products and services	• Rejuvenation technologies
Major challenge 6: Embedding reliability and trust	**Topic 6.1:** Reliability of software and new hardware	• Code coverage of reliability tooling and porting • Simulation and mock-up based approaches for handling concurrency
	Topic 6.2: Robustness (trustworthy, secure, safe, privacy-aware)	• Trustworthy, secure, safe, privacy-aware • Testing self-adapting systems using simulation
	Topic 6.3: Security and privacy as a service	• Design for security and privacy as a service

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Model inference to enable re-use of existing subsystems in SOS	• Model-based testing taking re-use of uncontrolled SOS into account
• Embedded software architectures to enable SoS	• Exploiting hybrid computer platforms, including efficient software portability
• Interface management enabling systems to become part of SOS	
• Middleware controlling dynamically embedded (mobile) hardware solutions • Compilers and link to new hardware	• Programming languages for developing large-scale applications for embedded SoS
• Simulation on a virtual platform	• Digital twin
• Model-based testing	
• Dynamical embedded software	• Autonomous embedded software
• End-of-life and evolving off-the-shelve/open source solutions	
• Enabling secure updates and extending useful life	• Distinct core system versus applications and services
• Continuous certification	• Interplay between legacy
• Federated intelligence at the edge	
	• Use of AI in autonomous systems
• Actual usage based learning applied for accelerators and hardware/software co-design	
• Design for green-aware products	
• Design for extending lifetime	
• Embed reliability on software architecture level	• Use of quantum computing
• Define a maturity model for robustness of embedded software and beyond	
• Architecture for security and privacy as a service	

1.3.6
SYNERGY WITH OTHER THEMES

Opportunities for joint research projects, including groups outwith the ECS community, can be expected in several sections of the **Application** chapter, the sections in the technology value stack and with cross sectional sections. There are strong interactions with the **System of Systems** section. In the **System of Systems** section, a reasoning model for system architecture and design is one of the main challenges. Part of system architecture and design is the division in which the system functions will be solved in hardware, and which will be solved in **Embedded Software**. **Embedded Software** can be divided into two parts: software enabling the hardware to perform, and software implementing certain functionalities. Furthermore, there are connections with the cross-technology sections, **Artificial Intelligence, Edge Computing and Advanced Contro**l, and the **Architecture and Design: Methods and Tools.** With respect to AI, applying AI in embedded solutions will be part of the **Embedded Software and Beyond** section, while innovating AI will be part of the **AI, Edge Computing and Advanced Control** section. With respect to the **Architecture and Design: Methods and Tools** section, all methods and tools belong there. The challenges of preparing useful embedded solutions will be part of the **System of Sytems** section and the **Embedded Software and Beyond** section. The embedded software solutions for new computing devices, such as quantum computing, will be part of the **Long-Term Vision** chapter.

1.4

Foundational Technology Layers

SYSTEM OF SYSTEMS

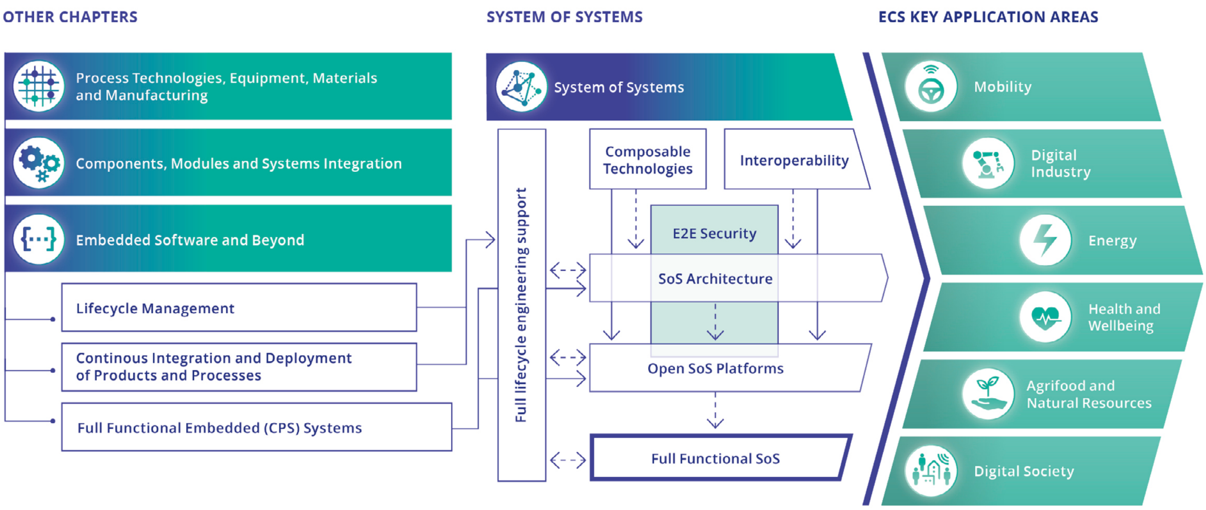
1.4.1
SCOPE

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

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

According to the definition of SoS (Maier, 1998), they must satisfy five characteristics: (i) the operational independence of constituent systems; (ii) the managerial independence of constituent systems; (iii) geographical distribution; (iv) emergent behaviour; and (v) evolutionary development processes. A system that does not satisfy these characteristics (specifically the first two) is not considered an SoS.

In modern hyper-connected digital solutions, systems rarely operate independently. On the contrary, the primary added value of these digital solutions is the cooperation between heterogeneous systems to solve more complex problems by exploiting the set of multi-technology, multi-brand and even multi-domain functionalities generated by the cooperation. While talking or reading ,SoS is typically pronounced entirely "System of Systems", so "an SoS" sounds odd. An SoS emerges from the composition/integration of multiple systems to perform a task or reach an objective that none of the constituent systems can perform or reach on their own. In the SoS, each constituent system is considered a "black box": it remains operationally and managerially autonomous and/or independent, relying on its hardware, software



Structure: System of Systems. (Source: EFECS-SRIA 2021)

F.16

and networking resources, and remaining focused on its own goals. At the SoS level, the constituent systems cooperate, coordinate and adapt to achieve the SoS goals, and to provide additional features, capabilities and functionalities unavailable in the constituent systems.

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

Like a nervous system – ie, partially centralised, distributed and peripheral – a software integration platform is a key element of a SoS, partially running on the enterprise side (e.g. in the cloud), and partially in the various geographically distributed entities of the SoS (including the edge). The integration platform is the element of the SoS that is "conscious" of the SoS in its integrity, and provides the functionalities to manage and operate the SoS (e.g. subsystems interfacing and integration, interoperability, full monitoring and control of the constituents embedded and CPS, operation management, engineering full lifecycle support, trust management, data acquisition and storage, data analysis and visualisation, etc).

SoS platforms even play an important role for the ECS value chain and the related ecosystem, representing the structural element that physically and virtually contributes to keeping all the elements bonded together. SoS platforms allow for control of the information flow, enabling the creation of added-value services and applications, contributing to the development of relations between the value chain stakeholders, as well as generating and implementing new business opportunities.

To create added value, an SoS need to be trustable, and here end-to-end security issues have to be properly taken into account. A secure SoS should be able to defend against both deliberate attacks and accidental threats, and also its misuse. Moreover, it is not enough to ensure that each of the constituent systems is secure in the pre-deployment phase, but also that the composed/integrated SoS, whose exact composition may be not known in advance, is secure. Dynamically adapting security requirements and risks mitigations should be considered over time, and in handling emergent behaviours arising due to the complex interactions among the constituents of the SoS.

Technical solutions in the SoS platform domain should be open and ensure a certain level of domain independency, simplifying their adoption and allowing their re-use in different vertical applications. At the same time, it is also unrealistic to imagine that a single SoS platform could drive an entire market because, considering the interdisciplinarity and complexity required to develop them, very seldom will a single vendor be able to provide a complete end-to-end and domain-independent solution. However, platform "competition" will at least have to identify a set of European solutions that covers key vertical domains.

1.4.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

There is a very strong market pull for systems of embedded and CPS in supply chains, smart grids, smart cities, etc, and there is also a similar situation for very complex systems such as autonomous cars, lithography machines, operation theatres, etc (Advancy, 2019).

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

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

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

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

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

Application breakthroughs

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

- interoperability of health data.
- the shift in focus from acute, hospital-based care to early prevention.
- strengthening where and how healthcare is delivered, supporting home-based care.
- stronger participation of citizens in their own care process, enhancing patient engagement.
- supporting the clinical workforce and healthcare consumers to embrace technology-enabled care.
- supporting cost-effective and high-quality healthcare that maximises a patient's overall outcomes.

Improved, secure safe and interoperable System of Systems will further support healthcare and wellbeing application breakthroughs regarding, for example:

- P4 healthcare deployment, enabling digital health platforms.
- the healthcare system paradigm transition from treatment to health prevention, enabling the shift to value-based healthcare.
- building a more integrated care delivery system, and supporting the development of the home as the central location of the patient.
- enhancing access to personalised and participative treatments for chronic and lifestyle-related diseases.
- enabling more healthy life years for an ageing population.

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

- achieving the Green Deal for mobility with the 2Zero goals of –37.5% CO_2 by 2030.
- increased road safety through the CCAM programme.
- competitiveness of the European industrial mobility digitalisation value chain.
- ensuring inclusive mobility for persons and goods by providing mobility access to everyone, with a focus on special needs.

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

- enabling necessary functional and data integration of the heterogenous energy grid landscape, from production, storage, transmission, distribution through to consumption.
- an energy supply infrastructure for e-mobility, digital life and industry 4.0.
- "plug and play integration" of ECS into self-organised grids and multimodal systems.
- solving safety and security issues of self-organised grids and multimodal systems.
- significant reduction and recovery of losses (application and relating to service-oriented architecture, SoA).

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

- winning the global platform game on various application sectors (that are currently strong) and in building effectively and, at a high level, outperforming applications and systems for industrial and business needs.
- preparing for the 5G era in communications technology, especially its manufacturing and engineering dimension.
- solving IoT cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive.
- interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management that allows for the (semi)autonomous deployment and operation of a large number of devices.
- decision support for AI, modelling and analytics in the cloud and also in edge/fog settings.

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

- enabling workforce efficiency regardless of location.
- stimulating social resilience in the various member states, providing citizens with a better work/life balance and giving them freedom to also have leisure time at different locations.

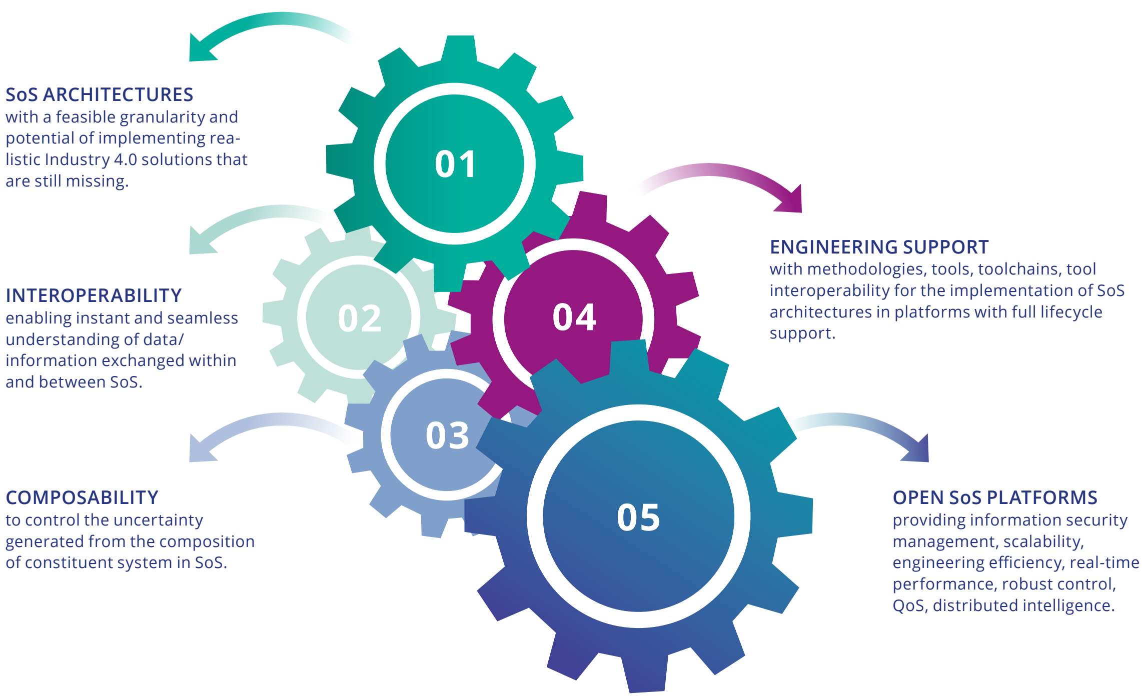
- ubiquitous connectivity, giving people broader employability and better protection against social or economic exclusion.
- enabling European governments, companies and citizens to have closer cooperation, and to develop reliable societal emergency infrastructures.

1.4.3
STRATEGIC ADVANTAGE FOR THE EU

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

The shift in the automotive sector towards electrification and autonomous driving necessitates a large adoption of systems of embedded and cyber-physical systems in vehicles and also roadside infrastructure. The European market has a high-end profile that can pave the way for this technology shift. Fast-paced technology and competence development, combined with the practical innovation scenarios outlined in the chapter on applications, will help develop strategic advantages for European industry.

THREE MAIN DIRECTIONS FOR INNOVATION



Three main directions for innovation. (Source: Eurotech)

F.17

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

SoS have been originally conceived and studied in the defence domain, but they are (and will be) vital infrastructure for many other vertical domains, including transportation, energy, healthcare and wellbeing, natural resource management, agriculture, disaster response, consumer products, finance, media, etc. In all these verticals, the shared enabling technology is represented by open SoS platforms that can play a central role in digitalisation solutions to orchestrate entire supply chains, manage assets, production, operations, processes, marketing and sales, and also in ensuring business continuity and resilience during global crises. The market for open SoS platforms is still very new, and several aspects still need to be completely constructed. Nevertheless, IoT platforms, which currently represent the larger subset of the SoS platforms market, is a very rapidly growing market: a recent study indicated that IoT platform revenues amounted to US $55 billion in 2019 and are expected to reach US $66 billion by 2020, with an annual growth of 20% (Juniper, 2020). With the impact of IoT and its evolution towards SoS, the current and future expectations of the market justify investment in SoS research and innovation (Azzoni, 2020).

The Advancy report on embedded intelligence very clearly points to the SoS market pull for the complete ECS value chain, with market growth being projected at €3.4–10.6 trillion (Advancy, 2019). Rapid EU advancement in the SoS area is therefore critical to the whole ECS value chain.

1.4.4 MAJOR CHALLENGES

1.4.4.1 Major challenge 1: SoS architecture

SoS require architecture that encompasses the multidimensional, multi-stakeholder, multi-technology and their evolutionary nature.

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

1.4.4.1.1 State of the art

One the one hand, major information/communications/control/technology platform providers are offering complete industrial solutions for complex systems. In fact, companies such as Schneider Electric[22], Siemens[23], Bosch[24], Emerson[25], ABB[26] and Advantech with its co-creation platform[27], are currently offering proprietary digital platforms supporting the design, implementation and operation of SoS architectures tailored for dedicated solutions in sectors including water and waste water, minerals and mining, oil and gas, energy sectors and smart cities.

On the other hand, a set of solutions such as the IMC-AESOP approach[28], the IoT Automation Arrowhead Framework[29] and the PERFoRM solution[30] are developing the background for architecture frameworks that are formalised and linked to standardisation activities in national and international innovation platforms. The DIN Specification 91345 "Reference Architecture Model for Industry 4.0" (RAMI 4.0), the "Industrial Internet Architecture" (IIA), the "High Level Architecture of the Alliance for Internet of Things Innovation", the "NIST Big data Reference Architecture", to name but a few, can be considered as reference architectures building the state of the art for supporting dedicated SoS solution architecture. A complementary overview of such architecture frameworks is shown in *Figure F.18* (taken from Tekinerdogan, 2017) and other public architectures.

1.4.4.1.2 Vision and expected outcome

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

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

Some important but necessary aspects of SoS and SoCPS architecture are:

- security and trustability.
- safety.
- stability.
- composability.
- evolution.
- interoperability.
- engineering tools and procedures.

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24 *https://blog.bosch-si.com/bosch-iot-suite/*

25 *https://www.emerson.com/de-de/automation/operations-business-management/plantweb-digital-ecosystem*

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28 *https://link.springer.com/book/10.1007/978-3-319-05624-1*

29 *https://www.taylorfrancis.com/books/e/9781315367897*

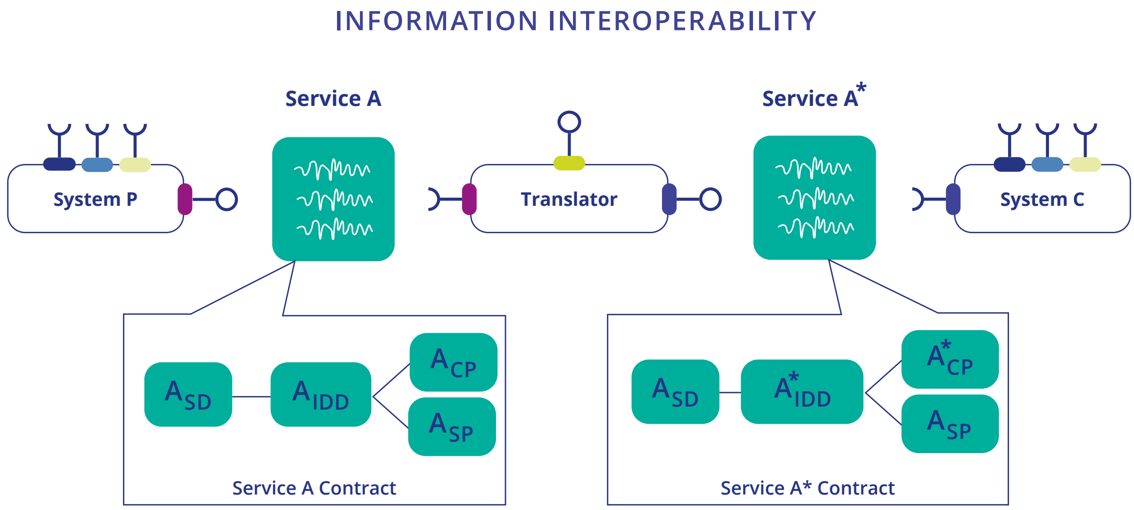
30 *https://www.taylorfrancis.com/books/e/9780429263316*

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

F.18 *SoS architecture panorama (Source: Tekinerdogan, 2017)*

1.4.4.1.3 Key focus areas

The key focus for SoS architectures is how such architectures can enable and leverage these necessary architecture aspects while also enabling the adaptation of such architecture to specific application solutions.



F.19

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

1.4.4.2 Major challenge 2: SoS interoperability

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

1.4.4.2.1 State of the art

Interoperability in the SoS domain is a rising problem for cost-effective engineering and operation of systems of embedded and cyber-physical systems (see *Figure F.19*).

There is currently no industrial solution to this problem. Academia and industry are experimenting with approaches based on, for example, ontologies (Moutinho et al, 2017), machine learning (Nilsson et al, 2019) and open semantic frameworks (Mayer et al, 2017). No clear winning approach can be identified based on current research results.

1.4.4.2.2 Vision and expected outcome

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

1.4.4.2.3 Key focus areas

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

- efficient and flexible engineering procedures.
- engineering tools that support the complete engineering process in both design- and run-time.
- support for key automation requirements.
- automated engineering.

1.4.4.3 Major challenge 3: Composability of embedded and cyber-physical systems in SoS

SoS' intrinsic nature is dynamic, and SoS evolve with components, functions and purposes added, removed and modified along their lifecycle. An SoS has properties, behaviours and functionalities that do not reside in any particular constituent system, and allow the SoS to achieve its goals. These properties, functionalities and behaviours at the SoS level emerge from the composition of the constituent systems and, being potentially unknown, must be detected, identified, understood and controlled since the result of the composition could be uncertain. SoS architectures and platforms, in conjunction with the proper engineering support, should provide solutions to monitor, diagnose and control the uncertainty of emergent behaviours.

1.4.4.3.1 State of the art

Composability is a multi-dimensional key aspect of SoS, one that affects their architectures, properties, functionalities and behaviours from different perspectives (evolvability, trust, interoperability, scalability, availability, resilience to failures, etc). Primarily, composability must ensure the persistence of the five major attributes that characterise a SoS (Maier, 1998, see *Section 1.1*). Vertical (hierarchical) composability provides the most common way to build a SoS that is typically structured in a hierarchical stack composed of adjacent layers. Vertical composability has to deal with the different abstraction levels of the stack layers, adopting aggregation and de-aggregation solutions to compose the constituent systems of the SoS. Architectural composability, on the other hand, is fundamental for SoS design, specifically when critical requirements such as trust or safety must be satisfied (see Neumann, 2004, for an extensive report on trustworthy composable architectures).

The inclusion of AI in embedded and cyber-physical systems increases the required level of trust, as well as the uncertainty of the results of the composition process (see, for example, Wagner, 2015). In the hierarchical structure of an SoS, the constituent systems that are at the same level typically compose horizontally (in parallel or serially), potentially generating competing behaviours or generating chains of constituent systems. Serial composability represents a critical issue for all properties that are not automatically transitive, such as trust. When the constituent systems expose high-level services, service composability allows for the creation of new services at the SoS level combining the resources, functionalities, information, etc, of the constituent systems and providing new added-value services. Eventually, the engineering process deals with composability, enabling it by design (already present from the constituent systems level) and/or managing it during the operations of the SoS, to address the dynamic nature of SoS in time (run-time composability associated with evolutionary development).

1.4.4.3.2 Vision and expected outcome

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

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

Ensuring composability at the SoS level represents a very challenging goal, one that if not addressed generates serious and critical consequences, and can even prevent the integration of the SoS. Indeed, considering a property that characterises a constituent system with a certain attribute, it is not guaranteed that the same property will characterise it when the constituent system becomes part of an SoS. In addition, if the property is still present, it is not guaranteed that it will have the same attribute. The same applies to the constituent system's functionalities, behaviours, etc. The emergent properties, functionalities and behaviours in an SoS generate uncertainty due to the effect of the composition (and/or integration) of the constituent systems. When composition affects trust, interoperability, scalability, availability, resilience to failures, etc, the impact of the uncertainty could potentially be extremely serious.

The importance of composability is accentuated by AI, which is largely diffusing in the constituent systems of an SoS, and which significantly increases the complexity, variability and fuzziness of composability results. AI enables a completely new category of applications for SoS, and the availability of specific solutions for the validation, verification and certification of SoS composed of AI-based systems is a critical requirement. Predicting and controlling the effects of composability is also fundamental for the interaction of humans along the SoS lifecycle. Uncontrolled and unmonitored composition could lead to deviations from normal behaviours or generate unknown behaviours potentially dangerous for humans: composability solutions should protect human life. The increasing level of automation introduced by SoS accentuates this criticality, and will require that humans still intervene in cases of emergency (for example, in automated driving). The solutions proposed to manage composability will also have to support the multi-domain nature of SoS, the presence of different stakeholders in its lifecycle, and the different regulations and standards that apply to these domains. From an engineering perspective, emergent behaviours require that the development of SoS, applying composability, is evolutionary and adaptive over the SoS lifetime. In fact, SoS architectures and platforms, jointly with the proper engineering support, will have to provide solutions to control the uncertainty of composition and ensure adequate countermeasures.

1.4.4.3.3 Key focus areas

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

Composability in SoS is still an open research topic requiring significant effort. The key areas of research and innovation related to composability include:

- methods and tools for engineering composability of systems of embedded and cyber-physical systems.
- evolutionary architectures for composability in systems of embedded and cyber-physical systems.
- composability solutions for trust, availability, scalability, interoperability, resilience to failures or other emergent behaviours.

- composability in systems of cyber-physical systems supported by virtual engineering (e.g. digital twins).
- methods and tools to manage emergencies in embedded and composable systems of cyber-physical systems.
- service-based vertical and horizontal composability to enable high-level, and potentially cross-domain, interoperability of embedded and cyber-physical systems.

1.4.4.4 Major challenge 4: Systems of embedded and cyber-physical systems engineering

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

1.4.4.4.1 State of the art

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

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

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

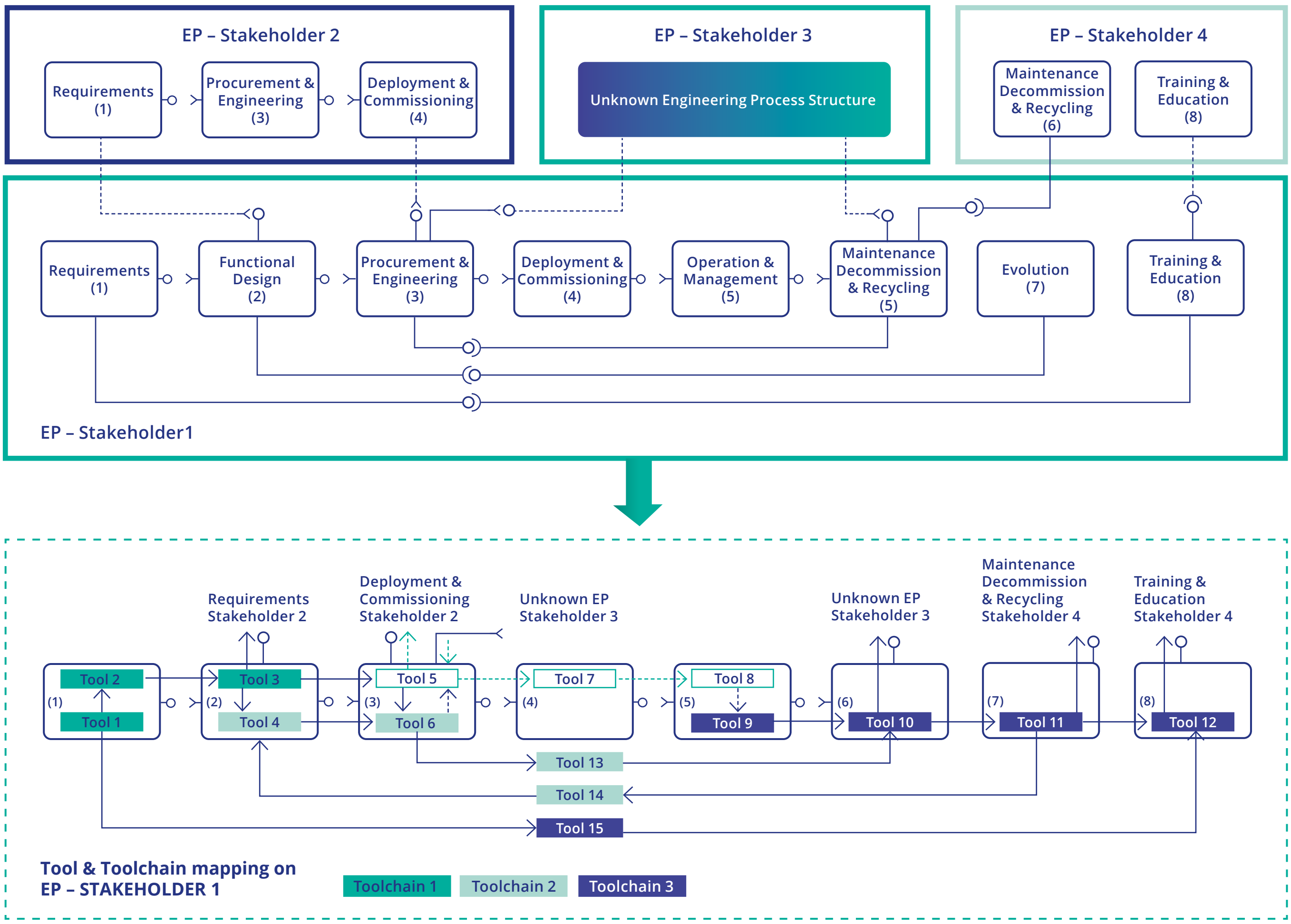
1.4.4.4.2 Vision and expected outcome

The European leadership in application fields such as automotive and industrial automation indicates some excellent skillsets in the art of the SoS engineering. In the short to medium term, Europe has to transfer these skills into systematic and robust engineering procedures supported by integrated and efficient toolchains.

This is expected to lead to automated engineering processes and toolchains that can be integrated between multiple stakeholders, multiple brands and multiple technologies, supporting engineering efficiency, solution quality and sustainability, (Urgese et al, 2020) cf. *Figure F.20*):

- flexible engineering procedures.
- supported by interoperable and flexible toolchains.
- integration of multi-stakeholder engineering processes.

INTEGRATION OF MULTIPLE SERVICE-BASED ENGINEERING PROCESSES



Example of conceptual service-oriented view on the integration of multiple service-based engineering processes (EP) from different stakeholders, including the engineering process mapping with integrated toolchains and tools (Urgese et al, 2020)

F.20

1.4.4.4.3 Key focus areas

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

- efficient and flexible engineering processes.
- engineering tools supporting the complete engineering process along the system's lifecycle.
- support for key automation requirements.
- automated engineering.
- testing validation and verification (TV&V).

In particular, SoS TV&V introduces a significant challenge, mainly due to complexity, to the effects of composition (not always known in advance) and to SoS dynamic evolution over time. For SoS, a full TV&V procedure prior to deployment is practically unrealistic. Typically, the TV&V of each constituent system is

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

F.21 *Open SoS integration frameworks and platforms (Source: Paniagua and Delsing, 2020)*

asynchronous and independent of SoS, challenging the SoS TV&V with feature and capability evolution. For this motivation, a structured framework methodology and tools is necessary to demonstrate an appropriate level of confidence that the feature under test is present in the SoS, and that no undesirable behaviours are also present. This implies a need for end-to-end system capabilities metrics and, according to the flow of data, control and functionalities across the SoS, additional test points, recurring tests and AI-empowered data collection. This analysis should be considered to address changes in the constituents systems and to receive feedback on on anomaly behaviours..

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

1.4.4.5 Major challenge 5: Open system of embedded and cyber-physical systems platforms

Open SoS platforms should ensure information security management, SoS scalability, SoS engineering efficiency, SoS real-time performance, SoS robust control, SoS QoS and SoS-distributed intelligence.

1.4.4.5.1 State of the art

The current industrial state-of-the-art SoS are based on extensions to existing major enterprise resource planning (ERP), manufacturing execution system (MES), supervisory control and data acquisition (SCADA), distributed control systems (DCS) and programmable logic controllers (PLC) products. Such extensions are mostly based on a central service bus concept. Such service buses are responsible for integrating legacy

ERP, MES, SCADA, DCS and PLC technologies from multiple vendors, at best. Europe is the leading player for industrial automation and digitalisation, with a very strong position in the upcoming areas of autonomous driving, smart energy, smart agriculture and smart cities.

To take the next step, Europe and other regions have invested in a number of open SoS integration frameworks and platforms. A summary of these are shown in *Figure F.21* (Paniagua and Delsing, 2020).

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

1.4.4.5.2 Vision and expected outcome

Europe has a strong investment in large projects that have delivered open platforms for the implementation of solutions based on SoS platforms (Azzoni, 2020). Considering the platforms referred in *Figure F.21*, Arrowhead, AUTOSAR, FiWare and BaSys have all been developed with substantial European participation.

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

This requires new and improved platform technologies comprising:

- robust design- and run-time integration and orchestration of functionalities at the edge.
- platform support for multi-level security, security management scalability, engineering efficiency, real-time performance, closed loop and digital control, QoS, distributed intelligence and other key application area requirements.
- interoperability to legacy SoS technology.
- interoperability to existing and emerging IoT and SoS technologies and platforms.
- a high degree of autonomous operation and failure mitigation.
- enabling of SoS flexibility.

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

1.4.4.5.3 Key focus areas

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

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

1.4.5
TIMELINE

The following table illustrates the roadmaps for **System of Systems**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: SoS architectures	**Topic 1.1:** Modular architectures	• Architectures with a feasible granularity and potential for implementing realistic Industry 4.0 solutions
	Topic 1.2: Extra-functional properties	• Lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc
	Topic 1.3: AI support for extra-functional requirements	
Major challenge 2: Interoperability	**Topic 2.1:** Engineering process for interoperability along the lifecycle of SoS	
	Topic 2.2: Service-based vertical and horizontal interoperability of SoS	• Data and information modelling supporting service-oriented principles for value stream and supply chain
Major challenge 3: Composability	**Topic 3.1:** Persistence	• Persistence of operational independence, managerial independence, geographic distribution, emergent behaviour and evolutionary development
	Topic 3.2: Emergent properties and behaviours	• Monitoring, diagnosis and control of security-related emerging behaviours, interoperability, scalability, availability independence, geographic distribution, emergent behaviour and evolutionary development
	Topic 3.3: Hierarchical, architectural and service level composability	• Models, architectures and service natively oriented to support composability • Composability in SoS • independence, geographic distribution, emergent behaviour and evolutionary development
Major challenge 4: Engineering support	**Topic 4.1:** SoS engineering	• Efficient, automated and complete toolchains ensure full lifecycle support • SoA-inspired engineering processes, toolchains and tools
	Topic 4.2: SoS dynamicity	• Engineering support for IoT emergent behaviours
	Topic 4.3: Interoperability	• Tool and toolchain interoperability to improve engineering support automation
Major challenge 5: Open SoS platforms	**Topic 5.1:** Open SoS integration platforms	• IoT-based open integration platforms
	Topic 5.2: Key application area requirements	• Multi-level security, security management scalability
	Topic 5.3: Legacy support	• Connectivity and interoperability for the inclusion of legacy systems in SoS
	Topic 5.4: Engineering support	• Engineering tools and toolchains supporting the complete engineering process along the lifecycle

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Architectures with a feasible granularity and potential of implementing realistic Industry 4.0 solutions	
• Lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc	
	• AI methods adopted to address conflicting extra-functional requirements
• Autonomous information translation	• Cost-effective engineering and operation of SoS
• Cross-domain interoperability	
• Full predictable and controllable composition of functional and extra-functional properties	• Full predictable and controllable composition of functional and extra-functional properties, also covering dynamically recombining SoS
• Monitoring, diagnosis and control of emerging behaviours related to resilience to failure independence	• Monitoring, diagnosis and control of AI-generated emerging behaviours
• Composability by design	
• Engineering support for SoS emergent behaviours	• Engineering support for emergent behaviours of very large SoS
• Multi-stakeholders and multi-domains automated engineering process	
• Vertical SoS integration platforms	• Robust SoS integration platforms capable of supporting a wide range of solutions in diverse fields of applications
• High degree of autonomous operation and failure mitigation, enabling of SoS flexibility	• Distributed intelligence
• Connectivity and Interoperability to existing and emerging IoT and SoS technologies and platforms	
• Engineering tools and toolchains supporting the complete engineering process along the lifecycle	

2.1
ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL

2.2
CONNECTIVITY

2.3
ARCHITECTURE AND DESIGN: METHODS AND TOOLS

2.4
QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

2

Strategic Research and Innovation Agenda 2021

CROSS-SECTIONAL TECHNOLOGIES

2.1

Cross-Sectional Technologies

ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL

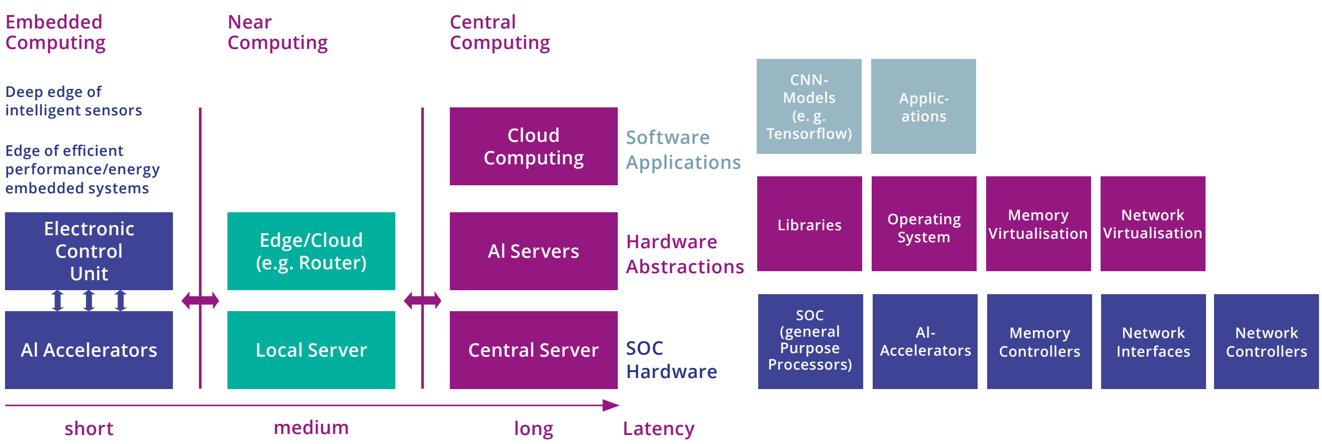
2.1.1
SCOPE

Our world has drastically changed due to digital technologies that are providing ever-increasing performance and autonomy to both existing and new applications at a constant or even decreasing cost. The promise of Artificial Intelligence (AI) places greater pressure on the delivery of improved performance for embedded systems and this class of applications – based on a lower energy and environmental footprint and at an affordable cost. AI could also enable the optimisation of the resources and energy of various applications to achieve higher performance with less resources.

Computing systems have diverse architectures, and also tend to form a continuum between extreme edge devices, edge devices, Internet of Things (IoT), fog, cloud and high-performance computing (HPC). In many applications, the necessary computations are increasingly being carried out on spatially distributed devices, with computing generally done where it is most efficient. This trend can be observed in edge computing and edge intelligence (e.g. cognitive cyber-physical systems (CPS), intelligent embedded systems, autonomous CPS), where raw data is transformed into information as early as possible to reduce throughput and communication costs, and to ensure privacy, efficiency and safety requirements. Indeed, having intelligent processing at the edge has also pushed forward the need for computing, storage and communication to be even more energy efficient and affordable.

One mainstream use for AI is to allow a better interface between the real world (physical world) and computing infrastructure (digital world) by interpreting naturally unstructured data, such as image files, audio files and physical sensor data, where analytic methods are inefficient or inexistent. In addition to purely cognitive reasoning, these devices also need to be able to take "decisions". Advanced control, processing vast amounts of data and inferring suitable control actions for complex systems, is another important part of such systems (self-driving vehicles, autonomous systems, etc).

THE CONTINUUM OF COMPUTING AND RELATIONS.



The continuum of computing and relations between the elements constituting an embedded AI system (Source: Gerd Teepe)

F.22

The availability of AI in an embedded format on the edge, capable of automating complex and advanced tasks, represents one of most significant innovations at the heart of the digital transformation, one that could, for example, help in the recovery from the Covid-19 pandemic and also ensure there is the required resilience for future crises[31].

The scope of this section is a focus on computing components, more specifically towards AI, edge computing and advanced control. These factors rely on process technology, embedded software, constraints of quality, reliability, safety and security, and are composing systems (SoS) that use architecture, design and tools to fulfil the requirements of the various application domains (refer to all these sections in this SRIA for more details).

The section will focus on the trade-off between power consumption, efficiency, managing complexity (and security, safety and privacy[32]) for different use cases that will tend to spread distributed Artificial Intelligences, and potentially create a permanent accessible AI continuum. Increasing European sustainability is also discussed, together with how to increase the lifespan of systems.

2.1.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

Driven by Moore's Law over the last 40 years, computing and communication have brought important benefits to society. Complex computations in the hands of users and hyper-connectivity have been sources of significant innovation and improvements in productivity, with a significant cost reduction for consumer goods – in electronic devices, traditional products (such as medical and machinery products) and for added-value services – at the global level.

AI introduces a radical improvement to the intelligence brought to such products through microelectronics, and could unlock a completely new spectrum of applications and business models. The technological progress in microelectronics has increased the complexity of microelectronic circuits by a factor of a 1,000 over the last 10 years alone, with the integration of billions of transistors on a single microchip. AI is therefore a logical step forward from the actual microelectronics control units: its introduction will significantly shape and transform all vertical applications over the next decade.

31 *https://www.eenewsembedded.com/news/nxp-developing-neural-networks-identify-covid-19*

32 *Security, safety and privacy will be covered in the section about "Quality, Reliability, Safety and Security"*

AI and edge computing will be core technologies for the digital transformation and to drive a sustainable economy. AI will allow for the analysis of data on the level of cognitive reasoning to take decisions locally on the edge (embedded intelligence), transforming the IoT into the Artificial Intelligence of Things (AIoT). Likewise, control and automation tasks traditionally carried out on centralised computer platforms will be shifted to distributed computing devices, making use of decentralised control algorithms, for example. AI, edge computing and advanced control algorithms will bring a significant reduction in energy consumption for data transmissions, save resources in the key domains of Europe's industrial systems and will improve the efficient use of natural resources, as well as contributing to the sustainability of many businesses.

Computing is at the heart of a wide range of fields. By controlling most of the systems with which humans interact, it enables transformational science (climate, combustion, biology, astrophysics, etc), scientific discovery and data analytics. However, the advent of AI on the edge, which enables complete or partially autonomous CPS, requires huge improvements in term of semantics and use case knowledge understanding, in addition to new computing solutions to manage them. Even if deeply hidden, these computing solutions directly or indirectly impact our ways of life: consider, for example, their key role in solving the societal challenges listed in the **Application** chapter, optimising industrial processes costs and the creation of cheaper products (e.g. delocalised healthcare).

Nevertheless, such computing solutions will also permit synergies between domains – e.g. self-driving vehicles with higher reliability and predictability, and medical systems that benefit from consumer smart bracelets or smart watches that allow for lifestyle monitoring to reduce the impact of health problems[33] (with a positive impact on the healthcare system costs, first-aid and insurance services) are being simplified and made more effective due to car location and remote control functionalities.

These computing solutions introduce both new security improvements and threats. Edge computing allows better protection of personal data, being stored and processed only locally, ensuring the privacy rights required by General Data Protection Regulation (GDPR). At the same time, however, the easy accessibility to devices and new techniques such as AI generates a unique opportunity for hackers to develop new means of attack. It then becomes paramount to identify interdisciplinary trusted computing solutions, and to develop the appropriate countermeasures to protect them in case of attack. For example, Industry 4.0 requires new, more decentralised, architectures, new infrastructures and new computational models that provide for a high level of synchronisation and cooperation of manufacturing

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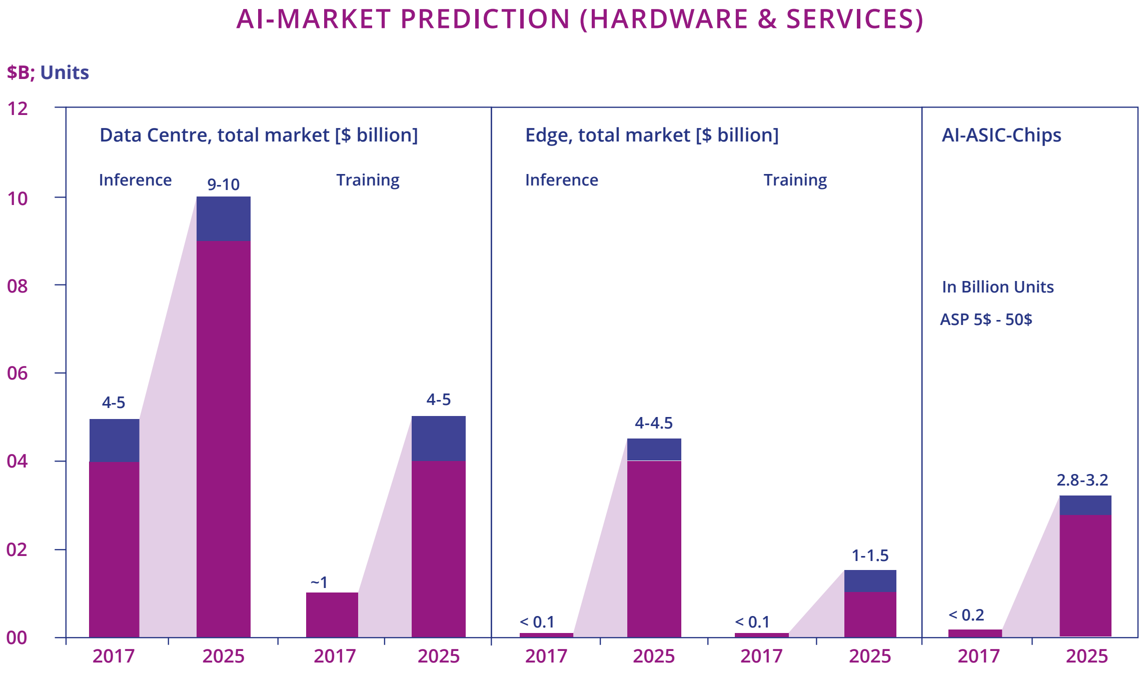
33 *https://indianexpress.com/article/technology/gadgets/apple-watch-panic-attack-detection-feature-watchos7-6404470/*



F.23 *Illustration of an extract of the challenges and the expected market trend for AI, edge computing and advanced control (Source: Tractica, May 2019, McKinsey & Company)*

processes, with a demand for resource optimisation and determinism that cannot be provided by solutions that rely just on "distant" cloud platforms or data centres[34], ensuring low-latency data analysis that is crucial for industrial application[35].

These computing solutions also have to consider the human beings in the loop: particularly with AI, solutions that ensure a seamless connection between human and machine will be key. Eventually, a **Major challenge** will be to keep the environmental impact of these computing solutions under control to help guarantee European industry sustainability and competitiveness.

Applications breakthroughs

Technologies that permit low-power solutions are nearly with us. What is now crucial is to integrate these solutions as close as possible to sensors. Low-power neural network accelerators will enable sensors to perform online, continuous learning, and to build complex information models of the world they perceive. Neuromorphic technologies, such as spiking neural networks and in-memory computing architectures, are compelling ways to efficiently process and fuse the streaming of sensory data, especially when combined with event-based sensors. These sensors, which involve technology such as retinomorphic cameras, are becoming extremely important, particularly in edge computing where energy can be a very scarce resource. A major issue for edge systems,

34 *Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M., Yin, B.: Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges. IEEE Access. 6, 6505–6519 (2018)*

35 *Jeschke, S., Brecher, C., Meisen, T., Özdemir, D., Eschert, T.: Industrial Internet of Things and Cyber Manufacturing Systems. In: Jeschke, S., Brecher, C., Song, H., and Rawat, D.B.(eds.) Industrial Internet of Things. pp. 3–19. Springer International Publishing, Cham (2017)*

CHALLENGES AND EXPECTED MARKET TRENDS OF AI

Date creation explosion & low level of use

only 15%

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

Global ICT energy consumption:

10%

of worldwide energy consumption already in 2018.

Deep learning training footprint:

> 200 000 kg of CO_2

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

ICT energy and CO_2 footprint

8–21%[2] (4% CO_2)[3]

of global worldwide electricity consumption and emissions.

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

Challenges and expected market trends of AI **F.24**

and even more so for AI-embedded systems, is energy efficiency and energy management. Implementation of intelligent power/energy management policies are fundamental to systems where AI techniques are part of processing sensor data, and power management policies are required to extend the battery life of the entire system.

To achieve intelligent sensors with online learning capabilities, semiconductor technologies alone will not suffice. Neuroscience and information theory will continue to discover new ways[36] of transforming sensory data into knowledge. These theoretical frameworks help model the cortical code, and will play an important role towards achieving real intelligence at the extreme edge.

As all this will happen on (extreme) edge devices, personal data protection must be achieved by design, and the amount of data traffic towards the cloud and the edge cloud should be reduced to a minimum. Such intelligent sensors not only recognise low-level features, but are also able to form higher-level concepts and require very little (or no) training. For example, while digital twins currently need to be handcrafted and built bit-by-bit, so to speak, tomorrow's smart sensor systems will develop digital twins autonomously by aggregating the sensory input that flows into them.

→

36 *Although our understanding of how the brain computes is still in its infancy, important breakthroughs in cortical (column) theory have been achieved in the last decade*

The key issues for the digital world are the availability of affordable computing resources and bringing the data to the computing node within an acceptable power budget. Computing systems are morphing from classical computers with a screen and keyboard to smartphones and deeply embedded systems in the fabric of things. This revolution on how we now interact with machines is mainly due to advances in AI, and more precisely machine learning (ML) and deep learning (DL), which allows machines to comprehend the world not only on the basis of various signal analysis but also on the level of cognitive sensing (vision and audio).

AI systems use training and inference to provide the proper functions of the system, and are significantly different in terms of the computing resources provided by AI chips. Training is based on analysis of past data using datasets, with the findings/patterns being built into an AI algorithm. The AI hardware used for training needs to provide computation accuracy, support sufficient representation accuracy – e.g. floating point or fixed point with long word length, large memory bandwidth, memory management, synchronisation techniques to achieve high computational efficiency, and fast write time and memory access to a large amount of data[37].

Reinforcement learning (RL) is a booming area of machine learning. It is based on how agents ought to take actions in an environment to maximise the idea of cumulative reward. Recent research[38] has developed systems able to discover their own reward function from scratch. Similarly, auto-ML allows for determining a “good” structure for a DL system to be efficient in a task. However, all these approaches are also very computer-demanding.

The inference here is the application of learned algorithms to real devices to solve specific problems based on existing data. The AI hardware used for inference needs to provide high-speed, energy-efficiency, low-cost, fixed-point representation, efficient reading memory access and effective network interfaces for the whole hardware architecture. The development of AI-based devices with increased performance and energy efficiency allows for AI inference "at the edge" (embedded intelligence), and to accelerate the development of middleware that permits a broader range of applications to run seamlessly on a wider variety of AI-based circuits. Companies such as Google, Gyrfalcon, Mythic and Syntiant are developing custom silicon for the edge – for example, Google has released Edge TPU (tensor processing unit), a custom processor to run TensorFlow Lite models on edge devices.

In summary, we can see the following disruptions on the horizon once (deep-edge) AI broadly enters the application space.

←

37 *GPT-3 175B from OpenAI is trained with 499 billion tokens (https://lambdalabs.com/blog/demystifying-gpt-3/) and required 3.14E23 FLOPS of computing for training.*

38 *https://arxiv.org/pdf/2007.08794.pdf.*

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39 *https://ec.europa.eu/digital-single-market/en/news/european-processor-initiative-consortium-develop-europes-microprocessors-future-supercomputers.*

- Various AI functionalities will be moved to local devices, including voice recognition and good environment understanding, allowing privacy-preserving functionalities.
- The AIoT will be enabled by AI.
- Federated functionalities will emerge (increasing the functionality of devices using capabilities, resources or neighbouring devices).
- Connected functionalities will also emerge. This will extend the control and automation of single systems (such as a truck or car) to a network of systems (e.g. a truck platoon), resulting in the networked control of CPS. The benefit of this is generally improved performance and safety, and it will also help form the basis for autonomous machines (including vehicles).
- The detection of events by camera and other long-range sensors (radar, lidar, etc) will become possible. Retina sensors will ensure the low-power operation of systems, and portable devices (e.g. for the blind) will be developed.
- The potential for disabled people to move their arms and legs will be enhanced, as AI-conditioned sensors will be directly connected to the brain.
- The use of voice commands will be significantly increased, improving the human–machine interface (HMI) with a reliable understanding of natural language.

2.1.3
STRATEGIC ADVANTAGE FOR THE EU

While Europe is recognised for its expertise in software, and especially in embedded systems architecture and software, it should continue to invest in this domain to remain an industry leader, despite fierce competition from countries such as the US, China and India. From this perspective, the convergence between AI and edge computing, what we call “embedded intelligence”, should be a top priority. Europe should benefit from its specificities, such as the European Green Deal initiative, to make its industry both sustainable and competitive. European companies also lead the field for embedded microcontrollers. For this, automotive, IoT and medical applications and all embedded systems that utilise a range of low-cost microcontrollers, require integrating a complete system, computing, memory and various peripherals into a single die. Here, proactive innovation is necessary to upgrade existing systems with the new possibilities offered by AI, CPS and edge computing, with a focus on local AI. These innovative applications will require greater processing power to remain competitive. However, power dissipation must not increase accordingly – in fact, a reduction is required. Europe has also lost some ground in the processor domain, but AI is an opportunity to regain part of its sovereignty in computing as completely new applications emerge. Mastering key future technologies is mandatory for European technological endeavour, as well as for attracting young talent and enabling innovation in the relevant applications.

Europe no longer has a presence in "classical" computing, such as processors for laptops and desktop, servers and HPC, but the drive towards edge computing, part of a computing continuum, is an opportunity to use its well-established expertise in embedded systems and to extend it to high-performance technology to develop embedded (or edge) high-performance computing (eHPC). The initiative of the European Commission, "for the design and development of European low-power processors and related technologies for extreme-scale, high-performance big-data and emerging applications, in the automotive sector", could reactivate the presence of Europe in that field, and has already led to the launch of the European Processor Initiative (EPI)[39].

AI-optimised hardware components – such as central processing units (CPUs), graphics processing units (GPUs), field-programmable gate arrays (FPGAs), application-specific integrated circuit (ASICs) accelerators and neuromorphic processors – are becoming increasingly important. European solutions already exist, and more EU action is needed to further extend its technological capabilities and secure its industrial competitiveness. One emerging approach to preventing dependence on closed processing technologies relies on open hardware initiatives (Open Compute Project, RISC-V, OpenCores, OpenCAPI, etc). The adoption of an open ecosystem approach, based on the globally and incrementally developed expertise of multiple actors, inhibits a single entity from purchasing or ceasing to exist for other reasons. The very low upfront cost of open hardware/silicon intellectual property (IP) reduces the barrier of innovation for small players to create, customise, integrate or improve Open IP to their specific needs. Due to open hardware being freely shared, and the manufacturing capabilities that still exist in Europe[40], prototyping facilities and the related know-how, a new wave of European start-ups could emerge that build on existing designs and create significant value by adding the customisation needed for industries such as automotive, energy, manufacturing and health/medical.

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

It is also very important for Europe to master the new key technologies for the future, such as AI and the drive for more localised computing, not only because it will sustain industry, but also to master the complete ecosystem of education, job creation and attracting young talent to this field while rapidly implementing the new measures presented in **Major challenge 4**.

2.1.4 MAJOR CHALLENGES

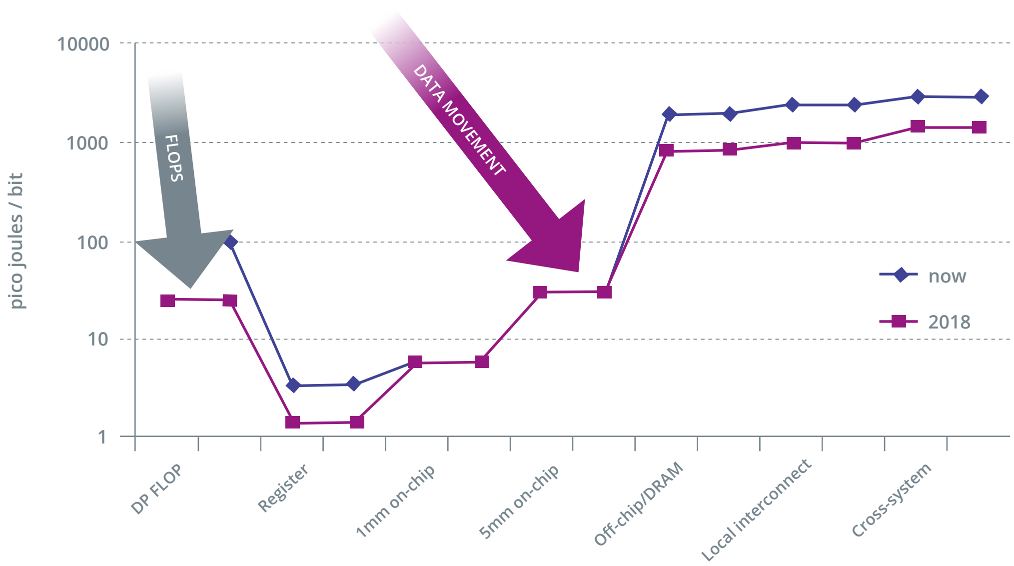
Four **Major challenges** have been identified for the further development of computing systems, especially in the field of AI, edge computing and advanced control.

- Increasing the energy efficiency of computing systems.
- Managing the increasing complexity of systems.
- Supporting the increasing lifespan of devices and systems.
- Ensuring European sustainability in AI, edge computing and advanced control.

2.1.4.1 Major challenge 1: Increasing the energy efficiency of computing systems

The advantages of using digital systems should not be hampered by their cost in terms of energy. For HPC centres, it is clear that the main challenge is not to reach the “exaflops” *per se*, but “exaflops” at a reasonable energy cost, which impacts the cooling infrastructure, the size of the “power plug” and globally the cost of ownership. At the other end of the spectrum, deep-edge devices should work for months on a small

ENERGY FOR COMPUTING AND DATA MOVEMENT



Energy for computing and data movement **F.25**

battery, or even by scavenging their energy from the environment (energy harvesting). Reducing the energy footprint of devices is the main way to fulfil the necessary sustainability for the European Green Deal. Multimodal energy harvesting (solar/wind, regenerative braking, dampers/shock absorbers, thermoelectric, etc) offers huge potential for electrical vehicles and other battery and fuel cell operated vehicles, in addition to energy-efficient design, real-time sensing of integrity, energy storage and other functions.

Power consumption should not be only seen at the level of the device, but at the level of the aggregation of functions required to fulfil a task. For example, neural networks can be very energy-demanding during their learning phase[41,42] , where millions (or even billions) of samples are presented to set the properties of the networks[43], but if the inference phase is also used billions of times (such as in smartphones), this could offset the large costs incurred in the learning phase. It has been said that "since 2012, the amount of compute used in the largest AI training runs has been increasing exponentially with a 3.5 month-doubling time (by comparison, Moore's law had an 18-month doubling period)[44]". Therefore, the gap between the need for computing power (and therefore the associated power consumption) of what will be available for training is widening.

The new semiconductor technology nodes do not really bring improvement on power per device; Dennard's scaling is coming to an end and moving to a smaller node no longer leads to a large increase

40 *Mainly for applications requiring good energy efficiency at a low cost, and not so much focused on the ultimate processing speed*

41 *https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes*

42 *https://arxiv.org/pdf/1906.02243.pdf*

43 *GPT-3 from OpenAI, which has 175B parameters is trained with 499 billion tokens. GPT-3 175B model required 3.14E23 FLOPS of computing for training (see https://lambdalabs.com/blog/demystifying-gpt-3/)*

44 *https://openai.com/blog/ai-and-compute/*

in the operating frequency or a decrease in the operating voltage. Therefore, for dissipated energy per surface, the power density of devices is increasing rather than decreasing. Transistor architecture, such as the fin field-effect transistor (FinFet), fully depleted silicon-on-insulator (FDSOI) and nanosheets, mainly reduce the leakage current (i.e. the energy spent by an inactive device).

In addition, there is the "memory wall". Today's limitations are not coming from the pure processing power of systems, but rather from the capacity to bring data to the computing nodes within a reasonable power budget sufficiently quickly.

Furthermore, system memory is only part of a broader data movement challenge, which requires significant progress in the data access/storage hierarchy from registers, main memory (progress of non-volatile memory (NVM) technology, such as the Intel's 3D-xpoint, etc), to external mass storage devices (progress in 3D-nand flash, storage class memory (SCM) derived from NVM, etc). In modern systems, large parts of the energy are dissipated in moving data from one place to another. For this reason, new architectures are required, such as in-memory computing, neuromorphic architectures (where the physics of NVM technology – phase-change memory (PCM), conductive-bridge random-access memory (CBRAM), magnetic RAM (MRAM), oxide-based RAM (OxRAM), resistive RAM (ReRAM), etc – can also be used for computing[45]) and lower bit count processing are of primary importance.

Power consumption can be reduced by the local treatment of collected data, not only at the circuit level but also at the system level, or at least at the nearest from the sensors in the chain of data transfer towards the data centre (excluding in the gateway). Whereas the traditional approach was to have sensors generate as much data as possible, and then leave the interpretation and action to a central unit, future sensors will evolve from mere data-generating devices to ones that generate semantic information at the appropriate conceptual level. This will obviate the need for high bit rates, and thus power consumption between the sensors and the central unit. Performing this type of "AI front-end processing" with low energy will be achieved through a myriad of techniques, ranging from event-based processing, dynamic precision neural networks, spiking neural networks and, of course, advances in device technology to create the appropriate neuronal and synaptic functionality and programmability, including online learning using local learning techniques with minimal need for labelled data.

In terms of control and automation, there is ongoing research towards distributed control algorithms, where complex interconnected systems are no longer controlled by one central entity but the control

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45 *D. C. Daly, L. C. Fujino and K. C. Smith, "Through the Looking Glass-2020 Edition: Trends in Solid-State Circuits From ISSCC," in IEEE Solid-State Circuits Magazine, 12(1), Winter, pp 8–24, 2020*

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46 *B. Dittmann et al, APL Materials, 2019*

is distributed among several interconnected agents. This significantly reduces the need to shift huge amounts of data that would normally be required for centralised control, and lessens the complexity of control algorithms and the effort in their parametrisation (comparable to the training of a neural network).

In summary, data should be transformed into information as early as possible in the processing continuum to globally improve global energy efficiency.

- Only end or middle point equipment is working, potentially with low or sleeping consumption modes.
- Data transfer through network infrastructures is reduced. Only necessary data is sent to the upper level (this also works for data tagging, such as in federated AI).
- Usage of computing time in data centres is also minimised.

AI training is crucial to being more energy efficient and greener. The search for the best solutions for a given use case should be a trade-off between the accuracy of the AI neural network (top-1, top-5), safety, security, the energy consumed during inference – averaged by the frequency of use of this inference – and that consumed for training. Techniques such as transfer learning and incremental/federated learning could also decrease the energy required by not having to learn from scratch each time.

The development of benchmarks and standardisation for HW/SW and datasets could be an appropriate measure to help reduce power consumption. Hence, energy consumption evaluation will be easy, and should include the complete view – from the learning/training phase to the inference phase.

To increase the energy efficiency of computing systems, especially in the field of systems for AI, edge computing and advanced control require the development of innovative hardware architectures at all levels, along with their associated software architectures and algorithms.

- At the technology level (FinFet, FDSOI, silicon nanowires/nanosheets), technologies are pushing the limits to ultra-low power. In addition, advanced architectures are moving from near-memory computing to in-memory computing with potential gains of 10 to 100 times, with neuromorphic computing going beyond the gains offered by the circuit level[46].

- At the device level, several type of circuit architectures are currently being run, tested or developed worldwide. The list is evolving from the well-known CPUs to increasingly dedicated systems on a chip (SoCs) – GPUs, TPUs, neuromorphic processing units (NPUs), etc – which are implemented very differently, from fully digital to mixed, or full analogue solutions.
  - Significant efforts have been made over the past few years to apply neural networks in the inference stage on less powerful computing ICs with lower memory size.
  - The NPU approach tries to be even closer to the brain.
  - Spiking neurons network is one promising solution, especially for reinforcement learning and very low power consumption. It can also be mixed with DL. Another advantage of this approach is the potential biocompatibility with living neurons, which could lead to HMIs and the replacement of some biological sensors.
  - Another way is to also perform invariant perceptive processing and produce semantic representation with any type of sensory input.

- At the system level:
  - Deep-edge AI (i.e. integrating AI inside or very close to the sensors or to local control) will allow AI to work in the 10–100 mW range with an estimated computing power 0.1–0.5 tera operations *per se*cond (TOPS)/watt by 2025. However, this could be negligible compared to

the consumption of the sensor (for example, a MEMS microphone can consume a few mA). In addition, devices can go into standby or sleep mode when not being used, so the connectivity does not have to be permanent. Considering the amount of devices already being deployed on the edge that rarely process data 24/7 (e.g. data centres), the possibility of leaving them in a low power state when not being used could have a significant impact on global energy consumption. The possibility to orchestrate and manage edge devices becomes fundamental from this perspective, and should be supported by design. Data servers, on the other hand, are always on even if they are loaded only to 60% of their computing capability.
- For embedded AI (AI in a smartphone, drones, etc) the power range will be between 100 mW to 1 Watt, with an estimated computing power of 1–5 TOPS/watt by 2025.

- At the data level:
  - Distributed AI and federated learning will reduce the number of data sent to the upper levels, and therefore limit global power consumption.
  - The various options for storing data should be taken into consideration.
  - Act on both the learning and inference parts of AI systems.

- At the tools level:
  - Co-design between HW/SW and algorithms (inference engines and associated algorithms) is mandatory to minimise the data moves and optimise power consumption.
  - Tools to reduce size of DL neural networks – for example, to optimise quantisation or for pruning – are also key for power efficiency.

The challenge is not only at the component level, but also at the system and even infrastructure level. The Open Compute Project, for example, was launched by Facebook to help deliver the most efficient designs for scalable computing through an open source hardware community.

2.1.4.1.1 State of the art

There has been an explosion in the development of computing systems that offer a multiplicity of implementations (chips, card, systems), and in particular to support new applications using AI. They cover a broad range of performance and power, from high end for servers to ultra-low power devices for the IoT *Figure F.26*.

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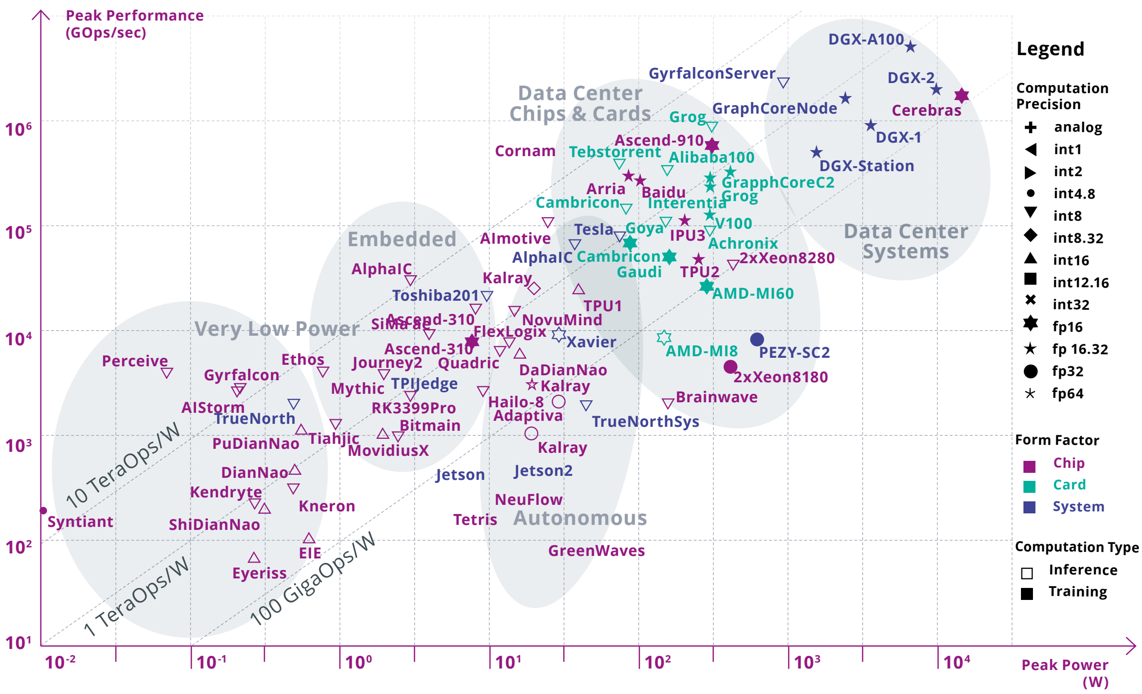
[47] *Source: Survey of Machine Learning Accelerators, Albert Reuther and Peter Michaleas and Michael Jones and Vijay Gadepally and Siddharth Samsi and Jeremy Kepner, 2020, arXiv 2009.00993, https://arxiv.org/abs/2009.00993*

[48] *Artificial Intelligence Chip Market, Next Move Strategy Consulting, November 2019*



Landscape of AI chips according to their peak power consumption and peak performance[47]

F.26

Currently, AI and DL are mainly developed by Google, Facebook, Apple, Amazon and Microsoft (GAFAM) and Baidu, Alibaba, Tencent and Xiaomi (BATX), who make the largest investments in this domain through the acquisition of other major players (both start-ups and known academics). They also have the large in-house databases required for the learning and computing facilities. In addition, all major companies (Google, Apple, Facebook, etc) have already developed their own chips for DL (e.g. Google has its line of TPUs) or have announced they are going to. The US and Chinese governments have also started initiatives to ensure they will remain prominent players in the field. According to a recent study[48], the global AI chip market was estimated at US $9.29 billion in 2019, and is expected to grow to US $253.30 billion by 2030, with a compound annual growth rate (CAGR) of 35.0% by 2020–30.

We should not forget that, besides the access of large (labelled) databases, advances in AI are also due to improved computing and storage that allows the processing of greater amounts of data, which means that AI algorithms can be "trained" for more applications. It will be a challenge for Europe to compete, but the emergence of AI at the edge, and its expertise in embedded systems, could be winning factors. However, the competition is fierce and the big names are in with big money[49], so Europe must act quickly as US and Chinese companies are already moving in this "intelligence at the edge" direction (with Intel Compute Stick, Google's Edge TPU, Nvidia's Jetson Nano and Xavier, etc).

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49 *For example, the Intel Neural Compute Stick 2, which is powered by the Intel Movidius Myriad X chip (Movidius was a European company), is sold at US$99. Google Edge TPU is also a US$75 USB accelerator integrating the Edge TPU. Nvidia introduced the Jetson Nano, a US$99, 472 GFlops, 5W board. It uses Gen-2 GPU cores (128 Maxwell CUDA cores) and a quad-core ARM® Cortex®-A57 processor. The Chinese company Sipeed also sells a US$12 board (MAIX Bit) (https://www.sipeed.com/index-en.html), that interfaces directly with a camera and an LCD, allowing off-the-box real-time image recognition. It uses the Kendryke K210 SoC, with a two 64-bit RISC-V CPU core, a KPU CNN accelerator for computing convolutional neural networks and an APU for processing microphone array inputs. The K210 also features a fast Fourier transform (FFT) accelerator. These are only few examples among many.*

To efficiently support new AI-related applications on both the server and client on the edge side, new accelerators need to be developed. For example, DL does not usually require a 32/64/128-bit floating point for its learning phase, but rather variable precision from 16- up to 128-bit floats. However, a close connection between the computing and storage parts is needed (neural networks are an ideal in-memory computing approach here). Storage also needs to be adapted to support AI requirements (specifically data accesses, co-location computing and storage), memory hierarchy, and local versus cloud storage.

Similarly, for at the edge, accelerators for AI applications will particularly require real-time inference with a view to reducing power consumption. For DL applications, arithmetic operations are simple (mainly multiply–accumulate), but they are carried out on datasets with a very large amount of data, for which access is challenging. In addition, intelligent data processing schemes are required to re-use data where there are convolutional neural networks or in systems with shared weights. Computing and storage are deeply intertwined. Of course, all the accelerators should also fit efficiently with more conventional systems.

Finally, new approaches can be used for computing neural networks, such as analogue computing, or using the properties of specific materials to perform computations (although, with low precision and high dispersion, the neural networks approach is able to cope with such limitations)[50, 51, 52]. Besides DL, the Human Brain Project, is a H2020 FET Flagship Project that targets the fields of neuroscience, computing and brain-related medicine, including, in its SP9, the neuromorphic computing platform SpiNNaker and BrainScaleS [53]. This platform enable experiments with configurable neuromorphic computing systems.

2.1.4.1.2 Vision and expected outcome

The key problem is to find the best trade-off between power consumption, efficiency, security, safety and privacy for different use cases that will spread distributed AIs, and potentially create a permanently accessible AI continuum.

Europe is a leader in embedded systems, CPS, components for the edge (sensors/actuators, embedded microcontrollers) and applications such as autonomous intelligent systems in automotive autonomous, connected, electric and shared (ACES) vehicles, railways, avionics and production systems. Leveraging AI-enabled controls to these sectors will improve the efficient use of energy resources and increase productivity. Accelerators are key elements to improving the efficiency and performance of existing systems (at the cost of greater SW complexity, see next Major challenge, but a useful objective here will be to automate this process).

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50 *Recent achievements in this field are, for example, the biologically inspired chip "TrueNorth" from IBM, and the neuromorphic chip developed by IMEC, capable of composing music by learning rules of composition, The Neuram3 H2020 project has just delivered a prototype chip with better performances than TrueNorth, etc*

51 *https://www.imec-int.com/en/artificial-intelligence*

52 *https://www.cerebras.net/, https://www.intel.fr/content/www/fr/fr/research/neuromorphic-computing.html, https://www.qualcomm.com/products/smartphones/mobile-ai*

53 *https://electronicvisions.github.io/hbp-sp9-guidebook/*

We should move from a local view (the device) to the "continuum" (the complete chain), and find the correct balance between edge computing, where computing is local (and when it is possible to do it at the edge because the operation does not require access to global data), and the transmission of data to data centres, which will need energy for the transmission (and therefore cost more at a global level). This is a complex equation to find the optimum, considering all parameters, such as the energy to build the edge device, etc. Interoperability between solutions is essential to ensure an optimal realisation of applications.

For edge/power efficient devices, perhaps ultra-dense technologies are not required, as cost and power efficiency can matter more than raw computational performance. The proposed approach of chiplets and interposers allows for a combination of various technologies, and the use of the most efficient combination for each function. This also allows a refocus on the efficiency of the system to the application in changing the compositions of the various chiplets on the interposer, bringing more application with domain-efficient systems at a more affordable cost.

Other (neuromorphic) architectures need to be further investigated and assess if they can provide the best use cases. One key element is the necessity to retain the neuronal network state after learning/training phase, since reinitialising after switch-off will increase global consumption. It is also very important to ensure co-optimisation of both the software and the hardware (and even co-design) to gain further efficiency.

AI, and especially DL, require optimised hardware support for efficient realisation.

- For the learning/training phase, many variable precision computations (from float16 to double that) require accelerators with efficient memory access and large multi-computer engine structures. Access to a large storage area is also necessary to store all the examples that are used during this phase.
- The inference phase (e.g. on the edge) will require low-power efficient implementation with closely interconnected computation and memory. Efficient communication between the storage (i.e. the synapses for a neuromorphic architecture) and the computing elements (the neurons for neuromorphic) are of paramount importance to ensure good performance.
- Emerging computing paradigms such as mimicking the synapses, using unsupervised learning such as spike-timing-dependent plasticity (STDP), might change the game by offering learning capabilities at relatively low hardware cost and without the need to access a large database. Instead of being realised by arithmetic logic unit (ALU) and digital operators, STDP can be realised by the physics of some materials, such as those used in NVMs.
- Developing solutions for AI at the edge (e.g. for self-driving vehicles, personal assistants and robots) is more in line with European requirements (privacy, safety) and know-how (embedded systems). Solution at the extreme edge (small sensors, etc) will require even more efficient computing systems due to their low cost and ultra-low power requirements.

2.1.4.1.3 Key focus areas

MAIN FOCUS AREAS	TOPICS	DETAILS
1. Promoting solutions based on:	**Topic 1.1:** Processing data where it is created, or where it is the most efficient	• Edge computing – distributed decision-making and computing (federating edge devices)
	Topic 1.2: Hybrid architecture merging classical CPU with new paradigms (e.g. neuromorphic) covering the complete stack	• Architecture – technology – interfaces – tools – learning/training and inference frameworks – optimisation (memory space, of various types (NVMs), etc) – operating systems
2. Improve performances:	**Topic 2.1:** Follow the steep increase of performances required by AI-based applications	• Embedded high-performance computing – high-performance AI-based architectures – high-efficiency AI on a chip platform
	Topic 2.2: Develop (accelerators) hardware and software architectures mainly targeting the edge, covering all the stack and focusing on energy efficiency	• At the device (e.g. transistor) level (e.g. using FDSOI technology) or using physics to make computations (use of NVMs as synapses) • At the circuit level (adaptative levels of activity -DVFS), reducing communications, using the optimum data representation (from floating point to integer, to binary, to spikes, etc • At the appliance/device level (efficient accelerators with multiple "sleep" modes), using chiplets and interposers to reduce the communication wire length and ensuring an optimal architecture build from "blocks" (chiplets) • At the distributed systems level (using federations of edge devices placing resources in common to achieve a common goal) • Linked with the cloud to cover the complete "continuum" of computing devices where applications and storage are spread
3. Address scalability issues	**Topic 3.1:** Mesh networks and distributed computing	
4. Address interoperability issues	**Topic 4.1:** Interoperability between solutions is essential to ensure an optimal realisation of applications. Common platforms could help ensure compatibility and data exchanges between devices.	
5. Develop AI-distributed solutions	**Topic 5.1:** Developing distributed solutions for AI systems that require less access to central resources, such as incremental learning done at the edge, or federated learning performed by a set of edge devices. Development of advanced control concepts for distributed (multi-agent) systems that also take uncertainties in communication and structure (topology) into account.	
6. Algorithms, HW/SW, SW co-design	**Topic 6.1:** Co-design of the algorithms, software and hardware to achieve the best efficiency	

F.27 *illustrates an extract of the challenges and the expected market trends for AI, edge computing and advanced control*

2.1.4.2 Major challenge 2: Managing the increasing complexity of systems

- Improving interoperability of systems.
- Facilitating the easy addition of modules to a system.
- Developing common interfaces and standards.
- Using AI techniques to help complexity management.

The increasing complexity of electronic embedded systems, hardware and software algorithms has a significant impact on the design of applications, engineering lifecycle and the ecosystems involved in the product and service development value chain.

Such complexity is the result of the incorporation of hardware, software and connectivity into systems, and their design to process and exchange data and information without addressing the architectural aspects. As such, architectural aspects such as optimising the use of resources, distributing tasks, dynamically allocating functions, providing interoperability, common interfaces and modular concepts that allow for scalability are typically not sufficiently considered.

Today's complexity to achieve higher automation levels in vehicles and industrial systems is best viewed by the different challenges that need to be addressed when increasing the number of sensors and actuators offering a variety of modalities and higher resolutions. These sensors and actuators are complemented by ever more complex processing algorithms to handle the large volume of rich sensor data. The trend is reflected in the value of semiconductors across different vehicle types. While a conventional automobile contains roughly US $330 of semiconductor content, a hybrid electric vehicle with a full sensor platform can contain up to US $1,000–3,500 of semiconductors. Over the past decade, the cost contribution for electronics in vehicles has increased from 18–20% to about 40–45%, according to Lam Research. These numbers will increase further with the introduction of autonomous, connected and electric vehicles that make use of AI-based HW/SW components.

This approach necessitates the use of multiple high-performance computing systems to support the cognition functions, which consume 2–5 kW, which is at least twice the size of a typical combustion engine. Moreover, the existing electrical/electronic (E/E) architectures impose that the functional domains are spread over separated and dedicated electronic control units (ECUs). This approach is hampering the upscaling of automation functionality, as well as putting a constraint on effective reasoning and decision-making.

To achieve the required increased level of automation in automotive, transportation and manufacturing, disruptive frameworks are being considered that provide a higher order of intelligence. Several initiatives to deliver hardware and software solutions for increased automation are ongoing. Companies such as Renesas, Nvidia, Intel/Mobileye and NXP are building platforms to enable Tier 1s and original equipment manufacturers (OEMs) to integrate and validate automated drive functions. Nevertheless, the “vertical” distribution of AI functionality is difficult to achieve across the traditional OEM/Tier 1/Tier 2 value chain. Due to the long innovation cycle associated with this chain, vertically integrated companies such as Tesla/Waymo currently seem to hold an advantage in the space of autonomous driving. Closed AI component ecosystems represent a risk as transparency in decision-making could prove hard to achieve, and sensor-level innovation may be stifled if interfaces are not standardised. Baidu (Apollo), Lyft, Voyage and Comma.ai take a different approach as they develop software platforms that are open, and which allow external partners to develop their own autonomous driving systems through on-vehicle and hardware platforms. Such an open and collaborative approach might be key to accelerating development and market adoption.

Next-generation energy- and resource-efficient electronic components and systems that are connected, autonomous and interactive will require AI-enabled solutions that can simplify the complexity and implement functions such as self-configuring to adapt the parameters and resource usage based on context and real-time requirements. The design of such components and systems will require a holistic strategy based on new architectural concepts and optimised HW/SW platforms. Such architectures and platforms will need to be integrated into new design operational models that consider hardware, software, connectivity and sharing of information: (i) upstream from external sources, including sensors to fuse computing/decision processes; (ii) downstream for the virtualisation of functions, actuation, software updates and new functions; and (iii) mid-stream information used to improve the active user experience and functionalities.

However, the strategical backbone technologies to realise such new architectures are still not available. These technologies include smart and scalable electronic, components and systems (controllers, sensors and actuators), AI accelerator hardware and software, security engines, and connectivity technologies. A holistic end-to-end approach is required to manage the increasing complexity of systems, to remain competitive and to continuously innovate the European electronic components and systems ecosystem. This end-to-end approach should provide new architecture concepts, HW/SW platforms that allow for the implementation of new design techniques, system engineering methods and leverage AI to drive efficiencies in processes.

Based on the European's semiconductor expertise and in view of its strategic autonomy, there is an incentive for Europe to build an ecosystem of electronic components, connectivity and software AI, especially considering how the global innovation landscape is rapidly changing due to the growing importance of digitalisation, intangible investment, and the emergence of new countries and regions.

As such, an holistic end-to-end AI technology development approach enables advances in other industrial sectors by expanding the automation levels in vehicles and industrial systems while increasing the efficiency of power consumption, integration, modularity, scalability and functional performance.

This new strategy should be anchored by a bold new digitalisation transformation since digital firms perform better and are more dynamic: they have higher labour productivity, expand faster and have better management practices[54].

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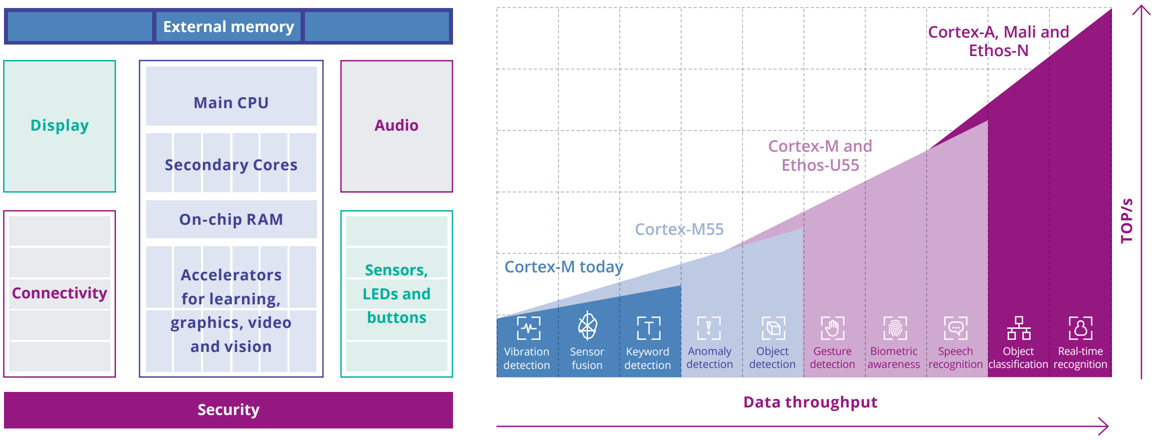
[54] *In this context, the European Investment Bank emphasis in their "Who is Prepared for the Digital Age? report in 2020 that European firms lag the US in adopting digital technologie,s with only 66% of manufacturing firms in the EU, compared to 78% in the US, having adopted at least one digital technology*



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

F.28

2.1.4.2.1 State of the art

According to the ABI Research, it is expected that 1.2 billion devices capable of on-device AI inference will be shipped by 2023, with 70% of them coming from mobile devices and wearables. Open source hardware, championed by RISC-V, will produce a new generation of open source chipsets designed for specific ML and DL applications at the edge. The market size for ASICs responsible for edge inference is expected to reach US $4.3 billion by 2024, including SoCs with integrated AI chipset, discrete ASIC and hardware accelerators. The French start-up GreenWaves is one European company that is using RISC-V cores to target the ultra-low power ML space. Its devices, GAP8 and GAP9, use 8- and 9-core compute clusters, while custom extensions give its cores a 3.6x improvement in energy consumption compared to unmodified RISC-V cores.

Qualcomm has also launched the fifth-generation Qualcomm AI Engine, which is composed of Qualcomm Kyro CPU, Adreno GPU, and Hexagon Tensor Accelerator (HTA). Developers can use CPUs, GPUs or HTAs in the AI engine to carry out their AI workloads. In addition, Qualcomm launched the Qualcomm Neural Processing software development kit (SDK) and Hexagon NN Direct to facilitate the quantisation and deployment of AI models directly on the Hexagon 698 Processor.

The development of the neuromorphic architectures is accelerating as the global neuromorphic AI semiconductor market size is expected to grow. Huawei and MediaTek have incorporated their SoCs into IoT gateways and home entertainment, while Xilinx has focused on machine vision through its Versal ACAP SoC. Nvidia has also advanced its developments based on GPU architecture, the Nvidia Jetson AGX platform, which offers a high performance SoC that features GPU, Arm-based CPU, DL accelerators and image signal processors.

Arm is developing the new Cortex-M55 core designed for ML applications, which is used in combination with the Ethos-U55 AI accelerator that is designed for resource-constrained environments. These new Arm designs are allowing customised extensions and developing new cores designed for ultra-low-power ML.

In the next few years, hardware will serve as a differentiator in AI, and AI-related components will constitute a significant proportion of future demand for different applications. According to McKinsey, by 2025 it is expected that AI-related semiconductors will account for almost 20% of all demand, which would translate into about US $65 billion in revenue, with opportunities emerging at data centres and the edge.

In addition, PWC has said it believes the market for AI-related semiconductors will expand to more than US $30 billion by 2022. The market for semiconductors powering inference systems is likely to remain fragmented since potential use cases (facial recognition, robotics, factory automation, autonomous driving, surveillance, etc) will require tailored solutions. In comparison, training systems will be primarily based on traditional CPUs, GPUs, FPGA infrastructures and ASICs.

2.1.4.2.2 Vision and expected outcome

The reference architectures for future AI-based systems need to provide modular and scalable solutions that support interoperability and interfaces among platforms that can exchange information and share computing resources to allow the functional evolution of silicon-based embedded systems.

The evolution of AI-based components and embedded systems is no longer expected to be linear, and will depend on the efficiency and features provided by AI-based algorithms, techniques and methods applied to solve specific problems. This allows for the enhancement of the capabilities of AI-based embedded systems using open architecture concepts to develop HW/SW platforms, enabling continuous innovation instead of patching the existing designs with new features that will ultimately block further development of specific components and systems.

Europe has an opportunity to develop and use open reference architecture concepts for accelerating the research and innovation of AI-based components and embedded systems at the edge and deep edge that can be applied across industrial sectors. The use of reference open architecture will support the increase of stakeholder diversity and AI-based embedded systems, IoT/IIoT ecosystems. This will result in a positive impact on market adoption, system cost, quality and innovation, and will support the development of interoperable and secure embedded systems supported by a strong European R&D&I ecosystem.

Europe can, and should, drive the development of scalable and connected HW/SW AI-based platforms. Such platforms will efficiently share resources across platforms and optimise computation based on needs and functions. As such, the processing resource will dynamically adjust the type, speed and energy consumption of processing resource depending on the instantaneous required functionality.

This can be extended to the different layers of the architecture by providing scalable concepts for hardware, software, connectivity, AI algorithms (inference, learning) and the design of flexible heterogenous architectures that optimise the use of computing resources.

Optimising the performance parameters of AI-based components in embedded systems within the envelope based on energy efficiency, cost, heat dissipation, size and weight using reference architecture can scale across the information continuum from end-point deep edge to edge, cloud and data centre.

2.1.4.2.3 Key focus areas

- Evolving the architecture, design and semiconductor technologies of AI-based components and systems, integration into IoT/IIoT devices' semiconductor chips with applications in automation, intelligent connectivity, enabling seamless interactions and optimised decision-making for semi-autonomous and autonomous systems.
- New AI-based HW/SW architectures and platforms with increased dependability, optimised for increased energy efficiency, low cost, compactness, and providing balanced mechanisms between performance and interoperability to support the integration into various applications across industrial sectors.

- Edge and deep-edge components, architectures and interoperability concepts for AI edge-based platforms for data tagging, training, deployment and analysis.
- Deterministic behaviours, low latency and reliable communications are also important for other vertical applications, such as connected cars, where edge computing and AI represent the enabling technology, independently from the aspects of sustainability. The evolution of 5G is strongly dependent on edge computing and multi-access edge computing (MEC) developments.
- Developing new design concepts for AI-based embedded systems to facilitate trust by providing reliable design techniques that enable the end-to-end AI systems to be scalable, make correct decisions in a repetitive manner, provide mechanisms to be transparent, explainable and able to achieve repeatable results, and embed features for AI models' and interfaces' interpretability.
- Distributed edge-computing architecture with AI models running on distributed devices, servers or gateways away from data centres or cloud servers.
- Scalable hardware-agnostic AI models capable of delivering comparable performance on different computing platforms (e.g. Intel, AMD or Arm architectures).
- Seamless and secure integration on HW/SW embedded systems with the AI models integrated in the SW/HW and application programming interfaces (APIs) to support configurable data integrated with enterprise authentication technologies through standards-based methods.
- Development of AI-based HW/SW for multi-tasking and to provide techniques for adapting the trained model to produce close or expected outputs when provided with different but related sets of data. These new solutions must provide dynamic transfer learning by assuring the transfer of training instance, feature representation, parameters and relational knowledge from the existing trained AI model to a new one that addresses the new target task.
- HW/SW techniques and architectures for self-optimising, reconfiguring and self-managing the resource demands (memory management, power consumption, model selection, hyperparameter tuning for automated ML scenarios, etc).
- Edge-based robust energy-efficient AI-based HW/SW for processing incomplete information with incomplete data, in real time.
- End-to-end AI architecture, including the continuum of AI-based techniques, methods and interoperability across sensor-based systems, device-connected system gateway-connected systems, edge processing units, on-premises servers, etc.
- Developing tools and techniques that facilitate the management of complexity (e.g. using AI methods).

2.1.4.3 Major challenge 3: Supporting the increasing lifespan of devices and systems

Increasing the lifetime of an electronic object is very complex and has multiple facets. This includes the life extension of the object itself up to the movement of some of its critical parts into other objects, and ultimately of the recycling of raw material into new objects. This domain of lifetime extension is very error prone as it is extremely easy to confuse some very different concepts, such as upgradability and re-use, up to recycling.

The first level of lifetime extension is obviously an upgrade to avoid replacing the object, and instead to improve its features and performance either through a hardware or software update. This concept is not new, as has been applied in several industrial domains for many years. The new aspect of AI systems is being able to upgrade while also preserving the existing level of safety and performance. For previous systems based on algorithmic approach, the behaviour of the system could be evaluated offline by validating the upgrade using a predefined dataset that is sufficiently representative of the operating conditions, and being aware of how the data is processed. In the case of AI, matters are very different, as how the data are processed is not always understood, but what is key is the dataset themselves and the results they produce. In these conditions, it is important to have a framework where people can reasonably validate their modification, whether in hardware or software, to ensure an adequate level of performance and safety, especially for systems where human life is critical.

The second aspect of increased lifetime is to re-use a system in an application framework that is less demanding in terms of performance, power consumption, safety, etc. To re-use something in an environment for which it was not initially designed, it is key to be able to qualify the part in its new environment. To achieve a very challenging goal; the main question is: "what are the objective parameters to take into account to guarantee that the degraded part is compatible with its new working environment?".

The other main area of lifetime extension is how AI can identify very low signals in a noisy data environment. In the case of predictive maintenance, for instance, it is difficult for complex machinery to identify in advance a potential failing part. The machinery is more complex and it is less possible to achieve a complete analytic view of the system that would allow simulation, and then identify in advance potential problems. Due to AI and collecting large datasets, it is possible to extract some extremely complex patterns that can allow very early identification of parts with a potential problem. AI could not only identify these parts, but also give some advice regarding when an exchange is needed before failure, and then help in maintenance task planning.

Whatever the solution used to extend the lifetime of systems, it cannot be achieved without a strong framework regarding standards and, even more importantly, for an AI qualification framework of solutions. AI systems are new and currently involve little standardisation. Therefore, it is of great importance that effort is devoted to this aspect of AI hardware software development. Europe has a very diverse industrial structure, which is a strength if all players have early access to the standards frameworks for AI and its development vectors. Open access is therefore as crucial for the European AI ecosystem as the ability to upgrade and participate in the development of AI interfaces. Another very significant point is how we qualify an AI solution. Compared to computing systems based on algorithms, there are numerous tools and environments to detect and certify if a system has a given property due to static code analysis, formal proof, worst-case execution time, etc. For AI, most of these solutions are not applicable as the performance of the system depends on the quality of the datasets used for training, and the quality of data used during the inference phases.

For this reason, we recommend a strong and dedicated focus on forthcoming AI standards. Nevertheless, we need to bear in mind that standards are a strong business lever, and ensure that European companies can build on top of standards and generate value at the European level. For instance, android is open source but there is no way to produce a competitive smartphone without a Google android licence.

2.1.4.3.1 State of the art

Interoperability, modularity, scalability, virtualisation and upgradability are well known in embedded systems, and already widely applied. However, they are completely new in AI and nearly non-existent in edge AI. In addition, self-x (learning/training, configuration or reconfiguration, adaptation, etc) is extremely promising but still being researched or at a low level of development. Federative learning and prediction on the fly will also certainly take a large place in future edge AI systems, where many similar equipment collect data (smartphone, electrical vehicles, etc) and could be improved and refreshed continuously. Below is a list of some of the potential developments for the different aspects of this challenge.

Increasing lifespan from technological bricks

- Developing HW/SW architectures and hardware that support software upgradability and extending the software's useful life: Software upgradability is necessary in nearly all systems, and hardware should be able to support future updates. AI is introducing additional constraints compared to previous systems. The multiplicity of AI approaches (ML, DL, semantic, symbolic, etc) and neural network architectures based on a huge diversity of neuron types (CNN, RNN, etc), and the potential complete reconfiguration of neural networks for the same system (linked to a same use case) with a retraining phase based on an adapted set of data, make upgradability much more complex. This this why HW/SW, related stacks, tools, and datasets compatible with the edge AI system must be developed in synergy. HW/SW plasticity is necessary whatever the AI background principle of each system to make them upgradable and interoperable as much as possible, and to extend the system's lifetime. HW virtualisation will help to achieve this, as will standardisation. The key point is that lifespan extension, as with power management, produces requirements that must be considered from day one of the system's design. It is impossible to introduce them near the end without rigorous re-working.

- Standardisation: Standards are very difficult to define as they should not be overly restrictive to avoid limiting innovation, but not be too open to avoid numerous objects that are compliant with the standard but not really interoperable because they do not support the same options of the same standard. For this reason, the concept of introducing standards early in the innovation process must be complemented by a visionary perspective with a view to extending the prospective standards for future expansions in function, feature, form and performance.

- Modularity and scalability: For AI, an additional dimension must be integrated into the modularity/scalability landscape relating to the learning/training phase and dataset. The major questions concern upgrading the training of an AI without restarting from the beginning, and how to add/upgrade an AI implementation. Also, it is important to consider how to add new data to a given dataset and integrate this knowledge into the existing AI. All these issues are new challenges that need to be addressed for AI systems to make them fully modular and scalable.

- Re-use: A concept called "second life" actually re-uses parts of systems [55]. Such re-use could be adapted to edge AI if some basic rules are followed. First, it is possible to extract the edge AI HW/SW module that is performing a set of functions – for example, the module that

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55 *For example, car builders are building a stream to re-use Li-ion car batteries when those batteries have a degraded level of energy storage that is not sufficient for electrical vehicles. Instead of recycling directly the valuable metals from those battery packs, it may be useful to remove them from vehicles and to repurpose them for a second-life application in energy storage services that are suitable to their reduced performances.*

performs classification for images, movements detection, sounds recognition, etc. Second, the edge AI module can be requalified and recertified by downgrading its quality level. A module implemented in aeronautic systems, for instance, could be re-used in automotive or industrial applications, or a module used in industry could be re-used in consumer applications. Third, the AI network could be retrained to fit the second life, Similar use case – for example, going from smart manufacturing to smart home. Last, a business model will be affordable only if such second-life, use is on a significant volume scale. A specific edge AI-embedded module integrated into tens of thousands of cars could be removed and transferred to a new consumer product being sold on the market.

- Prediction and improvements: Prediction/improvements with pure analytics techniques is always difficult. Very often, the analytic behaviours of some system parts are not known, and then either approximate models are developed or it is just ignored. Due to AI, such a system will be able to evolve based on data collected during its running phase. AI techniques will allow better prediction method based on real data, allowing for the creation of aggregated and more pertinent indicators not possible with a pure analytic approach.

- Realising self-x (adaptation, reconfiguration, etc): For embedded systems' self-adaptation, self-reconfiguration has an enormous AI potential in many applications. Usually in self-reorganising systems, the major issue is how to self-reorganise while preserving the key parameters of a system (performance, power consumption, real-time constraints, etc). For any system, there is an operating area that is defined in the multidimensional operating parameter space, and which has coherent requirements. Of course, very often the real operating conditions do not always cover the whole operating domain for which the system was initially designed. With AI, when some malfunctioning parts are identified, it could then be possible to decide – by using AI and data accumulated during the system's operation – if it affects the behaviour of the system regarding its real operating conditions. If this is not the case, it could be considered that the system can continue to work, with maybe some limitations that are not vital to its normal operation. This would then extend its lifetime "in place". The second case is to better understand the degraded part of a system, and then its new operating space. This can be used to decide how it could be integrated into another application, ensuring that the new operating space of the new part is compatible with the operating requirements of the new hosting system.

- Self-learning technics hold promise: Predictions from natural language understanding (NLU) on the fly or by keyboard typing, predictive maintenance on mechanical systems (e.g. motors) are being increasingly researched. Many domains could benefit from such AI in mobility, smart building, communications infrastructure [56], etc.

[56] *https://cecas.clemson.edu/~avahidi/wp-content/uploads/2016/10/chen.pdf, http://www.osti.gov/biblio/1409303, https://www.researchgate.net/publication/224190659_An_experimental_study_on_the_fuel_reduction_potential_of_heavy_duty_vehicle_platooning, https://www.iea.org/reports/digitalisation-and-energy*

2.1.4.3.2 Vision and expected outcome

Intelligent reconfigurable control concepts are an essential key technology for increasing the re-use and service life of hardware and software components. Such modular solutions at the system level require the consideration of different quality or development stages of sensors, software or AI solutions. If the resulting uncertainties (measurements, predictions, estimates by virtual sensors, etc) are assessed in networked control concepts, the interoperability of agents/objects of different generations can be designed in an optimal way.

- Optimisation: Optimisation at the operational level of a networked control system ensures that goals and cost functions for distributed agents are adopted in an overall optimal sense. In this context, continuous monitoring and diagnosis also play a crucial role for the optimisation of product lifetime. Where a large amount of data is collected during daily life operation (e.g. usage, environment, sensor data), big data analysis techniques can be used to predictively manipulate the operational strategy (e.g. to extend service life). Similarly, an increase in power efficiency can be achieved by adjusting the calibration in individual agents. For example, a fuel cell electric vehicle has an operation strategy that decisively determines durability and service life.

- Another essential factor for increasing the lifespan of products is the intelligent use and handling of real-world data from products that are already in use, and from previous generations of these. On the one hand, this allows for optimal adaptation of the operating strategy to, for example, regionally, seasonally, or even individually varying use patterns. On the other hand, the monitoring of all agents (e.g. fleets of vehicles) also enables very precise estimates and predictions of certain conditions. This enables the detection of early failures of individual objects, but also the timely implementation of countermeasures. Such approaches can be referred to as “distributed monitoring”.

- Distributed predictive optimisation is possible whenever information about future events in a complex system is available. Examples here are load predictions in networked traffic control or demand forecasts for smart energy supply networks. In automation, the concept of dual control involves monitoring and state observation, leading to safety-aware and reconfigurable automation systems. Naturally, all these concepts, as they concern complex distributed systems, must rely on the availability of a vast amount of data, something commonly associated with the term “big data”. Note that in distributed systems the information content of big data is mostly processed, condensed and evaluated locally, thus relieving both the communication and computational infrastructure.

- Distributed monitoring: Future systems will be equipped with even more sensors, and the continuous exchange of data will open numerous possibilities for the monitoring and diagnosis of individual systems and components. Autonomous vehicles, with their vast onboard sensors, are just one example. Distributed monitoring collects data from various interconnected agents in real time (truck platoon, aircraft swarm, smart electricity distribution network, fleet of electric vehicles, etc), and uses these data to draw conclusions about the state of the overall system (such as the state of health or the state of a function). This allows for the detection of changing behaviour or faulty conditions in the systems, and even to isolate them by attributing causes to changes in individual agents in the network, or the ageing of individual objects and components. Such detection should be accomplished by analysing the continuous data stream that is available in the network of agents. A statistical or model-based comparison of the individual objects with each other provides additional insights. Thus, for example, early failures of individual systems could be predicted in advance.

- Dynamic reconfiguration: A critical feature of AI circuits is the ability to dynamically change their functions in real time to match the computing needs of the software, AI algorithms and the data available, and then to create software-defined AI circuits and virtualise AI functions on different computing platforms. The use of reconfigurable computing technology for IoT devices with AI capabilities allows hardware architecture and functions to change with software, providing scalability, flexibility, high performance and low-power consumption for the hardware. The reconfigurable computing architectures, integrated into AI-based circuits, can support several AI algorithms (e.g. convolutional neural networks (CNNs), fully connected neural networks, recursive neural networks (RNNs), etc), and to increase the accuracy, performance and energy efficiency of the algorithms as integrated as part of software-defined functions.

One challenge of the AI edge model is the upgradability of the firmware updates, as well as the new learning/training algorithms for edge devices. This includes the updates over the air and the device management of the updating of AI/ML algorithms based on the training and retraining of the networks (neural networks, etc), which for IoT devices at the edge is very much distributed and adapted to the various devices. The challenge of the AI edge inference model is to gather sufficient data for training to refine the inference model as there is no continuous feedback loop for providing this.

2.1.4.3.3 Key focus areas

- Developing HW/SW architectures and hardware that support software upgradability and the extension of software's useful life considering AI specificities. As discussed, the upgradability of solutions is now a very important issue, one that has been integrated into design for a while. Nevertheless, with AI new challenges arise such as data management, certification of a new AI system and integration of new learning/training capabilities. The main difference with traditional approaches based on analytic solutions is the fact that it used to be possible to validate the solution "out of place", meaning validating how data are processed independently of the data themselves. In the case of AI, data are at the heart of the solution, so validation must be carried out on a sample of data that must considered representative of the unknown data, which can then be processed later by the system. This is one of the major difficulties regarding upgradability.

- Realising self-x (adaptation, reconfiguration, etc) for embedded systems. Reconfiguring solutions has been at the heart of computing systems for decades, either at the hardware or software level. This is not new, but has certainly become much more important for AI systems. In addition to all the challenges that traditional systems face, which also apply to AI systems, there are new ones to consider related to how to manage the learning phase with existing data and the inference phase for new data. As well as standard tooling, which could be in place for computing systems, upgrades will be needed to support AI solutions, and especially all aspects relating to data management. This is a mandatory evolution to maintain the productivity of design/development teams at a competitive level.

- Improving interoperability, modularity and complementarity between generations of devices. This is a valid concern for any system. It has been considered for years on traditional computing systems more or less successfully, depending on the parameters taken into account in the reusability process. For AI, things are somewhat more complex as all the data side has to be integrated into the decision process (learning/training phase and inference phase), but more simply at the same time, as this process can itself benefit from AI power. In any case, special attention must be paid to integrating modularity/upgradability in the data aspect, and how AI techniques can help in this direction. Once again, specific tooling is required to maximise the productivity of development teams while preserving the compliance of systems to their requirements.

- Developing the concept of second life for components. This is an important concept for improving the lifetime of systems. It should be examined on the following levels.
  - How to increase lifetime “in place” – meaning, what can be done to increase the lifetime of a system in its initial function? In that respect, AI can help by offering a much better view on system behaviour, and by allowing many more pertinent solutions than those provided by pure analytic approach.
  - Due to AI, the second view can facilitate the re-use of a function block from one application to another to ease the migration. This provides improved understanding of the key working parameters of the initial solution and the possible match of this solution to a new working environment. To achieve this, it is important to have the right tooling that allows the system designer to make the transition in a very secure and predictive way and with good productivity. It is mandatory to be in a situation where re-use is better than using new.

2.1.4.4 Major challenge 4: Ensuring European sustainability in AI, edge computing and advanced control

Technology is strongly affected by sustainability. This can very frequently tip the scale between technologies that are promising but not practically usable, and technologies that really make a difference. Data centres, a fundamental element for the digitalisation process, are already trying to follow a positive trend towards sustainability, especially important as they consume a great deal of energy[57], are responsible for significant carbon emissions and, at the product end-of-life, generate much electronic waste.

Today, the percentage of global electricity consumed by data centres is estimated to exceed 3%, while CO_2 emissions are estimated to reach 2% of worldwide emissions[58, 59], with cloud computing being responsible for half of such emissions. Moves have already been made to try to reduce the power consumption of data centres by improving their efficiency, using green energy to power them, and also by introducing new computing paradigms that could indirectly reduce their environmental footprint. A recent study has predicted that, without energy-efficient

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57 *Andrae, Anders. (2017). Total Consumer Power Consumption Forecast.*

58 *Koronen, C., Åhman, M. & Nilsson, L.J. Data centres in future European energy systems—energy efficiency, integration and policy. Energy Efficiency 13, 129–144 (2020)*

59 *https://datacentrereview.com/content-library/490-how-to-reduce-data-centre-energy-waste-without-sinking-it-into-the-sea*

solutions, by 2025[56] data centres will consume 20% of the world's energy, with a carbon footprint rising to 5.5% of global emissions. Shifting computing to the edge, for example, could bring a reduction in data traffic, and data centres' storage and processing.

However, data centres' environmental footprint is also due to their production, installation and maintenance, as well as their use of greenhouse gases and the production of significant electronics and chemical toxic waste (e.g. liquid coolants)[38].

Data centres represent just a small portion of the technologies potentially involved in the digital transformation, which largely relies on the move to edge computing, AI, IoT, hyper-connectivity, etc – that is, on technologies that could significantly impact the overall sustainability of digitalisation solutions. In recent years, AI, edge computing and advanced control have been a focus for the scientific community, environmental entities and public opinion due to their increasing levels of energy consumption, questioning the sustainability of these technologies and, indirectly, their impact on corporate, vertical applications and societal sustainability. This situation has been worsened by the Covid-19 pandemic, which has generated a worldwide reduction of power consumption as a result of global lockdown restrictions while at the same time causing a huge spike in internet usage. For instance, NETSCOUT Systems measured an increase of 25–35% in global internet traffic in March 2020 just from the move to more remote working, online learning and entertainment. This spike in internet use provides a flavour of the implications of digitalisation on sustainability. Reducing energy of computing and storage devices is therefore a Major challenge (**see Major challenge 1**).

Shifting to green energy is certainly a complementary approach to ensuring sustainability, but the conjunction of AI and edge computing – edge AI – has the potential to provide sustainable solutions with a wider and more consolidated impact. Indeed, a more effective and longer-term approach to sustainable digitalisation implies reconsidering the current models adopted for data storage, filtering, analysis, processing and communication. By embracing edge computing, for example, it is possible to significantly reduce the amount of unnecessary and wasteful data flowing to and from the cloud and data centres, with an architectural and structural solution that permanently reduces overall power consumption. The edge computing paradigm also makes AI more sustainable: it is evident that cloud-based ML inference is characterised by a huge network load, with a concomitant serious impact on power consumption and huge costs for organisations. Transferring ML inference and data pruning to the edge, for example, could exponentially decrease digitalisation costs and enable sustainable businesses.

It is also important to note that the sustainability of AI, edge computing and advanced control depends on a wider set of factors, including energy consumption, extending data storage, processing and management, but has also the engineering processes adopted to design and develop edge/AI solutions – from the way they are operated and maintained, to the electronics waste they produce, etc.

2.1.4.4.1 State of the art

AI, and particularly embedded intelligence with its ubiquity and capacity to integrate with the environment and disappear in it, is significantly influencing many aspects of our daily lives, our society, the environment, the organisations in which we work, etc. AI is already affecting several heterogeneous and disparate sectors, such as companies' productivity[60], environmental applications such as nature preservation[61], society in terms of gender discrimination and inclusion[62, 63], smarter transportation systems[64], to mention just a few examples. The effect of AI on these sectors is expected to generate both positive and negative effects on the sustainability of AI itself, as well as the solutions based on AI and on their users[65, 66]. It is difficult to extensively assess these effects, and to date there has been no comprehensive analysis of their impact on sustainability. One recent study[67] has tried to fill this gap, analysing AI from the perspective of 17 Sustainable Development[68] Goals (SDGs) and 169 targets internationally agreed in the 2030 Agenda for Sustainable Development . This study found that AI can enable the accomplishment of 134 targets, but may also inhibit 59 targets in the areas of society, education, healthcare, green energy production, sustainable cities and communities.

From a technological perspective, AI sustainability depends, in the first instance, on the availability of hardware[69] and software technologies. From an application perspective, automotive, computing and healthcare are propelling the large demand of AI microchips and, considering the application domains, of microchips for embedded intelligence and edge AI. Both research and industry are trying to provide technologies that lead to sustainable solutions able to redefine traditional processor architectures and memory interfaces. We have already seen that near- and in-memory computing can lead to parallel processing in a sustainable way.

The second important component of AI that impacts sustainability is represented by software, and involves the engineering tools adopted to design and develop AI algorithms, frameworks and applications. The majority of AI software and engineering tools use an open source approach to ensure performance, quality and software engineering sustainability. If the entire community contributes, for instance, there is greater potential to distribute the engineering effort, reduce costs, improve the quality of the result, security, etc. Open source codes published on shared repositories, such as GitHub, can be analysed, executed, tested and verified by other researchers and developers in the community. Hence, the source code[70] can evolve and improve faster, and new algorithms can be developed much more quickly, potentially generating new applications with a shorter time to market. In this case, sustainability is measured in terms of software efficiency and performance, engineering costs, products quality, price and business aspects.

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60 *Acemoglu, D. & Restrepo, P. "Artificial Intelligence, Automation, and Work". NBER Working Paper No. 24196 (National Bereau of Economic Research, 2018)*

61 *Norouzzadeh, M. S. et al. « Automatically identifying, counting, and describing wild animals in camera-trap images with deep learning". Proc. Natl Acad. Sci. USA 115, E5716–E5725 (2018)*

62 *Bolukbasi, T., Chang, K.-W., Zou, J., Saligrama, V. & Kalai, A. Man is to computer programmer as woman is to homemaker? Debiasing word embeddings. Adv. Neural Inf. Process. Syst. 29, 4349–4357 (2016)*

63 *Tegmark, M. Life 3.0: Being Human in the Age of Artificial Intelligence (Random House Audio Publishing Group, 2017)*

64 *Adeli, H. & Jiang, X. Intelligent Infrastructure: Neural Networks, Wavelets, and Chaos Theory for Intelligent Transportation Systems and Smart Structures (CRC Press, 2008)*

65 *Jean, N. et al. "Combining satellite imagery and machine learning to predict poverty". Science (80) 353, 790–794 (2016)*

66 *Courtland, R. "Bias detectives: the researchers striving to make algorithms fair". Nature 558, 357–360 (2018)*

67 *Vinuesa, R., Azizpour, H., Leite, I. et al. "The role of artificial intelligence in achieving the Sustainable Development Goals". Nat Commun 11, 233 (2020)*

68 *UN General Assembly (UNGA). A/RES/70/1. "Transforming our world: the 2030 Agenda for Sustainable Development". Resolut 25, 1–35 (2015)*

69 *AI is boosting the semiconductor industry, which already has a market worth US$68.5 billion by the mid-2020s, according to IHS Markit. The boom in this market is due to the availability of emerging processor architectures for GPUs, FPGAs, ASICs and CPUs that enable applications based on deep learning and vector processing.*

Sustainability through open technologies also extends to open data. The publication of open data is facilitating the work of researchers and developers in ML and DL, with numerous images and text databases being used to train the models and become benchmarks. A few such examples are ImageNet (14 million images in open data), MNIST and WordNet (English linguistic basis).

For expert systems, open source rules engines are currently available (Clips, Drools distributed by Red Hat, DTRules by Java, Gandalf on PHP). Open source also covers development libraries: for example, Nvidia Rapids is a set of libraries in Python dedicated to ML and based on APIs CUDA-X supporting the distribution of data treatment amongst several GPUs and servers. Amazon and Google have also developed libraries to help produce smart assistants based on NLU and running on data centres. With these libraries, some small companies have also developed assistance in embedded systems that protect privacy by design, as well as providing open source datasets for NLU benchmarks and inference libraries for embedded DL neural networks. These libraries are optimised for on-the-fly prediction in speech streaming, drastically reducing the latency.

Eventually, with open source initiatives being so numerous, heterogeneous and adopting different technologies, they will provide a rich set of potential solutions, allowing for the selection of the most sustainable depending on the vertical application. Open source is a strong attractor for applications developers, as it gathers their efforts around similar solutions for given use cases, democratises those solutions and speeds up their development. GAFAM have greatly understood this, and elaborated business models in line with open source. Frida Polli[71] has also described seven very simple principles for designing more ethical AI, with the open source method being one of them. Open source represents a sustainable development approach embraced by almost all the large players in the AI software market, and which are proposing their open source frameworks to create, for example, DL networks (Tensorflow at Google, PyTorch/Caffe at Facebook, CNTK at Microsoft, Watson at IBM, DSSTNE at Amazon). However, GAFAM also have strategies to utilise these aspects to undermine the advantages – for example, Amazon, with its "Alexa Communication Kit" (ACK) is providing a low-cost connected microcontroller that an edge device manufacturer can directly integrate into their products, freeing them of the burden of developing, accessing and managing the cloud, and ensuring security, authentication, set-up, management, over-the-air updates, as well as adding voice control of their products through Alexa. This approach is quite interesting for a manufacturer, but then they are tied to the ecosystem, and do not master the AI aspects of their product.

70 *An example of open source software is FAIR (Facebook AI Research), published in May 2018, or OpenGo, the open source version of an AI winning at Go game (Open Sources ELF OpenGo de Yuandong Tian et Larry Zitnick, May 2018)*

71 *https://www.fastcompany.com/90386065/seven-very-simple-steps-to-design-more-ethical-ai*

This is a danger for Europe, that vertical companies will rule AI applications and development because they also master the complete value chain. First, they have the large compute infrastructure for large learning networks[72], and they have control of most of the value chain. Europe therefore has to address the end-to-end value chain. 90% of revenues in Europe are made by small and medium-sized enterprises (SMEs), and since their products result in the cooperation of multiple participants in the value chain, European stakeholders should really cooperate with each other.

The crisis linked to the Covid-19 pandemic has made it clear that geopolitics is taking over the efficiency of outsourcing (sovereignty, decrease of availabilities of goods from abroad), leading to an evolution in business models. It has also led to an understanding that Europe needs to join forces to solve this global challenge. Sharing information and resources must be in the next business model, with coordination of the value chain being crucial: the strength of the vertical companies (GAFAM, BATX, but also Samsung) shows that the chain is coordinated by these companies' management. European coordination, and an understanding by each participant that the success of the complete value chain is paramount, is important to support SME's business model to avoid them being eaten up (buy-out of European SMEs). Since modern digital solutions cannot be provided by just one company (because of complexity, multi-disciplinarity and business dynamics), the future of European innovation is dependent on alliances in the value chain (from value chain to value network). Software, protocols and standards act as a glue. Data management, aggregation of data and the exchange of data is crucial[73] to create a working value chain. For example, semiconductor companies must move up in the value chain, offering solutions and services, not just components.

There has recently been significantly greater attention given to the identification of sustainable computing solutions in modern digitalisation processes. Climate changes and initiatives such as the European Green Deal[74] are generating more sensitivity to sustainability topics, highlighting that we must always consider the impact of technology on our planet, which has a delicate equilibrium and limited resources[75]. The computing approaches available today are on the list of the technologies that could potentially lead to unsustainable impacts.

2.1.4.4.2 Vision and expected outcome

The convergence of AI and edge computing, known as "embedded intelligence" or "edge AI", is expected to provide a reasonable trade-off towards sustainability, providing processing power and intelligent algorithms only where and when it is needed, requiring less storage and using connectivity in an optimal way. Today, decentralised

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72 *GPT-3 175B model required 3.14E23 of computing for training. Even at theoretical 28 TFLOPS for V100 GPU, this will take 355 GPU-years and cost US$4.6 million for a single training run)from https://lambdalabs.com/blog/demystifying-gpt-3/)*

73 *Taking into account the intellectual properties rights of each participant, and a fair sharing of the benefits.*

74 *https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en*

75 *12. Nardi, B., Tomlinson, B., Patterson, D.J., Chen, J., Pargman, D., Raghavan, B., Penzenstadler, B.: „Computing within limits". Commun. ACM. 61, 86–93 (2018).*

computing is again becoming[76, 77] extremely important as the amount of data to be transmitted and processed are limited by aspects such as network bandwidth, security, power consumption and, more generally, sustainability.

Sustainability of edge computing and AI is affected by many technological factors, and at the same time it is having a positive impact on future digitalisation solutions. Edge computing offers a second life to a vast amount of existing hardware already deployed, provided with decent computing power and resources, and currently underused. New initiatives are trying to include/integrate these computers into edge computing solutions, and a research area specifically focused on the energy-sensitive use of resources and the balancing of processing load is rapidly growing. Extremely usefully, AI is resulting in automating these optimisations and balancing algorithms (see, for example, Autoscale from Facebook) that, with embedded intelligence, could be also brought on the edge. Solutions for the integration/inclusion of existing hardware will have a positive impact on sustainability, and open up new business opportunities.

Two of the primary drivers for the adoption of edge computing are its real-time and low-latency potentialities. Processing data on site completely removes the latencies that characterise cloud-based solutions, offering real-time or near real-time applications for the final user, that contribute to social sustainability of edge AI and provide a competitive advantage with respect to centralised solutions. Moreover, in advanced control, real-time reactions could generate instabilities in the control mechanisms, and the real-time capabilities of solutions based on edge computing should address this issue to ensure sustainability. More generally, the reasonable adoption of edge AI at the application level significantly contributes to sustainability: senseless applications based on edge AI should be avoided.

Edge computing will also significantly reduce network traffic, freeing up bandwidth, impacting network efficiency, reliability and power consumption.

Innovation in edge computing security represents a key factor for social and business sustainability. Processing information on the edge reduces the risks of confidentiality and privacy issues, but very soon will represent just another target for the cybercriminal. Sustainable security solutions must be identified to protect the edge, and should be linked to new business models that support a decentralised and distributed computing architecture.

The presence of AI on the edge will affect sustainability in different ways. Learning capabilities are typically expensive in terms of cost, power consumption, required resources, etc, but will allow for reliable

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76 *Decentralised computing is not a novelty, and was adopted a long time before the advent of cloud-computing: currently, edge computing embraces a wide set of paradigms, including fog computing, mobile edge computing, mobile cloud computing, etc.*

77 *Some standards are emerging (e.g. IEC 62541, IEEE 1934, ETSI MEC, etc), but there is no one consolidated scenario.*

and predictable behaviours and create consolidated models with a positive return of investment based on the increased efficiency of the process and services adopting those models. Considering security and privacy, edge computing increases the protection of information, but the presence of intelligence on the edge will bring the creation of new insightful data that, if not adequately protected and managed, could lead to the social unsustainability of edge AI (confidentialities and privacy abuses, trade unfairness, people discrimination, etc). Code mobility (e.g. container technologies) could also reduce data protection on the edge, increasing the exposure of confidential and private information. At the application level, edge AI has a potential positive impact on ecologic sustainability: consider, for example, the application of AI for optimising and reducing power consumption in manufacturing plants, buildings, households, etc. The potential impact is clear, but to ensure real sustainable development and benefits, edge AI solutions will have to ensure that the costs savings are significantly larger than those required to design, implement and train AI.

More generally, the implementation, deployment and management of large-scale solutions based on edge AI could be problematic and unsustainable if proper engineering support, automation, integration platforms and remote management solutions are not provided. At this level, the problem of sustainability includes business models, organisational aspects, companies' strategies and partnerships, and extends to the entire value chain proposing edge AI-based solutions.

From an engineering perspective, leveraging open source will help to develop European advanced solutions for edge AI (open source hardware, software, training datasets, open standards, etc). Edge AI sustainable engineering will have to face many challenges, including:

- supply chain integrity for development capability, development tools, production and software ecosystems, with support for the entire lifecycle of edge AI-based solutions.
- security for AI systems by design, oriented also to certify edge AI-based solutions – European regulations and certification processes could lead to a globally compelling advantage.
- Europe needs to establish and maintain a complete R&D ecosystem around AI.
- Europe should address the end-to-end value chain and supports its SMEs.
- identification of a roadmap for standardisation that does not hinder innovation, with the right balance to ensure European leadership in edge AI.
- Europe must strive to lead a vibrant ecosystem for AI with respect to R&D, development and production, security mechanisms, certifications and standards.

2.1.4.4.3 Key focus areas

— Energy-efficiency improvement:

- New materials and electronic components oriented to low and ultra-low power solutions.
- 3D-based device scaling for low-power consumption.
- Strategies for self-powering nodes/systems on the edge.
- Low and ultra-low power communications.
- Efficient cooling solutions.

— Improving sustainability of AI, edge computing and advanced control:

- Re-use of knowledge and models generated by embedded intelligence.
- Energy- and cost-efficient AI training.
- Efficient and secure code mobility.
- Open edge computing platforms that provide remote monitoring and control, security and privacy protection, and are linked to appropriate business models.

- Solutions for the inclusion/integration of existing embedded computers on the edge.
- Policies and operational algorithms for power consumption at the edge computing level.

— Leveraging open source to help developing European AI advanced solutions on the edge:

- Open source hardware.
- Open source software.
- Open source training datasets.
- Europe must address the end-to-end value chain.

— Engineering support to improve sustainable AI, edge computing and advanced control:

- Engineering process automation for full lifecycle support.
- Edge AI security by design.
- Engineering support for AI, edge computing and advanced control verification and certification, addressing end-to-end solutions.

2.1.5 TIMELINE

The following table illustrates the roadmaps for **Artificial Intelligence, Edge Computing and Advanced Control**.

MAJOR CHALLENGE	TOPIC
Major challenge 1: Increasing the energy efficiency of computing systems	**Topic 1.1:** Processing data where it is created
	Topic 1.2: Development of innovative hardware architectures: e.g. neuromorphic
	Topic 1.3: Developing distributed edge computing systems (*)
	Topic 1.4: Interoperability (with the same class of application) and between classes
	Topic 1.5: Scalable and modular AI (**)
	Topic 1.6: Co-design: algorithms, HW, SW and topologies

SHORT TERM (2021–2025)	MEDIUM TERM (2026–2029)	LONG TERM (2030–2035)
• Development of algorithms and applications where processing is moved towards edge as far as it is possible • New memory management	• Development of hybrid architectures, with smooth integration of various processing paradigms (classical, neuromorphic, deep learning), including new OSs supporting multiple computing paradigms • Advanced memory management	• Dynamic instantiation of multi-paradigm computing resources according to the specifications of the task to be performed. Automatic interfacing, discovery, and configuration of resources
• Development of neuromorphic based chips and support of this new computing model. Development of other computing paradigms (e.g. using physics to perform computing). Use of other technologies than silicon (e.g. photonics) • New In-memory computing accelerators	• Integration of neuromorphic and other computing within classical systems • Supporting tools integrating multiple computing paradigms. • Use of 2.5D, interposers and chiplets, with efficient interconnection network, e.g. using photonics)	• Integration in the same package of multiple computing paradigms (classical, Deep Learning, neuromorphic, photonic, etc) • Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and re-use of chiplets in different designs • Exploring potential use of quantum computing in Artificial Intelligence?
• Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: federated learning) • Development of edge (ex: fog) type of computing (peer to peer)	• Federated learning or similar approach demonstrating high performance for selected applications • Edge computing demonstrating high performance for selected applications	
• Create gateways between various solutions, beyond ONNX • Developing open architectures (for fast development) with maximum reuse of tools and frameworks • Interfaces standards (more than solutions) (could help explainability, with a move from black to grey boxes)	• Common interface architecture, with dynamic binding: publishing of capabilities for each device/block, flexible data structure and data converters, dynamic interconnect. • Promoting European standard for interoperability cross application silos. • Interfaces publishing non-functional properties (latency, bandwidth, energy, etc)	• At all levels (from chips to systems), automatic interoperability, adaptation to the data structure and physical interface, considering the communication characteristics. (mid-term: automatic translator of data and data format) • Global reconfiguration of the resources to satisfy the functional and non-functional requirements (latency, energy, etc)
• Using the same software development infrastructure from deep edge to edge and possibly HPC applications. • Use of similar building blocks from deep edge to edge devices	• Scalable architecture (in three dimensions). Use of interposer and chiplets to build chips for various applications (for edge and for HPC applications) with the same hardware building blocks	• Linear and/or functional scalability • Digital twin (functionalities simulation) • Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and re-use of chiplets in different designs
• Quick implementation and optimization of HW for the new emerging algorithms	• Tools allowing semi-automatic design exploration of the space of configurations, including variants of algorithms, computing paradigms, hardware performances, etc..	• Auto-configuration of a distributed set of resources to satisfy the application requirements (functional and non-functional)

MAJOR CHALLENGE	TOPIC
Major challenge 2: Managing the increasing complexity of systems	**Topic 2.1:** Balanced mechanisms between performance and interoperability
	Topic 2.2: Development of trustable AI
	Topic 2.3: Developing distributed edge computing systems (*)
	Topic 2.4: Scalable and modular AI (**)
	Topic 2.5: Easy adaptation of models
	Topic 2.6: Realizing self-x (***) Self-optimise, reconfiguration and self-management
	Topic 2.7: Using AI techniques to help in complexity management

SHORT TERM (2021–2025)	MEDIUM TERM (2026–2029)	LONG TERM (2030–2035)
• Exposing the non-functional characteristic of devices/blocks and off-line optimisation when combining the devices/blocks	• On-line (dynamic) reconfiguration of the system to fulfill the requirements that can dynamically change (self-x)	• Drive partitioning through standards
• Move to security section	• Move to security section	• Move to security section
• See items above in increasing the energy efficiency of computing systems	• See items above in Increasing the energy efficiency of computing systems	• See items above in increasing the energy efficiency of computing systems
• See items above in increasing the energy efficiency of computing systems	• See also items above in increasing the energy efficiency of computing systems • Data and learning driven circuits design	• See items above in increasing the energy efficiency of computing systems
• Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: federated learning) • Easy migration of application on different computing platforms (different CPU – x86, ARM, Risc V- different accelerators) • Create a European training reference database for same class of applications/use cases network learning	• Optimization of the Neural Network topology from a generically learned networks to an application specific one. • Use of HW virtualisation • Automatic transcoding of application for a particular hardware instance (à la Rosetta 2)	• Generic model-based digital development system
• Add self-assessment feature to edge devices	• Automatic reconfiguration of operational resources following the self-assessment to fulfil the goal in the most efficient way	• Modelling simulation tools for scalable digital twins
• Using AI techniques for the assessment of solutions and decrease the design space exploration.	• Automatic generation of architecture according to a certain set of requirements (in a specific domain)	• Modelling simulation tools for scalable digital twins

MAJOR CHALLENGE	TOPIC
Major challenge 3: Supporting the increasing lifespan of devices and systems	**Topic 3.1:** HW supporting software upgradability
	Topic 3.2: Realising self-X (***) Also partially in managing the increasing complexity of systems
	Topic 3.3: Improving interoperability (with the same class of application) and between classes, modularity and complementarity between generations of devices Also partially in Increasing the energy efficiency of computing systems
	Topic 3.4: Developing the concept of second life for components (link with sustainability)
Major challenge 4: Ensuring European sustainability in AI, edge computing and advanced control	**Topic 4.1:** Energy efficiency improvement
	Topic 4.2: Improving sustainability of AI, edge computing and advanced control
	Topic 4.3: Leveraging open source to help developing European AI advanced solutions on the edge
	Topic 4.4: Engineering support to improve sustainable AI, edge computing and advanced control

SHORT TERM (2021–2025)	MEDIUM TERM (2026–2029)	LONG TERM (2030–2035)
• Create a European training reference database for same class of applications/use cases network learning • European training benchmarks (methods and methodologies) • Framework tools for HW/SW for fast validation and qualification • Interfaces standards compatible with most of AI approaches	• HW virtualisation based on AI algorithms • Generic AI functions virtualisation • European training standards (compliance/certification	• Explainable AI
• Unsupervised learning techniques • Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: federated learning)	• HW virtualization based on AI algorithms • Generic AI functions virtualisation	• Explainable AI
• Developing open architectures (to fast develop) with maximum re-use of tools and frameworks • Interfaces standards (more than solutions) (could help explainability move from black to grey boxes) • Clarified requirements for embedded AI in industry	• Generic AI functions modules by class of applications/use cases + virtualisation	
• Inclusion of existing embedded systems on the edge (huge market opportunity) • Library of generic set of functions (standardisation) • Basic data collection for predictive maintenance	• Generic set of functions for multi-applications/use cases • Global data collections for predictive maintenance by applications/use cases	• Standardize flow for HW/SW qualification of generic set of functions (including re-training) which are used in a downgraded application/use case
• Materials and electronic components oriented to low and ultra-low power solutions • Low and ultra-low power communications • Strategies for self-powering nodes/ systems on the edge • Efficient cooling solutions	• 3D-based device scaling for low energy consumption	
• Energy and cost-efficient AI training • Inclusion of existing embedded systems on the edge (huge market opportunity)	• Efficient and secure code mobility • Reuse of knowledge and models generated by embedded intelligence	
• Open source software • Open source training datasets • Open edge computing platforms	• Open source hardware	
• Sustainability through engineering process automation • Continuous engineering across the product lifecycle	• Holistic development environment • Engineering support for AI verification and certification • Edge AI security by design	

2.1.6
SYNERGY WITH OTHER THEMES

The scope of this section is to focus on computing components, and more specifically towards **AI, Edge Computing and Advanced Control**. These elements rely heavily on **Process Technologies, Equipment, Materials and Manufacturing**, **Embedded Software and Beyond**, limits on **Quality, Reliability, Safety and Cybersecurity**, and are composing systems (**System of Systems**) that use **Architecture and Design** techniques to fulfil the requirements of the various application domains. Please refer to all these sections in this SRIA for more details.

For example, there are close links with the section on **Quality, Reliability, Safety and Cybersecurity** on the topics of increasing “trustworthiness” of computing systems, including those using AI techniques:

- making AI systems “accepted” by people, as a certain level of explainability is required to build trust with their users.
- developing approaches to verify, certify, audit and trace computing systems.
- making systems correct by construction, and stable and robust by design.
- systems with predictable behaviour, including those using deep learning techniques.
- supporting European principles, such as privacy and having “unbiased” databases for learning, for example.

Embedded Software is also important, and the link to this is explained in the corresponding section. Systems and circuits used for AI are of course developed applying **Architecture and Design**, and tools techniques and manufactured based on technologies developed in **Process Technologies** (e.g. use of non-volatile memories, 3D stacking, etc). Artificial intelligence techniques can be also used to improve efficiency in several application domains (see chapter **ECS Key Application Areas**).

2.2

Cross-Sectional Technologies

CONNECTIVITY

2.2.1
SCOPE

The connectivity and interoperability technology focus enabling the projected commercial and societal benefits are related to the OSI model layers 1, 5 and 6. This focus is motivated by where the **Major challenges** have been identified (see *Figure F.29*).

Scope for OSI layer 1

The scope covers the following types of physical layer connectivity.

— **Cellular:**
- Beyond 5G.
- Early 6G investigation.

— **Low power wide area:**
- Cellular: narrow band IoT, LTE, 6G, etc.
- Non-cellular: SigFox, LoRa, M-Bus, etc.

— **Low power short range:**
- Wireless: existing (BT, WiFi, etc) or innovative technologies (mmW, etc).
- Wired: covering both high-speed optical and copper interconnect (USB, DOCIS, etc).

— **High speed:**
- Wireless: point to point mmW and satellite communication (low earth orbit and geosynchronous equatorial orbits).
- Wired: high-speed optical (400 Gb+, etc) and copper interconnect (Ethernet, etc).

LAYER		DATA UNIT	FUNTION
HOST LAYERS	7. Application		Network process to application.
	6. Presentation	Data	Data representation, encryption and decryption, convert machine-dependent data to machine-independent data.
	5. Session		Interhost comunication, managing sessions between applications.
	4. Transport	Segments	Reliable delivery of segments between points on a network.
MEDIA LAYERS	3. Network	Packet/Datagram	Addressing, routing and (not necessarily reliable) delivery of datagrams between points on a network.
	2. Data link	Bit/Frame	A reliable direct point-to-point data connection.
	1. Physical	Bit	A (not necessariliy reliable) direct point-to-point data connection.

Major challenges: OSI Model **F.29**

PHYSICAL LAYER CONNECTIVITY	ECS KEY APPLICATIONS					
	MOBILITY	ENERGY	DIGITAL INDUSTRY	HEALTH AND WELLBEING	AGRIFOOD AND NATURAL RESOURCES	DIGITAL SOCIETY
	3.1	3.2	3.3	3.4	3.5	3.6
Cellular	X	X	X	X	X	X
Low power wide area		X	X	X	X	X
Low power short range	X		X	X		X
High speed	X	X	X			X

F.30 *Major challenge: Ensuring European leadership in terms of connectivity technologies*

The main challenge will be to ensure European leadership in terms of connectivity technologies (for example, standards) as well as associated hardware technology supporting the development of connectivity solutions (chipset, module, etc).

Scope for OSI layer 5 and 6

The scope addressed here is the interoperability between technologies at OSI layers 5 and 6. This interoperability covers the following underlying aspects:

- protocols at all technology levels: Internet, operational and legacy.
- Security: Such as protocol security, payload encryption, certificates, tokens and key distribution.
- Data semantics: Supporting machine-to-machine understanding of transferred data/information.

2.2.2 TECHNOLOGY-ENABLED SOCIETAL BENEFITS

Beyond their economic impact, connectivity and interoperability are also expected to play a key role in many societal challenges to be faced in the coming decades. As will be illustrated in this section, the societal benefits associated with connectivity are key assets for improving the living standard of European citizens, as well as maintaining Europe leadership in this area.

- Industrial improvements: The industrial transition to Industry 4.0, with the its massive usage of automation and digitalisation accompanied by AI-supported analytics, puts much higher demands on the availability and reliability of high-speed, secure, low or guaranteed latency connectivity. Given the large amount of legacy connectivity and emerging new connectivity, interoperability over technology generations and between application domains will become an enabler for competitivity.

- Healthcare improvement: Connectivity has the potential to improve medical behaviour for patients and healthcare professionals, as well as the delivery of better medical services. Connected devices can transform the way healthcare professionals operate by allowing remote diagnosis and more efficient means of treatment. For example, patient information could be sent to hospitals via mobile and internet applications, thus saving travel time and service costs, and also substantially improving access to healthcare, especially for rural populations. Connectivity and associated devices and services could complement and improve existing medical facilities. From the citizen side, the monitoring of illnesses can also be enhanced by mobile and internet applications designed to remind patients of their treatments, and to control the distribution of medicinal stocks.

- Energy and environment: One of the projected impacts of digitalisation is an improved ability to optimise energy utilisation and minimise environmental footprints. Connectivity and interoperability are here critical elements of the information and communications technology (ICT) infrastructure that is essential to allow such optimisation and minimisation. The size of the energy efficiency market was estimated at US $221 billion in 2015, which was 14% of the global energy supply investments (IEA, 2016b), divided between buildings (53%) transport (29%) and industry (18%) (IEA, 2016a).

- Improve public services, social cohesion and digital inclusion: ICT technologies have long been recognised as promoting and facilitating social inclusion – i.e. the participation of individuals and groups in society's political, economic and societal processes. One way in which ICT technologies can expand inclusion is through effective public services that rely on ICT infrastructure, and through digital inclusion (i.e. the ability of people to use technology). These three aspects are deeply intertwined, and span dimensions as diverse as disaster relief, food security and the environment, as well as citizenship, community cohesion, self-expression and equality. Public authorities can enhance disaster relief efforts by promoting the spread of information online and by implementing early warning systems. The internet also enables relief efforts through crowd-sourcing: for instance, during Typhoon Haiyan in the Philippines, victims, witnesses and aid workers used the web to generate interactive catastrophe maps through free and downloadable software, helping disseminate information and reduce the vulnerability of people affected by the disaster. Communities can also be strengthened by connectivity, thereby promoting the inclusion of marginalised groups.

- Pandemic and natural disaster management: The growing demand for remote interactions amid the coronavirus pandemic has highlighted a need for connectivity technology, potentially accelerating adoption in the mid-term of new technology such as 5G. Lightning-fast speeds, near-instantaneous communications and increased connection density are key to supporting massive remote interactions, which has become of increasing importance for many organisations and enterprises as anxiety rises concerning the management of health or natural disasters. Two key areas – telehealth and teleconferencing – are becoming critical for enterprise operations amid pandemics or natural disasters, and an increased dependence on these areas will help strengthen the appeal of improved connectivity (for example, beyond 5G and 6G) and make connectivity a key sovereignty topic for Europe.

Applications breakthroughs

Improvements in connectivity technology will have an impact on all ECS application areas. For health and wellbeing, connectivity interoperability issues are addressed by enabling faster translation of ideas into economically viable solutions, which can be further scaled up in daily health practice. Examples of health and wellbeing application breakthroughs supported here are:

- a shift in focus from acute, hospital-based care to early prevention.
- strengthening where and how healthcare is delivered, supporting home-based care.
- stronger participation of citizens in their own care processes, enhancing patient engagement.
- supporting the clinical workforce and healthcare consumers to embrace technology-enabled care.

Improved, secure and interoperable connectivity will further support healthcare and wellbeing application breakthroughs regarding, for example:

- healthcare deployment, enabling digital health platforms.
- healthcare system paradigm transition from treatment to health prevention, enabling the shift to value-based healthcare.
- building a more integrated care delivery system, supporting the development of the home as the central location for the patient.
- enhancing access to personalised and participative treatments for chronic and lifestyle-related diseases.
- enabling more healthy life years for an ageing population.

In the mobility application area, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding:

- achieving the Green Deal for mobility, with the 2Zero goals of –37.5% CO_2 by 2030.
- increasing road safety through the CCAM programme.
- strengthening the competitiveness of the European industrial mobility digitalisation value chain.

In the energy application domain, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding:

- significant reduction of connectivity energy demand.
- enabling necessary connectivity to the integration of the future heterogenous energy grid landscape.
- "plug and play integration" of ECS into self-organised grids and multimodal systems.
- solving safety and security issues of self-organised grids and multimodal systems.

In the industry application domain, the provision of improved, robust, secure and interoperable connectivity will support closing gaps such as:

- preparing for the 5G era in communications technology, especially its manufacturing and engineering dimension.
- long-range communication technologies, optimised for machine-to-machine (M2M) communication, a large number of devices and low bit rates, are key elements in smart farming.

- solving IoT cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive in the industry.
- interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management allowing for the (semi)autonomous deployment and operation of large numbers of devices.

In the digital society application domain, the provision of improved, robust, secure and interoperable connectivity will support the overall strategy regarding:
- enabling workforce efficiency regardless of location.
- stimulating social resilience in the various member states, providing citizens with a better work/life balance and giving them freedom to also have leisure time at different locations.
- ubiquitous connectivity, giving people a broader employability and better protection against social or economic exclusion.
- enabling European governments, companies and citizens to closer cooperation, and to develop reliable societal emergency infrastructures.

In the agrifood application domain, the provision of improved, robust, secure and interoperable connectivity will support innovations addressing the EU Green Deal regarding:
- reducting the environmental impact related to transport, storage, packaging and food waste.
- reducting water pollution and greenhouse gas emission, including methane and nitrous oxide.
- reducing the European cumulated carbon and cropland footprint by 20% over the next 20 years, while the improving climatic resilience of European agriculture and stopping biodiversity erosion.

2.2.3 STRATEGIC ADVANTAGE FOR THE EU

While connectivity is currently required in almost all application fields (consumer market, automotive, health and wellbeing, smart cities, etc), it is worth noting that European players are stronger in terms of the IoT and secured solutions due to hardware leaders such as NXP and STMicroelectronics, solution providers such as Gemalto and service providers such as Sigfox. On the other hand, mass market-oriented businesses such as smartphones is today dominated by the US (Qualcomm, Broadcom, etc) or Asian players (Huawei, Murata Manufacturing, etc), with European technology businesses being focused on system integration, digitalisation, analytics, sensors/actuators (Siemens, ABB, Schneider, Valmet, Metso, Ericsson, Nokia, Danfoss, Thales, Dassault, Philips, WV, Airbus, GKN, Skanska, BMW, Daimler, Bosch, SKF, Atlas Copco, STMicroelectronics, etc).

Consequently, to strengthen Europe's position and enable European industry to capture new business opportunities associated with the connected world we live in, it is vital to support European technological leadership in connectivity-supporting digitalisation based on IoT and SoS technologies (for example, by being at the forefront of new standard development for the current 5G initiative and the emerging SoS market). Moreover, to bring added value and differentiation compared to US and Asian competitors, European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report).

To illustrate the competitive value for Europe of connectivity and interoperability topics, we will summarise a few of the challenges associated with the connectivity requirement in a market where European industry has been historically strong or has to secure its position for strategic reasons.

- Automotive: The main driver here is the deployment of advanced driver-assistance systems (ADAS), which is a key opportunity for European semiconductor companies. Connectivity technology is consequently a **Major challenge** since inter-sensor communication requires high bandwidth, and therefore innovative solutions will be necessary to prevent network overloads. A broadband network with hierarchical architectures will be required to communicate in a reliable way with all the function domains of the car.

- Digital production: Production of goods and services already involves a multitude of data obtained from various sources. Digitalisation demands a drastic increase of data sources, ranging from sensors and simulators to models. Such data will be used for control, analytics, prediction, business logics, etc., with receivers such as actuators, decision-makers, sales and customers. Obviously, this will involve a huge number of devices with software systems that are required to be interoperable, and possible to integrate for desired combined functionality. This demands seamless and autonomous interoperability between the devices and systems involved, regardless of the chosen technology. Connectivity technology plays an important role for all application areas of the ECS-SRIA.

2.2.4 MAJOR CHALLENGES

2.2.4.1 Major challenge 1: Strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain

2.2.4.1.1 State of the art

Today's connectivity solutions require an incredibly complex electronic system comprising various functions integrated into a wide range of technologies.

Note that advanced digital functions such as the application processor and the baseband model are mastered by a limited number of US and Asian players (Hisilicon, Mediatek, Qualcomm and Samsung), and achieved in advanced complementary metal–oxide–semiconductor (CMOS) technology available at only two Asian businesses (Taiwan Semiconductor Manufacturing Company, TSMC, and Samsung). On this last point, it is worth noting that with Global Foundries stopping its development beyond the 14 nm node, the US is today (as is Europe) completely reliant on Asian foundries' manufacturing capabilities.

From their side, European players (Infineon, NXP, ST, etc) are strong on the analogue and RF front end module markets, mainly due to the availability of differentiated technologies developed and manufactured in Europe (for example, bipolar CMOS, BiCMOS, and RF silicon-on-insulator, SOI). Differentiated technologies are a key strength of the European ECS industry, especially when considering the connectivity market.

Consequently, to maintain Europe's leadership and competitiveness it is vital to ensure that European differentiated semiconductor technologies remain as advanced as possible. This is key to ensure that Europe secure's the market share in the connectivity market, and also strengthens its technology leadership by playing a major role in the development and standardisation of future connectivity technologies. This point is crucial to secure Europe sovereignty on the connectivity topic.

Moreover, over the last year the rising economic tension between the US and China has underlined the value of Europe's ECS supply chain. Once again, this is especially true for differentiated technologies. For example, advanced BiCMOS technologies are currently mastered by a limited number of US (GlobalFoundries and TowerJazz) and European (Infineon and ST-NXP) players. With Chinese companies being forced to move away from US providers, this creates a significant opportunity for Europe as the only viable alternative. Consequently, strengthening Europe's connectivity technology portfolio and associated manufacturing capacity to offer an independent and reliable supply chain is now a key challenge for all European ECS actors.

In addition to being able to provide the differentiated semiconductor technologies supporting the development of innovative connectivity solutions, it is important to note that some European players are proposing connectivity chipset solutions (for example, Sequans Communications and Nordic on the narrowband (NB) IoT topic) or full connectivity solutions (for example, SigFox). Supporting the growth of these existing actors and help emerging industry leaders is also a key challenge for Europe to capture a bigger proportion of the value chain, as well as to ensure its sovereignty on the connectivity topic in the long run.

2.2.4.1.2 Vision and expected outcome

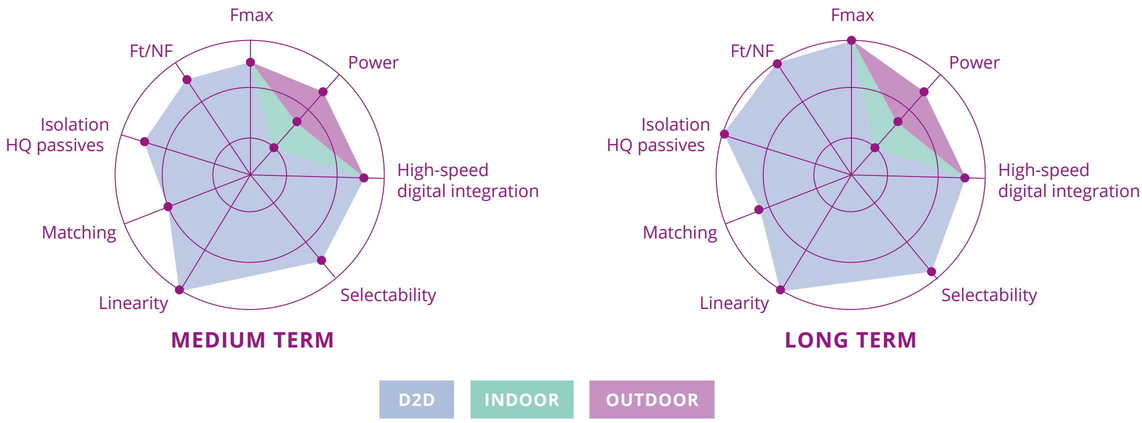
To address identified connectivity technology **Major challenge 1**, we propose the vision described below, which can be summarised by the following three key points (with associated expected outcomes).

Strengthening Europe's differentiated technologies portfolio

As discussed above, Europe's differentiated semiconductor technologies are key assets that should be both preserved and improved upon to secure European leadership in connectivity. Consequently, dedicated research should be encouraged, such as the technologies below (which are also promoted in the *Section 1.1* on **Process Technologies, Equipment, Materials and Manufacturing**).

- Advanced BiCMOS: targeting RF and mmW front-end modules.
- RF SOI: targeting RF and mmW front-end modules.
- GaN: targeting the high-power infrastructure market.
- FD SOI: targeting power-efficient connectivity solutions.
- GaAs/InP: targeting mmW applications.

The main challenge will be in improving achievable performances. To illustrate this, we have extracted the medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID to serve as a connectivity roadmap (see *Figure F.31*). We can see that whatever the type of application (device-to-device, D2D, indoor, outdoor), the requirements in analogue RF will mainly consist of achieving Fmax and FT ~500 GHz in 2025 and 1 THz in 2030, while NFmin will be well below 1 dB in the medium term, to reach 0.5dB in the long term. The only parameter that differentiates the types of applications is the output power, which outdoors should reach between 36 and 40 dBm per PA by the end of the decade. The biggest challenge for silicon or hybrid-on-silicon substrate technologies is expected to be the frequency challenge. Technologies such as GaN/Si and RF SOI will deliver power but for applications operating at less than 100 GHz.



F.31 *Medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID (Source: NEREID[78])*

Note that the vision presented in *Figure F.31* also applies to packaging and printed circuit board (PCB) technologies. It is also worth noting that while Europe is playing a key role in innovative differentiated semiconductor technologies, there is very little R&D activity or few players in Europe on the packaging and PCB side. This point is clearly a weakness that should be addressed to strengthen Europe's connectivity technology portfolio.

Securing Europe's differentiated hardware technology manufacturing

Beyond the development and enablement in Europe of innovative semiconductor technologies targeting the connectivity market, it will be key to safeguard and promote European manufacturing capability to both secure Europe economical interest (in terms of market share) and also address the sovereignty topic (since trade war issues can jeopardise the viability of Europe's industrial actors). To do so, in coordination with the *Section 1.1* on **Process Technologies, Equipment, Materials and Manufacturing**, the following topics should be supported.

- The enablement of the pilot line: The objective here is to support the deployment of additional manufacturing capabilities for technology already available in Europe, or to address new technologies (such as packaging or advanced PCB) to increase the technology portfolio available in Europe.
- The rise of new semiconductor equipment champions: To secure manufacturing capabilities in the long term, it will also be necessary to ensure that the required equipment is provided by European players. This is crucial to prevent any vulnerability in the European supply chain to possible international political or economic issues.

Strengthening Europe's connectivity technology portfolio (both hardware and IP)

Leveraging previously discussed differentiated semiconductor technology portfolio, innovative connectivity solutions (hardware, internet protocol (IP) or software) should be encouraged to enable Europe to take full advantage of its technology and manufacturing assets, and to capture market share at the component level. This action is crucial to secure Europe's position beyond 5G and preliminary 6G investigation and standardisation activities.

- Enable the development and manufacturing in Europe of highly integrated connectivity module/ systems.

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78 *https://www.nereid-h2020.eu/*

Since most of the value of a complex connectivity system will be captured at the module level, it is highly desirable to enable European players to rise up the value chain (in coordination with the section **Components, Modules and Systems Integration**).

In targeting systems and applications, it is important to consider the interconnection between subsystems, and focus should be on individual component technology development according to needs identified at the system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key.

Heterogeneous integration refers to the integration of separately manufactured components into a higher-level assembly that cumulatively provides enhanced functionality and improved operating characteristics. In this definition, components should be taken to mean any unit – whether individual die, device, component, and assembly or subsystem – that is integrated into a single system. The operating characteristics should also be taken in their broadest meaning, including characteristics such as system-level cost of ownership.

This is especially true for the hardware side in the context of the end of Moore's law. It is the interconnection of the transistors and other components in the integrated circuit (IC), package or PCB and at the system and global network level where future limitations in terms of performance, power, latency and cost reside. Overcoming these limitations will require the heterogeneous integration of different materials, devices (logic, memory, sensors, RF, analogue, etc) and technologies (electronics, photonics, MEMS and sensors).

2.2.4.1.3 Key focus areas

To support the vision presented in the previous paragraph, we propose to focus effort on the following key focus areas.

- Innovative differentiated semiconductor technology development targeting connectivity application.
- Innovative packaging and PCB technology targeting connectivity application.
- Pilot line enablement to support the strengthening of European manufacturing capability.
- Innovative semiconductor equipment enablement.
- Innovative connectivity solution development targeting hardware, IP and software items.
- Enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc) to help European players capture higher value in the connectivity market.

2.2.4.2 Major challenge 2: Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership

2.2.4.2.1 State of the art

Targeting connectivity solutions beyond 5G, R&D activity is today mainly focused on the three key challenges listed below.

Evaluating the advantage to use new spectrum (especially at mmW frequencies)

While to date the R&D evaluation has been focused on frequencies below 20 GHz, there is now some interest in assessing achievable performances with a higher frequency. For regulatory reasons, the 275 GHz – 325 GHz range holds promise as it enables the widest available bandwidth. As an illustration, to play a key role in preliminary 6G investigations, the US has facilitated their research on the 95 GHz – 3 THz spectrum over the coming decade. After a unanimous vote, the Federal Communications Commission (FCC) has opened up the “terahertz wave” spectrum for experimental purposes, creating legal ways for companies to test and sell post-5G wireless equipment.

Evaluating the opportunity to use new medium of propagation

Over the last few years, impressive results have been reported concerning high-speed millimetre wave silicon transceivers coupled to plastic waveguides. The state of art on the data rate is now at 36 Gb/s, with a short distance of 1 m in SiGe 55 mnm BiCMOS with 6pJ/b.meter working at 130 GHz. The maximum distance ever reported is 15 m, with 1.5 Gb/s data rate using 40nm CMOS at 120 GHz. In the 10 m distance – which, for instance, is the requirement for data centre applications – the state of the art is given by a data rate of 7.6 Gb/s at 120 GHz for 8m in 40nm CMOS, and a data rate of 6 Gb/s at 60 GHz for 12m in 65 nm CMOS. Although a 10 Gbps data rate, which is needed by data centres, seems feasible, questions remain over whether there is the required energy per bit to deliver this performance.

Exploring the benefits that AI could bring to connectivity technologies

While 5G is being deployed around the world, efforts by both industry and academia have started to investigate beyond 5G to conceptualise 6G. 6G is expected to undergo an unprecedented transformation that will make it substantially different from the previous generations of wireless cellular systems. 6G may go beyond mobile internet, and will be required to support ubiquitous AI services from the core to the end devices of the network. Meanwhile, AI will play a critical role in designing and optimising 6G architectures, protocols and operations.

For example, two key 5G technologies are software-defined networking (SDN) and network functions virtualisation (NFV), which have moved modern communications networks towards software-based virtual networks. As 6G networks should be more complex and heterogeneous, softwarisation is not going to be sufficient for beyond 5G networks. By enabling fast learning and adaptation, AI-based methods will render networks a lot more versatile in 6G systems. The design of the 6G architecture should follow an “AI-native” approach where intelligentisation will allow the network to be smart, agile, and able to learn and adapt itself according to changing network dynamics.

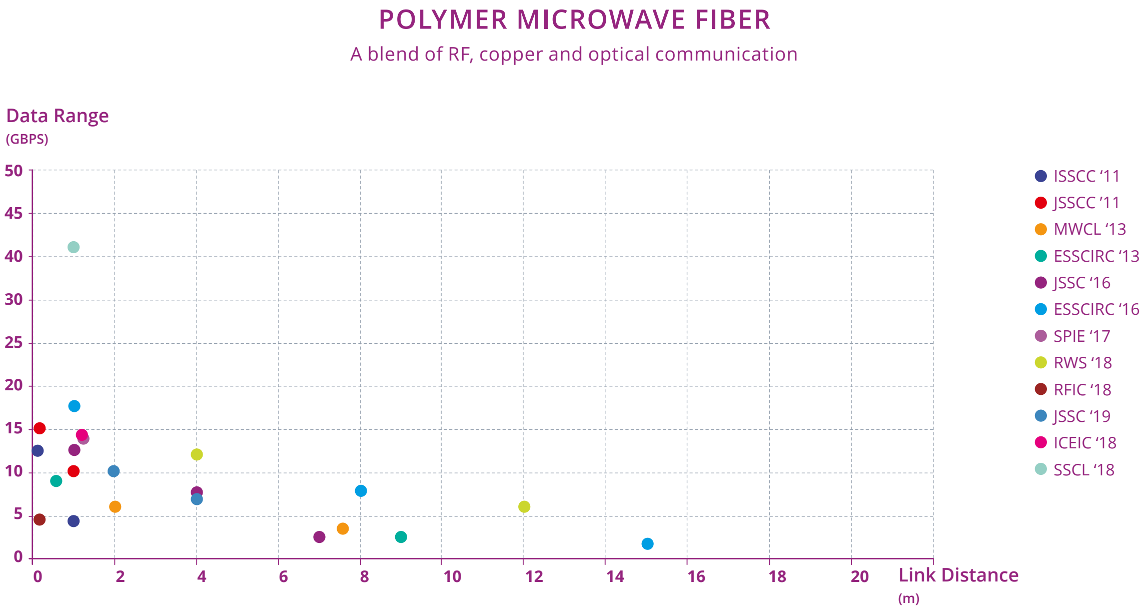
2.2.4.2.2 Vision and expected outcome

To address identified connectivity technology **Major challenge 2,** we propose the vision described below, which can be summarised in the following three points (with associated expected outcomes).

Assess achievable connectivity performances using new spectrums

To maintain European leadership on connectivity technology and ensure sovereignty, the development of new electronics systems targeting connectivity applications in non-already standardised (or in the process of being standardised) spectrums should be supported. A special focus should be dedicated to the frequency bands listed below.

- MmW connectivity application in the 200 GHz – 300 GHz band: With THz communication being a hot topic in the international community, European activity in the spectrum > 200 GHz should be encouraged. These investigations should help Europe play a role in the development of the new technology and assess its relevance to future 6G standards.
- Unlicensed connectivity in the 6 GHz – 7 GHz band: As WiFi 6 is currently being deployed in the US in the 5 GHz – 6.2 GHz band (on April 23 2020, the FCC approved the opening of 1200 MHz of spectrum to IEEE 802.11ax), this spectrum allocation is also under discussion in Europe. It is vital for Europe to support investigation on this frequency band to ensure that the next



Polymer microwave fiber – A blend of RF, copper and optical communication (Source: PMF state of art by KUL Professor Patrick Reynaert[79])

F.32

generation of WiFi technology is accessible to European citizen and businesses (without any limitation compared to other countries).

- Investigation of <10 GHz spectrum for 6G: While 5G was initially thought to be mainly linked to the mmW spectrum (for example, at 28 GHz), most of the current deployment effort is happening in the new < 6 GHz frequency bands. To complement the investigation of the above-mentioned THz communication, the evaluation and development of innovative connectivity technology <10 GHz should be encouraged. This may secure European leadership in future 6G proposals and standardisation activities.

Investigate new propagation medium to enable power-efficient and innovative connectivity technologies

New applications create the need for new connectivity technology. For example, autonomous driving requires very high-speed communication (currently 10 Gb/s and 40 Gb/s in the future) to connect all the required sensors to the central processing unit (CPU). While Ethernet is today perceived as the technology of choice, its deployment in cars is challenging since the electromagnetic interference (EMI) requirements of the automotive industry impose the use of shielded twisted pairs, which add cost and weight constraints. To address this need, intense R&D activity has been pursued over the last few years to assess the relevance of mmW connectivity using plastic waveguides (as described in the previous section).

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79 *http://www.polymermicrowavefiber.com*

Consequently, the development of innovative connectivity solutions using new mediums of propagation should be encouraged to enable innovative connectivity technology and ensure European leadership and sovereignty.

Integrate AI features to make connectivity technology faster, smarter and more power-efficient
The use of new spectrums or propagation mediums is not the only way to boost innovative connectivity technology. As mentioned, 5G has underlined the role of software to promote virtualisation and reconfigurability, but those concepts may not be sufficient to address the challenges related to the more complex connectivity technology that may be developed (for example, 6G).

To address this challenge, Artificial Intelligence is now perceived as a strong enabler. Consequently, in coordination with the AI section, the topics below should be supported.

- Investigate AI features at the edge: To improve the power efficiency of mobile devices and reduce the amount of data to be transmitted via the wireless network, the concept of AI at the edge (or edge AI) has been proposed. The idea is to locally process the data provided by the sensor using handheld device computing capability. Moreover, processing data locally avoids the problem of streaming and storing a lot of data to the cloud, which could create some vulnerabilities from a data privacy perspective.
- Use AI to make the connectivity network more agile and efficient: The idea here is to move to an AI-empowered connectivity network to go beyond the concept of virtualisation and achieve new improvement in terms of efficiency and adaptability. For example, AI could play a critical role in designing and optimising 6G architectures, protocols and operations.

2.2.4.2.3 Key focus areas

To support the vision presented in the previous paragraph, we propose that efforts should be focused on the following key focus areas:

- innovative connectivity system design using new spectrums (especially mmW).
- investigation and standardisation activity targeting 6G cellular application in the frequency band < 10 GHz.
- development of innovative connectivity technology using unlicensed frequency in the 6 GHz – 7 GHz band.
- development of innovative connectivity system using new propagation mediums.
- development of connectivity system leveraging the concept of edge AI.
- evaluation of the AI concept to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability.

2.2.4.3 Major challenge 3: Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics

2.2.4.3.1 State of the art

Europe has a very clear technology lead in automation and digitalisation technology for industrial use. The next generation of automation technology is now being pushed by Industry 4.0 initiatives backed by the EC and most EU countries. In the automotive sector, the autonomous car vision is the driver. Here, Europe again has a strong competitive position. Robust, dependable and interoperable connectivity are fundamental to market success in this area. In healthcare, the ageing population is the driver. Europe's position in this area is respectable but fragmented, making secure, evolvable and engineering-efficient connectivity a market cornerstone.

Interoperability is a growing concern among numerous industrial players. An example here is the formation of industrial alliances and associated interoperability project efforts. One of the directions chosen targets is to gather behind a few large standards. An example of this is showcased in *Figure F.33*.

To maintain and strengthen the European lead, advances in autonomous interoperability and associated efficient engineering capability are necessary. The game changers are:

- autonomous interoperability for SoS integration for efficient engineering at design-time and run-time.
- open interoperability frameworks and platforms.
- standardisation of the above technologies

2.2.4.3.2 Vision and expected outcome

To fully leverage this heterogeneous integration at the hardware level, software interoperability is a parallel challenge to provide connectivity that allows for autonomous SoS connectivity from IoT to back-end systems, enabling usage of available data for all areas of application. To do so, dedicated software tools, reference architecture and standardisation are key to supporting autonomous interoperability, thus enabling the provision of a widely interoperable, secure, scalable, smart and evolvable SoS connectivity.

This enormous challenge involves the interoperability of service or agent protocols, including encoding, security and semantics. Here, payload semantics interoperability is a specific focus, leading to architectures, technologies and engineering tools that support integration of SoS for all areas of application areas at design-time and run-time.

The objective here is for a technology that enables nearly lossless interoperability across protocols, encodings and semantics, while providing technology and engineering support foundations for the low-cost integration of very large, complex and evolvable SoS.

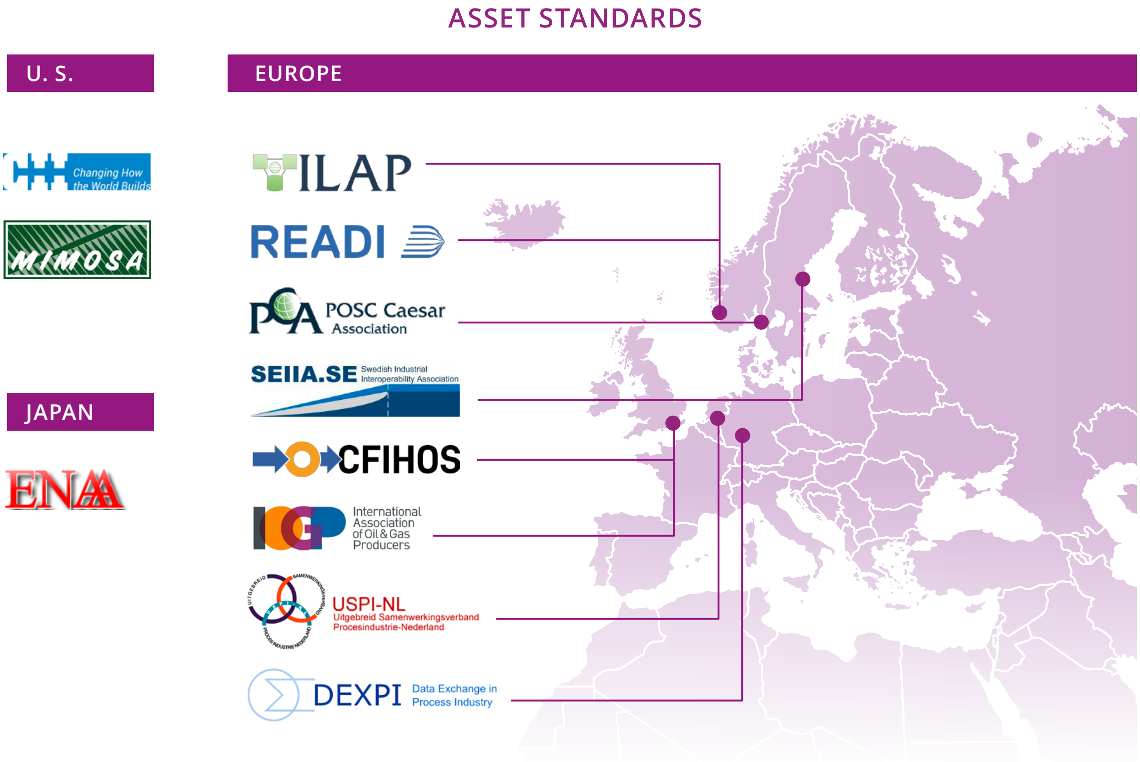
— Expected achievements are:

- open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, including 5G.
- open source engineering and implementation frameworks for the de facto standard SoS connectivity architecture.
- architecture reference implementations with performance that meets critical performance requirements in focused application areas.

2.2.4.3.3 Key focus areas

— The high-priority technical and scientific challenges in both design-time and run-time are:

- semantics interoperability.
- autonomous translation of protocols, encodings, security and semantics.
- evolvable SoS connectivity architectures and technologies over time and technology generations.



F.33 *ISO 15926 – Asset Standards worldwide (Source: Erik Molin, SEIIA)*

2.2.4.4 Major challenge 4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

2.2.4.4.1 State of the art

It is clear that the US is the security leader when it comes to computer connectivity. The big potential game changer here is 5G, where Europe currently has a leading role. To advance the European position, the establishment of connectivity architecture, reference implementation and associated engineering frameworks supporting primarily 5G and other wireless technologies is required. The primary application markets should connect to European strongholds such as automation, digitalisation and automotive. The game changers are:

- establishment of connectivity architecture standards with associated reference implementation and related engineering frameworks.
- SoS connectivity being interoperable, secure, scalable, smart and evolvable.

2.2.4.4.2 Vision and expected outcome

The enabling of SoS connectivity is fundamental for capturing the emerging SoS market and its very high growth rate. Efficient engineering and the deployment of interoperable, secure, scalable, smart and evolvable SoS connectivity will be key to this. This will help Europe lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

In certain domains such as automotive and industrial automation, Europe is the major player. Market studies (Artemis, 2019) indicate very large to extreme growth in the SoS market over the next five years.

This will provide a very strong market pull for all technologies and products upstream. Here, connectivity interoperability is a very important component, enabling tailored SoS solutions and efficient engineering. The vision is to provide interoperable connectivity architecture, reference implementation and associated engineering support and frameworks spanning technologies from legacy to 5G and upcoming 6G.

— Expected achievements

- Open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, including 5G.
- Open source engineering and implementation frameworks for the de facto standard SoS connectivity architecture.
- Architecture reference implementations with performance that meets critical performance requirements in focused application areas.

2.2.4.4.3 Key focus areas

— The high-priority technical and scientific challenges are:

- SoS connectivity architecture as a de facto standard.
- reference implementation of de facto SoS connectivity architectures.
- engineering frameworks for de facto standard SoS connectivity architecture.

2.2.5 TIMELINE

The timeline for addressing the **Major challenges** in this section is provided in the following table.

MAJOR CHALLENGE	TOPIC
Major challenge 1: Strengthening EU connectivity technology portfolio	**Topic 1.1:** Innovative differentiated semiconductor technology development targeting connectivity application
	Topic 1.2: Innovative packaging and PCB technology targeting connectivity application
	Topic 1.3: Pilot line enablement to support European manufacturing capability strengthening
	Topic 1.4: Innovative semiconductor equipment enablement
	Topic 1.5: Innovative connectivity solution development targeting hardware, IP and software items
	Topic 1.6: Enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc) to help European players capture higher value in the connectivity market
Major challenge 2: Investigate innovative connectivity technology (new spectrums or mediums) and new approaches to improve the existing ones to maintain the EU's long-term leadership	**Topic 2.1:** Innovative connectivity system design using new spectrums (especially mmW)
	Topic 2.2: Investigation and standardisation activity targeting 6G cellular application in frequency band < 10 GHz
	Topic 2.3: Development of innovative connectivity technology using unlicensed frequency in the 6 GHz – 7 GHz band
	Topic 2.4: Development of innovative connectivity systems using new propagation mediums
	Topic 2.5: Development of connectivity systems leveraging the concept of edge AI
	Topic 2.6: Evaluation of the AI concept to be able to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability

SHORT TERM (2021–2025)	MEDIUM TERM (2026–2029)	LONG TERM (2030–2035)
• TRL 4–6	• TRL 7–9	
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 4–6	• TRL 7–9	
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 4–6	• TRL 7–9	
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 4–6	• TRL 7–9	
• TRL 3–4	• TRL 5–6	• TRL 7–9
• TRL 4–6	• TRL 7–9	
• TRL 4–6	• TRL 7–9	

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 3: Autonomous interoperability	**Topic 3.1:** Semantics interoperability	• AI-supported translation of payload semantics based on a limited set of ontologies and semantics standards
	Topic 3.2: Autonomous translation of protocols, encodings, security and semantics	• Autonomous and dynamic translation between SOA-based services protocol, data encoding, data compression and data encryption
	Topic 3.3: Evolvable SoS connectivity architectures and technologies over time and technology generations	• TRL4–6
Major challenge 4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	**Topic 4.1:** SoS connectivity architecture as a de facto standard	• SoS connectivity architecture based on SOA established as a major industrial choice in the application domains of the SRIA
	Topic 4.2: Reference implementation of de facto SoS connectivity architectures	• Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (section SoS) reference implementation
	Topic 4.3: Engineering frameworks for de facto standard SoS connectivity architecture	• Reference implementation of an engineering framework with associated tools for SoS connectivity

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• General translation of payload semantics enabling application information usage	• General translation of payload semantics enabling application information usage
• Dynamic translation between major datamodel relevant for the ECSEL field of application.	• Autonomous and dynamic translation between a large set of datamodels relevant for the ECSEL field of application
• TRL 5–7	• TRL6–8
• SoS connectivity architecture based on SOA establised as the major industrial choice in the application domains of the SRIA	
• Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (section SoS) reference implmentation at TRL 8–9.	
• Reference implementation of an engineering framework with associated tools for SoS connectivity at TRL 8	

2.3

Cross-Sectional Technologies

ARCHITECTURE AND DESIGN: METHODS AND TOOLS

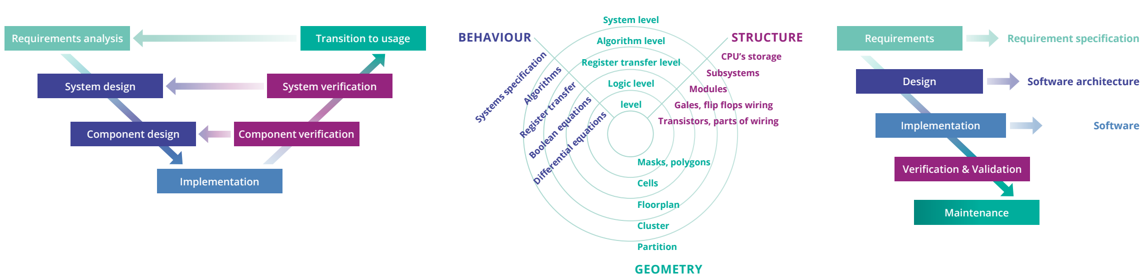
2.3.1
SCOPE

To strengthen European industry's potential to transform concepts cost- and effort-effectively into high-value and high-quality electronic components and systems (ECS)-based innovations and applications, two assets are essential: effective architectures and platforms at all levels of the design hierarchy; and structured and well-adapted design methods and development approaches supported by efficient engineering tools, design libraries and frameworks. These assets are key enablers to produce ECS-based innovations that are: (i) beneficial for society; (ii) accepted and trusted by end-users; and thus (iii) successful in the market.

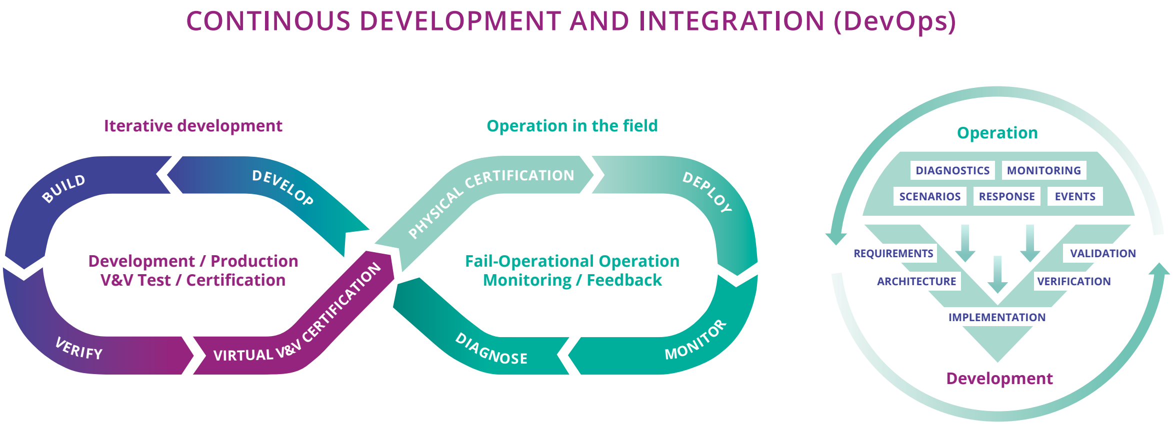
Future ECS-based systems will be intelligent (using methods from Artificial Intelligence (AI) and similar), highly automated and even autonomous and evolvable, meaning their implementation and behaviour will change over their lifetime (cf. *Chapter 3*). Such systems will be connected to, and communicate with, each other and the cloud, often as part of an integration platform or a system-of-system (SoS, see *Section 1.4*). Their functionality will largely be realised in software (cf. *Section 1.3*) running on high-performance specialised or general-purpose hardware modules and components (cf. *Section 1.2*), utilising novel semiconductor devices and technologies (cf. *Section 1.1*). This section describes needed innovations, advancements and extensions in architectures, design processes and methods, and in corresponding tools and frameworks, that are enabling engineers to design and build such future ECS-based applications with the desired quality properties (i.e. safety, reliability, cybersecurity and trustability, cf. *Section 2.4*). The technologies presented here are therefore essential for creating innovations in all application domains (cf. *Chapter 3*); they cover all levels of the technology stack (cf. *Chapter 1*), and enable efficient usage of all cross-cutting technologies (cf. *Chapter 2*).

Traditionally, there is a huge variety of design processes and methods used in industry, such as processes based on the V-Model in systems and software design, on Gajsky and Kuhn's diagram (Y-chart) in hardware design, on the waterfall model or any other kind of (semi-)formal process definition (see *Figure F.34*).

SIMPLIFIED EXAMPLES OF APPLIED "TRADITIONAL" DESIGN PROCESSES



Simplified examples of applied "traditional" design processes: V-Model, Gajsky–Kuhn diagram (Y-chart) and the waterfall model. These are heavily in use, but not sufficient to handle future ECS-based systems and products. **F.34**



F.35 *Simplified examples for continuous development processes (DevOps processes), Such processes are essential for building future ECS-based systems and products since they enable data collected during the operation phase to be used in iterative (continuous) development for updates of existing products.*

Adding to the variety of design processes in use, the practical instantiation of these processes differs between companies, and sometimes even between different engineering teams within the same company. Nonetheless, most of these processes have common properties. They comprise several steps that separate the numerous design and verification tasks into smaller parts, which are then processed sequentially and with iterations and loops for optimisation. These steps include: activities and decisions on requirements elicitation and management; technologies used; system architecture; system decomposition into subsystems, components and modules; hardware/software partitioning; implementation and integration; and validation and testing on all levels of the design hierarchy.

Due to the sheer size and complexity of current and future ECS-based products, the amount of functionality they perform, and the number and diversity of subsystems, modules and components they comprise, managing complexity and diversity have always been crucial in these processes. The trend of growing complexity and diversity in future ECS-based applications therefore increases the corresponding challenges, especially in employing model-based design approaches, and divide-and-conquer based approaches, both on a technical level. That is, modular, hierarchical designs need to be integrated into reference architectures and platforms, and also on an organisational level – i.e. by employing open source solutions to increase interoperability and thus cooperation.

A second commonality in the different design processes in use today is that almost all of them end after the complete system has been fully tested and validated (and, in some domains, been homologated/certified). Although feedback from production/manufacturing has sometimes been used to increase production quality (e.g. with run-to-run control in semiconductor fabrication), data collected during the lifetime of the system (i.e. from maintenance, or even from normal operations) are rarely taken into account. If such data are collected at all, they are typically used only for developing the next versions of the system. Again, for future ECS-based applications this will no longer be sufficient. Instead, it is vitally important to extend these processes to cover the complete lifecycle of products. This includes collecting data from system's operation, and to use this data within the process to: (i) enable continuous updates and upgrades of products; (ii) enable in-the-field tests of properties that cannot be assessed at design-time; and (iii) increase the effectiveness of validation and test steps by virtual validation methods based on this data. Apart from the technical challenges in collecting, and especially in analysing, this data in a meaningful way, compliance to the appropriate data protection regulations and privacy concerns of system's owners and users is an additional, non-technical challenge to be resolved. The resulting agile "continuous development processes" will ease quality properties assurance by providing design guidelines, design constraints and practical architectural patterns (e.g. for security, safety, testing), while giving engineers the flexibility and time to deliver the features that those development methodologies support ("quality-by-design solutions").

2.3.2 TECHNOLOGY-ENABLED SOCIETAL BENEFITS

The technologies developed here (methods and tools for developing and testing applications and their architectures) are the key enabler for European engineers to build future ECS, and with the desired quality properties (safety, security, reliability, trustworthiness, etc) at an affordable effort and cost. As such, these technologies are necessary preconditions for all the achievements and societal benefits enabled by such applications.

ECS-based applications are becoming increasingly ubiquitous, penetrating every aspect of our lives. At the same time, they provide greater functionality, more connectivity and more autonomy. Thus, our dependency on these systems is continuously growing. It is therefore vitally important that these systems are trustworthy – i.e. that they are guaranteed to possess a multitude of properties. They need to be safe, so that their operation never harms humans, or cause damage to human possessions or the environment; even in the case of a system malfunction, safety must be guaranteed. They also need to be secure: on the one hand, data they might collect and compute from unintended access must be protected; on the other hand, they must be able to protect the system and its functionality from unintended access by malicious forces (thus potentially endangering safety). In addition, they must be reliable, resilient, dependable, scalable and interoperable, as well as many other quality properties. Most of all, these systems must be trustworthy – i.e. users, and society in general, must be enabled to trust that these systems possess all these quality properties under all possible circumstances.

Trustworthiness of ECS-based applications can only be achieved by implementing all of the following actions.

- Establishing architectures, methods and tools that enable "quality by design" approaches for future ECS-based systems (this is the objective of this section). This action comprises:
  - Providing structured design processes, comprising development, integration and test methods, covering the whole system lifecycle and involving agile methods, thus easing validation and enabling engineers to sustainably build these high-quality systems.
  - Implementing these processes and methods within engineering frameworks, consisting of interoperable and seamless toolchains providing engineers the means to handle the complexity and diversity of future ECS-based systems.
  - Providing reference architectures and platforms that enable European Industries to re-use existing solutions and, most importantly, integrate solutions from different vendors into platform economies.
- Providing methodology, modelling and tool support to ensure that all relevant quality aspects (e.g. safety, security, dependability) are designed to a high level. This also involves enabling balancing trade-offs with those quality aspects within ECS parts and for the complete ECS, and ensuring their tool-supported verification and validation (V&V) at the ECS level.

- Adding quality introspection interfaces to systems to enable engineers, authorities and end-users can understand why systems behave in a certain way in a certain situation (see "explainable AI" in *Sections 2.1* and *2.4*), thus making AI-based and/or highly complex system behaviour accessible for quality analysis and further increasing user's trust in their correctness.

The technologies described in this section are thus essential to build high-quality future ECS-based systems that society trusts in. They are therefore key enablers for ECS and all the applications described in *Chapter 3.* In addition, these technologies also strengthen the competitiveness of European industry, thus sustaining and increasing jobs and wealth in Europe (as will be discussed in the next section).

2.3.3
STRATEGIC ADVANTAGE FOR THE EU

Traditionally, Europe is strong in developing high-quality products. European engineers are highly skilled in systems engineering, including integration, validation and testing, thus ensuring system qualities such as safety, security, reliability, etc, for their products. Nevertheless, even in Europe industrial and academic roadmaps are delaying the advent of fully autonomous driving or explainable AI, for instance. After the initial hype, many highly ambitious objectives have had to be realigned towards more achievable goals and/or are predicting availability with significant delay. The main obstacle, and reason for this technical slowdown, is that quality assurance methods for these kinds of systems are simply not available, or if they are, they are not able to cover all the complexity of future systems. Worldwide, even in regions and countries that traditionally have taken a more hands-on approach to safety and other system qualities – e.g. "learning-by-doing" – the market introduction of such systems has failed, mainly due to non-acceptance by users after a series of accidents, with timing goals for market introduction being extended accordingly.

The technologies described in this section will substantially contribute to enabling European Industries to build systems with guaranteed quality properties, thus extending Europe's strength in dependable systems to trustworthy, high-quality system design ("quality made in Europe"). This in turn will enable Europe to sustain existing jobs and create new ones, as well as to initiate and drive corresponding standards, thus increasing competitiveness.

Design frameworks, reference architectures and integration platforms developed with the technologies described in this section will facilitate cooperation between many European companies, leading to new design ecosystems building on these artefacts. Integration platforms, in particular, will provide the opportunity to leverage a high number of small and medium-sized enterprises (SMEs) and larger businesses into a platform-based economy mirroring the existing highly successful platforms of, for example, Google, Apple, Amazon, etc.

In itself, the market for design, development, validation and test tools is already considerable, with good growth potential. The DECISION study[80], for example, has put the global market for materials and tools at €141 billion in 2018 (EU share: €24 billion), while Advancy considers the global market for equipment and tools for building ECS-based products at €110 billion in 2016 (EU share: 25%), with an estimated growth to €200 billion by 2025[81]. However, as key enabling technologies, these tools and frameworks are also enabling the application markets (cf., *Chapter 3*), since without them it would not be possible to access these markets. Furthermore, the existence of cost-efficient processes implemented and supported by innovative development tools and frameworks that guarantee high-quality products typically reduces development time and costs by 20–50% (as shown by previous projects such as ENABLE S3, Arrowhead Tools, and many more). Thus, these technologies contribute substantially to European competitiveness and market access; cost-effectiveness also leads to lower pricing and therefore substantially contributes to making societal-beneficial technologies and applications accessible to everyone.

Last, but not least, the technologies described in this section will contribute significantly to additional strategic goals such as the European Green Deal, while extending design processes to cover the whole lifecycle of products also enables recycling, re-using and a more circular economy.

2.3.4 MAJOR CHALLENGES

We identified four **Major challenges** within the transversal topic "Architecture and Design: Methods and Tools".

- **Major challenge 1:** Extending development processes and frameworks to handle connected, intelligent, autonomous and evolvable systems: This challenge covers necessary changes in the processes used to develop future ECS-based system, especially their extension to cover the whole lifecycle.
- **Major challenge 2:** Managing new functionality in safe, secure and trustable systems: This challenge covers methods and the corresponding tool support to ensure high-quality ECS-based systems, especially with respect to the new capabilities/functions these systems will exploit.
- **Major challenge 3:** Managing complexity: This challenge deals with methods to handle the ever-increasing complexity of ECS-based systems.
- **Major challenge 4:** Managing diversity: Handling diversity in all aspects of developing ECS-based systems is a key objective.

←

80 *DECISION Etudes & Conseil (Eds). "Emerging Technologies in Electronic Components and Systems (ECS) – Opportunities Ahead". A study conducted for DG-CONNECT, 2019.*

→

81 *ARTEMIS-IA and ADVANCY (Eds). "Embedded Intelligence: Trends and Challenges", Nov. 2019.*

2.3.4.1 Major challenge 1: Extending development processes and frameworks (to handle connected, intelligent, autonomous, evolvable systems)

2.3.4.1.1 State of the art

There is currently a strict separation between the development and the operation of ECS-based systems. Data collected in any of these ”crosses the border” into the other phases (cf. *sub-section 2.3.1*).

Future ECS-based systems need to be connected, intelligent, highly automated, and even autonomous and evolvable (cf. *sub-section 2.3.1*). This implies a huge variety of challenges, including how to validate autonomous systems (considering that a full specification of the desired behaviour is inherently impossible), how to test them (critical situations are rare events, and the number of test cases implied by the open-world-assumption is prohibitively large), and how to ensure safety and other system quality properties (security, reliability, availability, etc) for updates and upgrades.

It is therefore necessary to overcome the “data separation barrier” and to “close the loop” by feeding relevant data collected during the operation phase back into the design phase to be used for continuous development within lifecycle-aware holistic design flows. In addition, engineering processes for future ECS-based systems should be extended to shift as much engineering effort as possible from physical to virtual engineering, and include advanced methods for systems and components design as well as new V&V methods enabling safety cases for future ECS-based systems.

2.3.4.1.2 Vision and expected outcome

The vision is to enable European engineers to extend design processes and methods to a point where they allow handling of future ECS-based systems with all their new functionality and capabilities for the whole lifecycle. Such extended processes must retain the qualities of the existing processes: (i) efficiency, in terms of effort and costs; (ii) enable the design of trustworthy systems, meaning systems that provably possess the desired quality properties of safety, security, dependability, etc; and (iii) are transparent to engineers, who must be be able to completely comprehend each process step to perform optimisations and error correction.

Such extended processes will cover the complete lifecycle of products, including production, maintenance, decommissioning and recycling, thereby allowing continuous upgrades and updates of future ECS-based systems that also address the sustainability and environmental challenges (i.e. contribute to the objectives of the Green Deal). As can be derived from the timelines at the end of this section, we expect supply chain-aware digital design flows enabling design for optimised manufacturing and operation (i.e. the “from design phase to operation phase direction” of the continuous design flow) for fail-aware cyber-physical systems (CPS), where selected data from operations is analysed and used in the creation of updates, by 2026. This will be completed through seamless and continuous development processes, including automated digital data flow based on digital twins and AI-based data analysis, as well as data collection at run-time in fail-operational CPS (i.e. “from operation to design phase” direction), by online validation, and by safe and secure deployment, by 2029.

These extended processes also require efficient and consistent methods in each of their phases to handle the new capabilities of future ECS-based systems (cf. **Major challenge 2**), as well as their complexity (cf. **Major challenge 3**) and diversity (cf. **Major challenge 4**).

2.3.4.1.3 Key focus areas

There are four key focus areas in this challenge.

Virtual engineering of ECS

Design processes for ECS must be expanded to enable virtual engineering on all hierarchy levels (i.e. from transistor level "deep down", up to complete systems and even System of Systems, cf. "Efficient engineering of software" in *Section 1.3* and "SoCPS and SoES engineering" in *Section 1.4* for more details of this software-focused challenge, especially with respect to SoS).

Central to this approach are "digital twins", which capture all necessary behavioural, logical and physical properties of the system under design in a way that can be analysed and tested (i.e. by formal, AI-based or simulation methods). This allows for optimisation and automatic synthesis (see also **Major challenge 1 and 2** in *Section 2.4*, and the key focus area "Modelling" in **Major challenge 2** of this section) – for example, of AI-supported, data-driven methods to derive (model) digital twins.

Supporting methods include techniques to visualise V&V and test efforts (including their progress), as well as sensitivity analysis and robustness test methods for different parameters and configurations of the ECS under design. Test management within such virtual engineering processes must be extended to also cover all layers of the design hierarchy, and be able to combine virtual (i.e. digital twin and simulation-based) and physical testing (for final integration tests, as well as for testing simulation accuracy).

To substantially reduce design effort and costs, a second set of supporting methods deal with the automatic generation of design artefacts such as identification and synthesis of design models, automatic scenario, use-case and test vector generation, generative design techniques, design space exploration, etc. Typically, these build upon AI-supported analysis of field data.

System and component design (methods and tools)

To fully enable virtual engineering, design processes have to switch completely to model-based processes, where those models may be constructed using data-driven methods. Models are needed for the system and all its components on every level of the design hierarchy, especially for sensors and actuators, as well as the environment of the ECS under design, including humans and their behaviour when interacting with the system. Model-based design will also enable: (i) modular and updateable designs that can be analysed, tested and validated both virtually (by formal methods, simulation, etc) and physically; and (ii) consistent integration of all components on all levels of the design hierarchy to allow application-aware HW/SW co-design.

Such processes must be implemented by seamless design and development frameworks comprising interoperable, highly automated yet comprehensible tools for design, implementation, validation and test on all levels of the design hierarchy, including support for design space exploration, variability, analysis, formal methods and simulation.

Lifecycle-aware holistic design flows

"Closing the loop" – i.e. collecting relevant data in the operation phase, analysing it (using AI-based or other methods) and feeding it back into the development phase (using digital twins, for example) – is the focus of this research topic. It is closely related to the **Major challenges** "Continuous integration and deployment" and "Lifecycle management" in *Section 1.3*, which examines the software part of ECS, and **Major challenges 1 and 2** in *Section 2.4*.

Closing the loop includes data collected during operation of the system on all levels of the hierarchy, from new forms of misuse and cyber-attacks or previously unknown use cases and scenarios at the system level, to malfunctions or erroneous behaviour of individual components or modules. Analysing this data leads to design optimisations and development of updates, eliminating such errors or implementing extended functionality to cover "unknowns" and "incidents".

Data on physical aspects of the ECS must also be collected and analysed. This includes design for optimised manufacturing and deployment, awareness of physical effects and interferences, consideration of end-of-life (EOL) of a product and recycling options within a circular economy.

All of these aspects must be supported by new approaches for multi-level modelling, analysis, verification and formalisation of ECS's operational reliability and service life (c.f. previous challenges), including a consequent usage of open (and inner) source in HW and SW for the complete product lifecycle.

Integration of new V&V methods

The required changes of current design processes identified above, as well as the need to handle the new systems capabilities, also imply an extension of current V&V and test methods. First, safety cases for autonomous systems need to rely on an operational design domain (ODD) definition – i.e. characterisation of the use cases in which the system should be operated, as well as a set of scenarios (specific situations that the system might encounter during operation) against which the system has actually been tested. It is inherently impossible for an ODD to cover everything that might happen in the real world; similarly, it is extremely difficult to show that a set of scenarios cover an ODD completely. Autonomous systems must be able to detect during operation whether they are still working within their ODDs, and within scenarios equivalent to the tested ones. V&V methods have to be expanded to show correctness of this detection. Unknown or new scenarios must be reported by the system as part of the data collection needed for continuous development.

Second, the need to update and upgrade future ECS-based systems implies the need to be able to validate and test those updates for systems that are already in the field. Again, corresponding safety cases have to rely on V&V methods that will be applied partly at design-time and partly at run-time, thereby including these techniques into continuous development processes and frameworks. For both of these challenges, energy- and resource-efficient test and monitoring procedures will be required to be implemented.

2.3.4.2 Major challenge 2: Managing new functionality in safe, secure and trustable systems

2.3.4.2.1 State of the art

Models are abstractions that support the relevant technical processes in various forms – for instance, they help systems engineers to accelerate and improve the development process. Specific models represent different aspects and allow different predictions, such as on performance characteristics, temporal behaviour, costs, environmental friendliness or similar. Ideally, models should cover all of these aspects in various details, representing the best trade-off between level of detail, completeness and the limitations listed below.

- Computing speed and performance: Models have different levels of complexity, and therefore the computational effort for the simulation sometimes varies considerably. For system considerations, very simple models are sometimes sufficient; for detailed technical simulations, extremely complex multi-physics 3D models are often required. To achieve the necessary performance, one solution can be the parallel processing of several simulations in the cloud.

- Effort involved in creating models: Very complex physically-based 3D models require considerable effort for their creation. For behavioural models, the necessary parameters are sometimes difficult to obtain or not available at all. For models based on data, extensive data collection and analysis has to be carried out. Further research is urgently needed to reduce the effort for model creation and parameterisation.
- Interfaces and integration: Often, different models from different sources are needed simultaneously in a simulation. However, these models are frequently created on different platforms, and must therefore be linked or integrated. The interfaces between the models must be further standardised. Interoperable models and (open source) integration platforms are needed here; they will also require further cooperation between manufacturers and suppliers.
- Models for software testing, simulation, verification, and for sensors: Another very complex field of activity concerns the model-based testing of software in a virtual environment (including virtual hardware platforms). This implies that sensors for the perception of the environment must also be modelled, resulting in further distortion of reality. The challenge here is to reproduce reality and the associated sensors as accurately as possible, including real-time capacity.

2.3.4.2.2 Vision and expected outcome

Efforts supporting the generation of realistic models in the entire lifecycle of a complex cyber-physical product remain very high, as the requirements for simulation accuracy, the number of influencing parameters of interest and the depth of detail are constantly increasing over time. On the other hand, the application of the highest fidelity models throughout the development process and lifecycle of products with cyber-physical components and software in turn creates numerous opportunities to save development, operating and maintenance costs. These opportunities arise in cyber-physical components or products such as vehicles, medical devices, semiconductor components, ultra-low-power components or any other elements in such complex technical systems. Therefore, research on advanced model-based design, development, and V&V methods and tools for the successful creation of safe, secure and trustable products in Europe is of utmost importance, and should be the highest priority of the research agenda. The vision is to derive efficient and consistent methods for modelling, designing and validating future ECS-based systems, supporting the different steps in the continuous development processes derived in **Major challenge 1** by 2026 (resp. by 2029).

2.3.4.2.3 Key focus areas

This challenge comprises the following three key focus areas.

Modelling techniques for new functionalities

Model generation includes different methods (e.g. data-driven techniques, physics- or rules-based abstraction techniques) for describing (modelling) the behaviour of safety-critical, mixed, physical and logical components on different, hierarchical system levels. Model generation finally results in model libraries that are suitable for different purposes (analysis techniques, simulation, etc). There are different aspects of the modelled artefact (of the system, component, environment, etc), such as their physical properties, their (timed) behaviour, and their functional and non-functional properties, which often are modelled with different modelling approaches using different modelling tools.

For the design of ECS-based systems, models are required on all levels of the design hierarchy and with different granularity (cf. *Sub-section 2.3.4.2.1*), ranging from physically-based 3D models of individual components via simplified models for testing component interaction to specific models for sensors and the environment, also taking into account statistical scattering from production and system changes during the service life.

Furthermore, it is important to create reusable, validated and standardised models and model libraries for system behaviour, system environment, system structure with functional and non-functional properties, SoS configurations, communication and time-based behaviour, as well as for the human being (operator, user, participant).

Most importantly, model-based design methods, including advanced modelling and specification capabilities, supported by corresponding modelling and specification tools, are essential. The models must be applicable and executable in different simulation environments and platforms, including desktop applications, real-time applications and hardware-in-the-loop (HiL) platforms.

Design and V&V methods for ECS evolving during lifetime (including AI-enabled systems)

The more complex the architecture of modern ECS systems becomes, the more difficult it is to model its components, their relevant properties and their interactions to enable the optimal design of systems. Classical system theory and modelling often reaches its limits because the effort is no longer economically feasible. AI-supported modelling can be used effectively when large amounts of data from the past or from corresponding experiments are available. Such data-driven modelling methods can be very successful when the exact behaviour of the artefact to be modelled is unknown and/or very irregular. However, the question of determining model accuracy is largely unsolved for these methods.

When AI-based functions are used in safety-critical components and systems, V&V are extremely important. Experience-based AI systems (including deep learning-based systems) easily reach their limits when the current operating range is outside the range of the training database. There can also be stochastic, empty areas within the defined data space, for which AI is not good at interpolating. Design methods for AI-enabled ECS must therefore take into account the entire operational domain of the system, compensate for the uncertainty of the AI method and provide additional safety mechanisms supervising the AI component (i.e. mechanisms to enable fail-aware and fail-operational behaviour).

A further source of uncertainty results from variabilities (production tolerances, ageing effects or physical processes that cannot be described with infinite accuracy) resulting from human interaction with the system and from other effects. For determining quality properties such as safety and reliability, these effects must be taken into account throughout the designs' V&V.

There are also structured (i.e. foreseeable at design-time) variabilities in technical systems in the form of configurable changes during their lifetime, whether through software updates, user interventions or other updates. For secure systems with structured variability, suitable SW and HW architectures, components and design methods, as well as tools for adaptive, extensible systems, are crucial. This includes (self-)monitoring, diagnosis, update mechanisms, strategies for maintaining functional and data security, and lifecycle management, as well as adaptive security and certification concepts.

Ultra-low power design methods

The potential application area for ultra-low power electronic systems is very high due to the rapidly advancing miniaturisation of electronics and semiconductors, as well as the ever-increasing connectivity enabled by it. This ranges from biological implants, home automation, the condition-monitoring of materials to location-tracking of food, goods or technical devices and machines. Digital products such as radio-frequency/radio-frequency identification (RF/RFID) chips, nanowires, high-frequency (HF) architectures, SW architectures or ultra-low power computers with extremely low power consumption support these trends very well. Such systems must be functional for extended periods of time with a limited amount of energy.

The ultra-low-power design methods comprise the areas of efficiency modelling and low-power optimisation with given performance profiles, as well as the design of energy-optimised computer architectures, energy-optimised software structures or special low-temperature electronics. The design must consider the application-specific requirements, such as the functional requirements, power demand, necessary safety level, existing communication channels, desired fault tolerance, targeted quality level, and the given energy demand and energy supply profiles, energy harvesting gains and, last but not least, the system's lifetime.

Exact modelling of the system behaviour of ultra-low power systems and components enables simulations to compare and analyse energy consumption with the application-specific requirements so that a global optimisation of the overall system is possible. Energy harvesting in the absence of other energy sources, and the occurrence of parasitic effects, must also be taken into account.

2.3.4.3 Major challenge 3: Managing complexity

2.3.4.3.1 State of the art

The new system capabilities (intelligent, autonomous, evolvable), as well as the required system properties (safe, secure, reliable, trustworthy), considerably increase complexity. Increasingly complex environments in which these systems are expected to operate, and the increasingly complex tasks (functionalities) that these systems need to perform in this environment, are a further source of intensified system complexity. Rising complexity leads to a dramatic upsurge in the effort of designing and testing, especially for safety-critical applications where certification is usually required. Therefore, an increased time to market and increased costs are expected, and competitiveness in engineering ECS is endangered. New and improved methods and tools are needed to handle this new complexity, and to enable the development and design of complex systems to fulfil all functional and non-functional requirements, and to obtain cost-effective solutions from high productivity. Three complexity-related action areas will help to master this change:

- methods and tools to increase design efficiency.
- complexity reduction methods and tools for V&V and testing.
- methods and tools for advanced architectures.

2.3.4.3.2 Vision and expected outcome

The connection of electronics systems and the fact that these systems change in functionality over their lifetime continuously drives complexity. In the design phase of new coordinated, highly autonomous and evolvable ECS, this complexity must be handled and analysed automatically to support engineers in generating best-in-class designs with respect to design productivity, efficiency and cost reduction. New methods and tools are needed to handle this new complexity during the design, manufacturing and operations phases. These methods and tools should work either automatically or be recommender-based for engineers to have the complexity under control.

Complexity increases the effort required, especially in the field of V&V of connected autonomous electronics systems, which depend on each other and alter over their lifetime. The innumerable combinations of ECS must be handled and validated. To that end, new tools and methods are required to help test engineers in creating test cases automatically, analysing testability and test coverage on the fly while optimising the complete test flow regarding test efficiency and cost. This should be achieved by identifying the smallest possible set of test cases sufficient to test all possible system behaviours. It is important to increase design efficiency and implement methods that speed up the design process of ECS. Methods and tools for X-in the loop simulation and testing must be developed, where X represents hardware, software, models, systems, and a combination of all these elements. A major result of this **Major challenge** will be the inclusion of complexity-reduction methods for future ECS-based systems into the design flows derived in **Major Challenge 1**, including seamless tool support, as well as modular architectures that support advanced computation methods (AI, advanced control), system improvements (updates), replacement and recycling by 2026. Building on these, modular and evolvable/extendable reference architectures and (hierarchical, open source-based) platforms that support continuous system improvement, self-awareness, health and environment monitoring, and safe and secure deployment of updates, will be realised by 2029.

2.3.4.3.3 Key focus areas

Methods and tools to increase design and verification efficiency

Design efficiency is a key factor for keeping and strengthening engineering competitiveness. Design and engineering in the virtual world using simulation techniques require increasingly efficient modelling methods of complex systems and components. Virtual design methodology will be boosted by X-in the loop, where X (HW, SW, models, systems) are included in the simulation process, which helps to increase accuracy and speed up multi-discipline co-simulation. This starts at the architecture and design evaluation, where real tests are implemented in a closed loop such as in the exploration process.

Complexity reduction methods and tools for V&V and testing

A second way to manage complexity is the complexity-related reduction of effort during the engineering process. Complexity generates most effort in test, and V&V, ensuring compatibility and proper behaviour in networking ECS. Consistent hierarchical design and architectures, and tool-based methods to design those architectures automatically, are needed. Advanced test methods with intelligent algorithms for test termination, as well as automated metrics for testability and diagnosis (including diagnosis during run-time), must be developed and installed. Recommender-based guidance supports where no automated processes can be used. Model-based V&V and test supported by AI techniques can help to minimise the efforts driven by complexity. Models and digital twins of ECS can also be used to calculate the test coverage and extract test cases automatically.

Methods and tools for advanced architectures

Complexity, and also future complexity, is mainly influenced by the architecture. Future architectures must support complex, highly connected ECS that use advanced computational methods and AI, as well as machine learning, which lead to a change of ECS over lifetime. For this, reference architectures and platform architectures are required on all levels of the design hierarchy (for the system and SOS levels, see also the challenges “architectures for SoS”, “SoS interoperability” and related challenges in *Section 1.4* on **System of Systems**).

An additional focus of architecture exploration and optimisation must be architectures that ease the necessary efforts for analysis, test, V&V and certification of applications. Hierarchical, modular architectures that support a divide-and-conquer approach for the design and integration of constituent modules with respect to subsystems have the potential to reduce the demand for analysis and V&V (“correct by design” approach). For the architecture exploration and optimisation itself, AI-based methods are needed to achieve a global optimum.

Apart from the benefits that reference architectures and platforms have at a technological level, they are also important economically. As integration platforms for solutions of different vendors, they serve as a focal point for value chain-based ecosystems. Once these ecosystems reach a certain size and market impact, the platforms can serve as the basis for corresponding "platform economies" (cf. **Major challenge** "open SoCPS and SoES platforms" in *Section 1.4*).

2.3.4.4 Major challenge 4: Managing diversity

2.3.4.4.1 State of the art

In the ECS context, diversity is everywhere – between polarities such as analogue and digital, continuous and discrete, and virtual and physical. With the growing diversity of today's heterogeneous systems, the integration of analogue-mixed signals, sensors, micro-electromechanical systems (MEMS), actuators and power devices, transducers and storage devices is essential. Additionally, domains of physics such as mechanical, photonic and fluidic aspects have to be considered at the system level, and for embedded and distributed software. The resulting design diversity is enormous. It requires multi-objective optimisation of systems (and SoS), components and products based on heterogeneous modelling and simulation tools, which in turn drives the growing need for heterogeneous model management and analytics. Last, but not least, a multi-layered connection between the digital and physical world is needed (for real-time as well as scenario investigations). Thus, the ability to handle this diversity on any level of the design hierarchy, and anywhere it occurs, is paramount, and a wide range of applications has to be supported.

2.3.4.4.2 Vision and expected outcome

The management of diversity has been one of Europe's strengths for many years. This is not only due to European expertise in driving more-than-Moore issues, but also because of the diversity of Europe's industrial base. Managing diversity is therefore a key competence. Research and development and innovation (R&D&I) activities in this area aim at the development of design technologies to enable the development of complex, smart and, especially, diverse systems and services incorporating the growing heterogeneity of devices and functions, including its V&V across mixed disciplines (electrical, mechanical, thermal, magnetic, chemical and/or optical, etc). New methods and tools are needed to handle this growing diversity during the phases of design, manufacturing and operation in an automated way. As in complexity, it is important to increase design efficiency on diversity issues in the design process of ECS. A major consequence of this challenge will be the inclusion of methods to cope with all diversity issues in future ECS-based systems introduced into the design flows derived in **Major challenge 1**, including seamless tool support for engineers.

2.3.4.4.3 Key focus areas

The main R&D&I activities for this third **Major challenge** are grouped into the following four key focus areas.

Multi-objective design and optimisation of components and systems

The area of multi-objective optimisation of components, systems and software running on SoS comprises integrated development processes for application-wide product engineering along the value chain. It also concerns modelling, constraint management, multi-criteria, cross-domain optimisation and standardised interfaces. This includes consistent and complete co-design and the integrated simulation of integrated circuits, package and board in the application context, and methods and tools to support multi-domain designs (electronic/electric and hydraulic, etc) and multi-paradigms (different vendors, modelling languages, etc). Furthermore, it deals with advanced design space exploration and iterative design techniques, the modular design of 2.5 and 3D integrated systems and flexible substrates, and the trade-offs between performance, cost, space, power and reliability.

Modelling, analysis, design and test methods for heterogeneous systems considering properties, physical effects and constraints

The area of modelling, analysis, design, integration and testing for heterogeneous systems considering properties, physical effects and constraints comprises methods and tools for the design, modelling and integration of heterogeneous systems, as well as hierarchical methods for HW/SW co-simulation and co-development of heterogeneous systems (including multi-scale and multi-rate modelling and simulation). Furthermore, it deals with modelling methods to consider operating conditions, statistical scattering and system changes, as well as hierarchical modelling and the early assessment of critical physical effects and properties from SoC up to the system level. Finally, there is a need for analysis techniques for new circuit concepts (regarding new technologies up to the system level), and special operating conditions (voltage domain check, especially for start-ups, floating node analysis, etc).

Automation of analogue and integration of analogue and digital design methods

The area of integration of analogue and digital design methods comprises metrics for testability and diagnostic efficiency, especially for analogue/mixed signal (AMS) designs, harmonisation of methodological approaches and tooling environments for analogue, RF and digital design and automation of analogue and RF design – i.e. high-level description, synthesis acceleration and physical design, modularisation and the use of standardised components.

Connecting the virtual and physical world of mixed domains in real environments

The main task in the area of connecting the virtual and physical worlds of mixed domains in real environments is an advanced analysis that considers the bi-directional connectivity of the virtual and physical world of ECS and its environment (including environmental modelling, multimodal simulation, simulation of (digital) functional and physical effects, emulation and coupling with real, potentially heterogenous, hardware, and integration of all of these into a continuous design and validation flow for heterogeneous systems, cf. **Major challenge 1 and 2** above). Furthermore, the key focus area comprises novel more-than-Moore design methods and tools, as well as models and model libraries for chemical and biological systems.

2.3.5
TIMELINE

2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

Major challenge 1: EXTENDING DEVELOPMENT PROCESSES AND FRAMEWORKS
(to handle connected, intelligent, autonomous, evolvable systems)

1 – VIRTUAL ENGINEERING OF ECS

1.a Digital twins of the system under development, under test and in use

1.b Test management, test cases on all hierarchical layers (from physical sensor input via bitvectors up to concrete scenarios), scenario generation / synthesis

1.c Visualisation techniques to support the V&V and test process and evaluate progress

1.d (AI-based) model identification, synthesis, improvement and parameterisation with measurement data

1.e Integration of AI and AI-based tools into engineering and development processes on all levels of the design hierarchy, to shorten development time, incl. metrics for quantification of covered design space, etc

1.f Operation strategy optimisation by means of virtual models and simulation

1.g Complete traceability of products and processes in virtual engineering, supporting sensitivity analysis and robustness investigation included in the optimisation process and the system monitoring process

2 – SYSTEM AND COMPONENT DESIGN (METHODS AND TOOLS)

2.a Model-based design technologies

2.b Data-driven design technologies

2.c Advanced system design processes (continuous development / DevOps, agile development, etc)

2.d Platform-based design

2.e Methods and tools for (automatically generated) monitoring of systems (based on their digital twins) including for anomaly detection (for both security and safety)

2.f Means to process and analyse traces (observations , loggings, etc) from tests efficiently to derive tangible knowledge for design improvements

2.g Consistent Integration of complete, application-aware co-design of ECS on all levels of the design hierarchy

3 – LIFECYCLE-AWARE HOLISTIC DESIGN FLOWS (I.E. "CLOSE THE LOOP" IN DEVELOPMENT AND PRODUCT LIFECYCLE)

3.a Design for optimised manufacturing and operation; awareness of physical effects and interferences; awareness of complete lifecycle, incl. energy, resource, CO_2 footprint, recycling, circular economy

3.b Augmented and virtual reality in design, development, manufacturing and maintenance processes

3.c Open (and inner) source in HW and SW for complete product lifecycle

3.d Exploiting data from the field for V&V and development, design and optimisation tasks – creating a system family with shared learning from operational data

3.e Analysis of ECS systems in operation to improve future design within a continuous development process (DevOps)

3.f Consistent methods and new approaches for (multi-level, multi-paradigm) modelling) , analysis, verification and formalisation of ECS's operational reliability and service life

3.g "Supply chain-aware" design flow: from requirements to optimised system architecture considering supply chain leveraging "seamless digital twin from component to design to manufacturing of system to operation"

3.h Holistic design flows taking into consideration and bridging the functional layers and architectural layers with lifecycles and value streams

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Major challenge 1: EXTENDING DEVELOPMENT PROCESSES AND FRAMEWORKS (to handle connected, intelligent, autonomous, evolvable systems)

4 – INTEGRATION OF NEW VERIFICATION AND VALIDATION METHODS

- 4.a Incorporation of V&V methods and technologies into virtual engineering resp. design frameworks, incorporation into continuous development process
- 4.b From offline V&V (@design-time) to online V&V (@run-time)
- 4.c Usage of AI and AI-based tools for V&V and development task (exploiting AI capabilities)
- 4.d Model-based and mixed real/virtual testing approaches, incl. V&V of system architecture by simulating system components on different levels of abstraction
- 4.e Energy and resource efficient test procedures and equipment
- 4.f V&V extended by lifetime monitoring of security and reliability aspects

Major challenge 2: MANAGING NEW FUNCTIONALITY IN SAFE, SECURE, AND TRUSTABLE SYSTEMS

1 – MODELLING TECHNIQUES FOR NEW FUNCTIONALITIES

- 1.a Model creation/elicitation, modelling techniques, modelling tools, model libraries – continuous development process
- 1.b Techniques and tools to model behaviour, timing, functional and non-functional properties of (a) components, (b) systems, (c) environment / real world, (d) test cases / scenarios
- 1.c Multi-scale modelling. Detailed and slow fine-grained models feed key parameters to design development models. The key parameters of these models are again used in real-time models as part of the system.
- 1.d Executable models of sensors (incl. accuracy, confidence, etc)

2 – DESIGN AND V&V METHODS FOR ECS EVOLVING DURING LIFETIME (INCL. AI-ENABLED SYSTEMS)

- 2.a Design methods for AI-enabled ECS continuous development process
- 2.b V&V of AI enabled ECS , trustable AI (incl. quality attributes like safety, security, reliability, etc, but also un biased decisions, explainability, etc)
- 2.c Methods and tools for online risk assessment
- 2.d Methods and tools for handling cooperation (with other CPS, with humans), incl. recognising and acting on the perceived intent of cooperation partners
- 2.e Incremental V&V for all system qualities (safety, security, reliability, trustworthiness, etc)
- 2.f V&V for safe & secure systems with structural variability
- 2.g Design methods and V&V for handling of uncertainty (in perception, in communication, in prediction, in trustworthiness of data sources, etc
- 2.h Lifetime monitoring; secure and GDPR-compliant data from from device to multiple stakeholders (incl. system manufacturer); support for analysis & issue identification

3 – ULTRA-LOW POWER DESIGN METHODS

- 3.a Advanced design methods for ultra-low-power design, focusing on component-level as well as on system-level (most potential in system architecture and system operation) continuous development processes
- 3.b Design methods for (autonomous) ultra-low-power systems, taking into account application-specific requirements
- 3.c Method for comprehensive assessment and optimisation of power management and power consumption

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Major challenge 3: MANAGING COMPLEXITY

1 – METHODS AND TOOLS TO INCREASE DESIGN EFFICIENCY

1.a XIL-testing (X-in-the-loop, X=model, system, software, hardware, etc, incl. mixed modes

1.b XIL simulation techniques and tools, speed up of simulation, accuracy of simulation, multi-domain co-simulation

1.c Efficient modelling, test and analysis for reliable, complex systems on different abstraction levels

1.d Evaluation of architecture and design of the ECS SW/HW with real tests

2 – COMPLEXITY REDUCTION METHODS AND TOOLS FOR V&V AND TEST

2.a Recommender-based guidance in V&V process for complex ECS systems

2.b Automated generation of test cases from models/digital twins of ECS systems

2.c Test coverage calculation by means of models and test cases (coverage-driven V&V)

2.d Minimising effort for V&V based on models, AI techniques

2.e Advanced test methods, intelligent concepts for test termination, automated metrics/tools for testability and diagnosis, extraction of diagnostic information)

2.f Methods and tools for consistent, hierachical design, V&V and test

2.g Energy and resource-efficient test procedures and equipment

3 – METHODS AND TOOLS FOR ADVANCED ARCHITECTURES

3.a Architecture exploration and optimisation, including multi-aspect optimisation (e.g. safety, security, comfort, functionality, etc), also (incl. AI-based optimisation methods)

3.b Architectures supporting advanced computation methods (AI, advanced control, etc)

3.c Architectures and tools for non-von Neumann and neuromorphic computing

3.d Architectures supporting self-awareness, health and environment monitoring on all levels of the design hierarchy

3.e Platform and middleware architectures, also for extremely distributed, multi-layered SoS and IoT applications

3.f Reference architectures for continuous system improvement, i.e. across evolving system generations

3.g Architectures for V&V and certification, including automatic evaluation of computation and deployment decisions (i.e. on chip, edge, fog, cloud)

3.h Modular and evolvable/extendable architectures (supporting traceability of evolution, also supporting modular updates, replacement and recycling for a circular economy)

3.i (SW-HW) architecture mapping (incl. resource mapping and tracing (communication, scheduling, etc), incl. requirement matching and tracing)

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Major challenge 4: MANAGING DIVERSITY

1 – MULTI-OBJECTIVE DESIGN & OPTIMISATION OF COMPONENTS AND SYSTEMS

1.a Model creation/elicitation, modelling techniques, modelling tools, model libraries – continuous development process

1.b Techniques and tools to model behaviour, timing, functional and non-functional properties of (a) components, (b) systems, (c) environment / real world, (d) test cases / scenarios

1.c Multi-scale modelling. Detailed and slow fine-grained models feed key parameters to design development models. The key parameters of these models are again used in real-time models as part of the system.

1.d Executable models of sensors (incl. accuracy, confidence, etc)

2 – MODELLING, ANALYSIS, DESIGN AND TEST METHODS FOR HETEROGENEOUS SYSTEMS CONSIDERING PROPERTIES, PHYSICAL EFFECTS AND CONSTRAINTS

2.a Methods and tools for design, modelling and integration of heterogeneous systems

2.b Hierarchical methods for hardware/software co-simulation and co-development of heterogeneous systems (multi-scale, multi-rate modelling and simulation)

2.c Modelling methods to take account of operating conditions, statistical scattering and system changes

2.d Hierarchical modelling and early assessment of critical physical effects and properties from SoC up to system level

2.e Analysis techniques for new circuit concepts and special operating conditions (voltage domain check, especially for start-ups, floating node analysis etc)

3 – AUTOMATION OF ANALOGUE AND INTEGRATION OF ANALOGUE AND DIGITAL DESIGN METHODS

3.a Metrics for AMS testability and diagnostic efficiency (including V&V & test)

3.b Harmonisation of methods and tooling environments for analogue, RF and digital design

3.c Automation of analogue and RF design (high-level description, synthesis acceleration and physical design, modularisation, use of standardised components)

4 – CONNECTING THE VIRTUAL AND PHYSICAL WORLD OF MIXED DOMAINS IN REAL ENVIRONMENTS

4.a Advanced analysis considering the connection of virtual and physical world and its environment

4.b Novel more than Moore design methods and tools

4.c Models and model libraries for chemical and biological systems

Start research activities aiming at *Technology Readiness Level* ***(TRL)*** *2–4 (applied research – validation in laboratory environment)* ***or higher***

Start research activities aiming at TRL 4–6 *(applied research – demonstration in relevant environment)* ***or higher***

Start research activities aiming at TRL 6–8 *(applied research – prototyping in an operational environment qualified)*

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2.3.6
SYNERGY WITH OTHER THEMES

The processes, methods and tools addressed in this section relate to all other chapters of the ECS-SRIA. They enable the successful development, implementation, integration and testing of all applications described in *Chapter 3,* cover all levels of the technology stack (as indicated in *Chapter 1*) and enable the sufficient usage of all transversal technologies described in *Chapter 2.* Thus, there is a high synergy potential to carry out joint research on these topics. This holds especially true for topics in *Section 2.4:* qualities such as safety and security described there are a driver for the technologies in this section, where we describe processes, methods and tools that enable engineers to design systems guaranteed to possess the required qualities in a cost- and time-efficient way.

There is also a high synergy potential with additional activities outside of the pure funded projects work: reference architectures, platforms, frameworks, interoperable toolchains and corresponding standards are excellent nuclei around which innovation ecosystems can be organised. Such ecosystems comprise large industries, SMEs, research organisations and other stakeholders. They are focused on a particular strategic value chain, certain technology or any other asset for which sustainability and continuous improvement must be ascertained. The main activities of such innovation ecosystems are, first, to bring together the respective communities, implement knowledge exchange and establish pre-competitive cooperation between all members of the respective value chains. Second, they should further the technology around which they are centred, i.e. by refining and extending the platform, providing reference implementations and making them available to the community, provide integration support, establish the standard, etc. Third, they should ensure greater education and knowledge-sharing. Fourth, they should develop those parts of the Strategic Research and Innovation Agenda and other roadmaps that are related to the respective technology, monitor the implementation of the roadmaps, and incubate new project proposals in this area.

Last, but not least, the technologies described in this section are essential and necessary, but they are also to a large extent domain-agnostic, and can thus also serve as a connection point with activities in other funding programmes (for example, PENTA, ITEA and other EUREKA clusters).

2.4

Cross-Sectional Technologies

QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

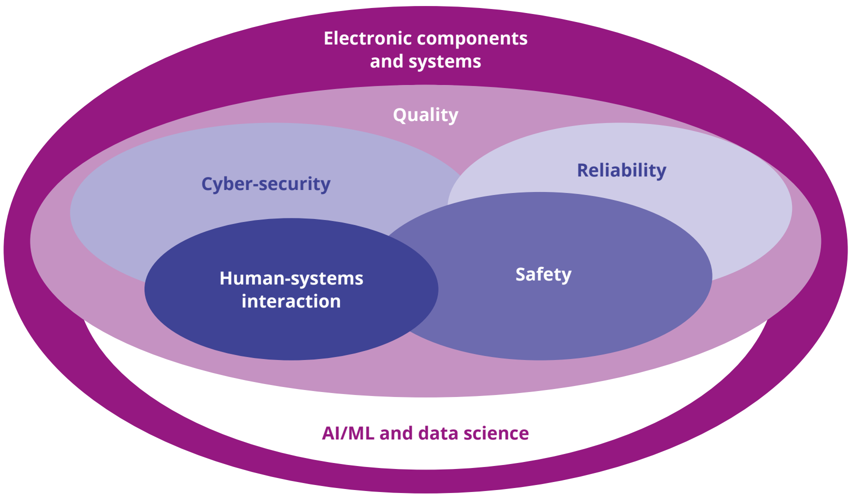
2.4.1
SCOPE

Modern technologies and new digitised services are key to ensuring the stable growth and development of the European Union and its society. These new technologies are largely based on smart electronic components and systems (ECS). Highly automated or autonomous transportation systems, improved healthcare, industrial production, information and communication networks, and energy grids all depend on the availability of electronic systems. The main societal functions[82] and critical infrastructure are governed by the efficient accessibility of smart systems and the uninterrupted availability of services.

Ensuring the reliability, safety and security of ECS is a **Major challenge** since the simultaneous demand for increased functionality and continuous miniaturisation of electronic components and systems causes interactions on multiple levels. This section addresses these complex interdependencies by considering input from, and necessary interaction between, major disciplines. The quality, reliability, safety and cybersecurity of electronic components and systems are, and will be, fundamental to digitised society (see *Figure F.36*).

In this section, we will discuss the following Major challenges:

- **Major challenge 1:** Ensuring HW quality and reliability.
- **Major challenge 2:** Ensuring dependability in connected software.
- **Major challenge 3:** Ensuring cyber-security and privacy.
- **Major challenge 4:** Ensuring safety and resilience.
- **Major challenge 5:** Human–system interaction.



F.36

[82] *Vital societal functions: services and functions for maintaining the functioning of a society. Societal functions in general: various services and functions, public and private, for the benefit of a population and the functioning of society.*

2.4.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

"The role of the technology is to allow persons to express their potential". Hans Rosling, in his book *Factfulness: Ten Reasons We're Wrong About the World – and Why Things Are Better Than You Think*, plots the life quality of the world's population in groups at successive levels. He shows how such groups, even those at the bottom level, will move forward over time to the next level. Technology can help accelerate that progression. An emblematic example of that is the project launched by Facebook and the Internet Society (ISOC) to develop internet exchange points (IXPs) throughout Africa. Albeit not without difficulty, IXPs help promote e-learning to improve education in the continent, and for connected drones to deliver medicines and other products to remote populations.

The recent Covid-19 pandemic has emphasised the importance of digital technology to the western world, with the recourse to robots in several hazardous situations, from disinfecting airplanes and hospital rooms, to delivering medication to isolated patients. Digital technology that can fit these diverse needs should address holistically concerns such as quality of service, reliability, safety, trustworthy, privacy, cybersecurity and human–system integration. A degraded behaviour in any of these dimensions, or an incorrect integration among them, would affect vital properties and could cause serious damage. In addition, such shortcomings in safety, reliability and security might even outweigh the societal and individual benefits perceived by users, thus lowering trust in, and acceptance of, the technologies. All these topics and features constitute the core of this section.

2.4.3
STRATEGIC ADVANTAGE FOR THE EU

Europe is internationally known for its high-quality product standards, which enjoy a strong international reputation. The European Union (EU) has a robust and reliable safety and product liability regulatory framework, and a rigorous body of safety standards, complemented by national, non-harmonised liability regulations. In the past, this has been a big success for European embedded systems in almost all industries, including automotive, telecommunications, manufacturing, railway, avionic and military defence, to name but a few of the many sectors where people rely on them.

However, in light of the two main drivers of digitalisation and connectivity, Europe is highly dependent on the supply of hardware and software from countries outside of Europe. Dominating market players in the information and communications technology (ICT) sector – such as the US companies Google, Apple, Facebook, Amazon and Microsoft (GAFAM) or the Chinese companies Baidu, Alibaba, Tencent and Xiaomi (BATX) – are expanding their products towards industrial domains. In addition, recent revelations regarding espionage and state-sponsored surveillance have initiated a debate on the protection of core EU values such as security, privacy, data protection and trust. Therefore, digital sovereignty – the ability of the EU to maintain a high level of control and security of its products, responding quickly if potential vulnerabilities are noticed – is of utmost importance. A strategic advantage can be achieved by designing reliable, safe and secure products where the dependencies to foreign products are transparently considered. A difference for EU products can also be achieved by treating privacy and necessary human interaction with its own set of independent standards, where technology will keep its limits according to European values when interacting with citizens.

2.4.4 MAJOR CHALLENGES

To introduce the topic presented in this section, we first present some definitions that will be useful helpful in following our **Major challenges**.

- Quality: Often defined as "the ability of a system being suitable for its intended purpose while satisfying customer expectations", this is a very broad definition that basically includes everything. Another widely used definition is "the degree a product meets requirements in specifications" – but without specifying the underlying specifications, the interpretation can vary a lot between different stakeholders. Therefore, in this section quality will be defined "as the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (burn-in) but no other type of testing". In this way, reliability, dependability and cybersecurity, which for some would be expected to be included under quality, will be treated separately.
- Reliability: This is the ability or the probability, respectively, of a system or component to function as specified under stated conditions for a specified time.
- Prognostics and health management: A method that permits the assessment of the reliability of the product (or system) under its application conditions.
- Functional safety: The ability of a system or piece of equipment to control recognised hazards to achieve an acceptable level of risk, such as to maintain the required minimum of operation even in the case of likely operator errors, hardware failures and environmental changes to prevent physical injuries or damages to the health of people, either directly or indirectly.
- Dependability: According to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here (192-01-01) can be an individual part, component, device, functional unit, equipment, subsystem or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01-27) and maintenance support performance (192-01-29), and in some cases other characteristics such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).
- Safety: Freedom from unacceptable risk of harm [CENELEC 50126].
- Security: Measures can provide controls relating to physical security (control of physical access to computing assets) or logical security (capability to login to a given system and application) (IEC 62443-1-1):
  - measures taken to protect a system.
  - condition of a system that results from the establishment and maintenance of measures to protect the system.
  - condition of system resources being free from unauthorised access, and from unauthorised or accidental change, destruction or loss.
  - capability of a computer-based system to provide adequate confidence that unauthorised persons and systems can neither modify the software and its data nor gain access to

the system functions, and yet ensure that this is not denied to authorised persons and systems.
- prevention of illegal or unwanted penetration of, or interference with, the proper and intended operation of an industrial automation and control system.

- Cybersecurity: The protection of information against unauthorised disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).
- Robust root of trust systems: These are based on cryptographic functionalities that ensure the authenticity and integrity of the hardware and software components of the system, with assurance that it is resilient to logical and physical attacks.

2.4.4.1 Major challenge 1: Ensuring HW quality and reliability

2.4.4.1.1 State of the art

With the ever-increasing complexity and demand for higher functionality of electronics, while at the same time meeting the demands of cutting costs, lower levels of power consumption and miniaturisation in integration, hardware development cannot be decoupled from software development. Specifically, when assuring reliability, separate hardware development and testing according to the second-generation reliability methodology (design for reliability, DfR) is not sufficient to ensure the reliable function of the ECS. A third-generation reliability methodology must be introduced to meet these challenges. For the electronic smart systems used in future highly automated and autonomous systems, a next generation of reliability is therefore required. This new generation of reliability assessment will introduce in situ monitoring of the state of health on both a local (e.g. IC packaging) and system level. Hybrid prognostic and health management (PHM) supported by Artificial Intelligence (AI) is the key methodology here. This marks the main difference between the second and the third generation. DfR concerns the total lifetime of a full population of systems under anticipated service conditions and its statistical characterisation. PHM, on the other hand, considers the degradation of the individual system in its actual service conditions and the estimation of its specific remaining useful life (RUL).

2.4.4.1.2 Vision and expected outcome

Since embedded systems control so many processes, the increased complexity by itself is a reliability challenge. Growing complexity makes it more difficult to foresee all dependencies during design. It is impossible to test all variations, and user interfaces need greater scrutiny since they have to handle such complexity without confusing the user or generating uncertainties.

The trend towards interconnected, highly automated and autonomous systems will change the way we own products. Instead of buying commodity products, we will instead purchase personalised services. The vision of **Major challenge 1** is to provide the requisite tools and methods for novel ECS solutions to meet ever-increasing product requirements and provide availability of ECS during use in the field. Therefore, availability will be the major feature of ECS. Both the continuous improvement of existing methods (e.g. DfR) and development of the new techniques (PHM) will be the cornerstone of future developments in ECS (see also **Challenges 1 and 2**, and especially the key focus areas on lifecycle-aware holistic design flows in *Section 2.3* **Architecture and Design: Methods and Tools**). The main focus of **Major challenge 1** will circulate around the following topics.

- Digitisation, by improving collaboration within the supply chain to introduce complex ECS earlier in the market.
- Continuous improvement of the DfR methodology through simultaneous miniaturisation and increasing complexity.

- Model-based design is a main driver of decreasing time-to-market and reducing the cost of products.
- Availability of the ECS for highly automated and autonomous systems will be successfully introduced in the market based on PHM.
- Data science and AI will drive technology development and pave the way for PHM implementation for ECS.

2.4.4.1.3 Key focus areas

Quality: *In situ* and real-time assessments

Inline inspection and highly accelerated testing methods for quality and reliability monitoring during production of ECS with ever-increasing complexity and heterogeneity for demanding applications should increase the yield and reduce the rate of early fails (failures immediately following the start of the use period).

- Controlling, beyond traditional approaches, the process parameters in the era of Industry 4.0 to minimise deviations and improve quality of key performance indicators (KPIs).
- Process and materials variabilities will have to be characterised to quantify their effects on hardware reliability, using a combination of empirical studies, fundamental RP models and AI approaches.
- Advanced/smart monitoring of process output (e.g. measuring the 3D profile of assembled goods) for the detection of abnormities (using AI for the early detection of standard outputs).
- Early detection of potential yield/reliability issues by simulation-assisted design for assembly/design for manufacturing (DfM/DfA) as a part of virtual prototyping.

Digitisation: A paradigm shift in the fabrication of ECS from supplier/customer to partnership

- Involving European stakeholders to resolve the issue of data ownership:
  - Create a best practice for sharing data across the supply chain while maintaining intellectual property (IP).
  - Standardise the data exchange format, procedures and ownership, and create an international legal framework.
  - Conceive and validate business models facilitating sharing data, models derived from data and algorithms dealing with data.
- Handling and interpreting big data:
  - Create a usable and time-efficient workflow for supervised learning.
  - Consistent data collection and annotation/labelling of relevant events.
  - Standardised model training and model testing process.
  - Standardised procedures for model maintenance and upgrade.
- Make a link between data from Industry 4.0 and model-based engineering:
  - Derive working hypotheses about system health.
  - Validate hypothesis and refine physics-based models.
  - Construct data models based on new knowledge derived from model-based engineering.
- Identify significant parameters that must be saved during production to be re-used later for field-related events, and vice versa – i.e. feed important insights derived from field data (product usage monitoring) into design and production.
- Evaluate methods for the indirect characterisation of ECS using end-of-line test data.
- Wafer fabrication inline and offline tests for electronics, sensors and actuators, and complex hardware (e.g. multicore, graphics processing unit, GPU) that also cover interaction effects such as heterogeneous 3D integration and packaging approaches for advanced nodes technologies.

Reliability: Tests and modelling

Continuous improvement of physics of failure (PoF) based methodologies combined with new data-driven approaches: tests, analyses and degradation, and lifetime models (including their possible reconfiguration):

- Identifying and adapting methodology to the main technology drivers.
- Methods and equipment for dedicated third-level reliability assessments (first level: component; second level: board; third level: system with its housing, e.g. massive metal box), as well as accounting for the interactions between the hierarchy levels (element, device, component, sub-module, module, system, application).
- Comprehensive understanding of failure mechanisms, lifetime prediction models (including multi-loading conditions), continuously updating for new failure mechanisms related to innovative technologies (advanced complementary metal–oxide–semiconductor (CMOS), µ-fluidics, optical input/output (I/O), 3D printing, etc).
- Accelerated testing methods (e.g. high temperature, high power applications) based on mission profiles and failure data (from field use and tests):
  - Use field data to derive hypotheses that enable improved prioritisation and design of testing.
- Standardise the format of mission profiles and the procedure on how mission profiles are deducted from multimodal loading.
- Understanding and handling of new, unforeseen and unintended use conditions for automated and autonomous systems.
- Embedded reliability monitoring (pre-warning of deterioration) with intelligent feedback towards autonomous system(s).
- Identification of the 10 most relevant field-related failure modes based on integrated mission profile sensors.
- Methods to screen out weak components with machine learning (ML) based on a combination of many measured parameters or built-in sensor data.
- New standards/methodologies/paradigms that evaluate the "ultimate" strength of systems – i.e. no longer test whether a certain number of cycles are "pass", but go for the limit to identify the actual safety margin of systems, and additionally the behaviour of damaged systems, so that AI can search for these damage patterns.
- Digital twin software development for reliability analysis of assets/machines, etc.

Design for reliability: Virtual reliability assessment prior to the fabrication of physical HW

Approaches for exchanging digital twin models along the supply chain while protecting sensitive partner IP and adaptation of novel standard reliability procedures across the supply chain.

- Digital twin as main driver of robust ECS system:
  - Identifying main technology enablers.
  - Development of infrastructure required for safe and secure information flow.
  - Development of compact PoF models at the component and system level that can be executed in situ at the system level – metamodels as the basis of digital twins.
  - Training and validation strategies for digital twins.
  - Digital twin-based asset/machine condition prediction.
- Electronic design automation (EDA) tools to bridge the different scales and domains by integrating a virtual design flow.
- Virtual design of experiment as a best practice at the early design stage.
- Realistic material and interface characterisation depending on actual dimensions, fabrication process conditions, ageing effects, etc, covering all critical structures, generating strength data of interfaces with statistical distribution.

- Mathematical reliability models that also account for the interdependencies between the hierarchy levels (device, component, system).
- Mathematical modelling of competing and/or superimposed failure modes.
- New model-based reliability assessment in the era of automated systems.
- Development of fully harmonised methods and tools for model-based engineering across the supply chain:
  - Material characterisation and modelling, including effects of ageing.
  - Multi-domain physics of failure simulations.
  - Reduced modelling (compact models, metamodels, etc).
  - Failure criteria for dominant failure modes.
  - Validation techniques.
- Standardisation as a tool for model-based development of ECS across the supply chain:
  - Standardisation of material characterisation and modelwling, including effects of ageing.
  - Standardisation of simulation-driven design for excellence (DfX).
  - Standardisation of model exchange format within supply chain using functional mock-up unit (FMU) and functional mock-up interface (FMI) (and also components).
  - Initiate and drive standardisation process for above-mentioned points.
  - Extend common design and process failure mode and effect analysis (FMEA) with reliability risk assessment features ("reliability FMEA").
  - Generic simulation flow for virtual testing under accelerated and operational conditions (virtual "pass/fail" approach).
- Automation of model build-up (databases of components, materials).
- Use of AI in model parametrisation/identification, e.g. extracting material models from measurement.

Prognostics health management of ECS: Increase in functional safety and system availability

- Self-monitoring, self-assessment and resilience concepts for automated and autonomous systems based on the merger of PoF, data science and ML for safe failure prevention through timely predictive maintenance.
- Self-diagnostic tools and robust control algorithms, validated by physical fault-injection techniques (e.g. by using end-of-life (EOL) components).
- Hierarchical and scalable health management architectures and platforms, integrating diagnostic and prognostic capabilities, from components to complete systems.
- Standardised protocols and interfaces for PHM.
- Monitoring test structures and/or monitor procedures on the component and module levels for monitoring temperatures, operating modes, parameter drifts, interconnect degradation, etc.
- Identification of early warning failure indicators and the development of methods for predicting the remaining useful life of the practical system in its use conditions.
- Development of schemes and tools using ML techniques and AI for PHM.
- Implementation of resilient procedures for safety-critical applications.
- Big sensor data management (data fusion, find correlations, secure communication), legal framework between companies and countries).
- Distributed data collection, model construction, model update and maintenance.
- Concept of digital twin: provide quality and reliability metrics (key failure indicator, KFI).
- Development of an algorithm for data scalability and availability.
- Availability of the data for the training algorithm.
- Accelerated testing methods.

- Development of AI-supported failure diagnostic and repair processes for improve field data quality.
- AI-based asset/machine/robot life extension method development based on PHM.
- AI-based autonomous testing tool for verification and validation (V&V) of software reliability.

2.4.4.2 Major challenge 2: Ensuring dependability in connected software

2.4.4.2.1 State of the art

Connected software applications such as those used on the Internet of Things (IoT) differ significantly in their software architecture from traditional reliable software used in industrial applications. The design of connected IoT software is based on traditional protocols originally designed for data communications for PCs accessing the internet. This includes protocols such as transmission control protocol/internet protocol (TCP/IP), the re-use of software from the IT world, including protocol stacks, web servers and the like. This also means the employed software components are not designed with dependability in mind, as there is typically no redundancy and little arrangements for availability. If something does not work, end-users are used to restarting the device. Even if it does not happen very often, this degree of availability is not sufficient for critical functionalities, and redundancy hardware and back-up plans in ICT infrastructure and network outages still continue to occur. Therefore, it is of the utmost importance that we design future connected software that is designed either in a dependable way or can react reliably in the case of infrastructure failures to achieve higher software quality.

2.4.4.2.2 Vision and expected outcome

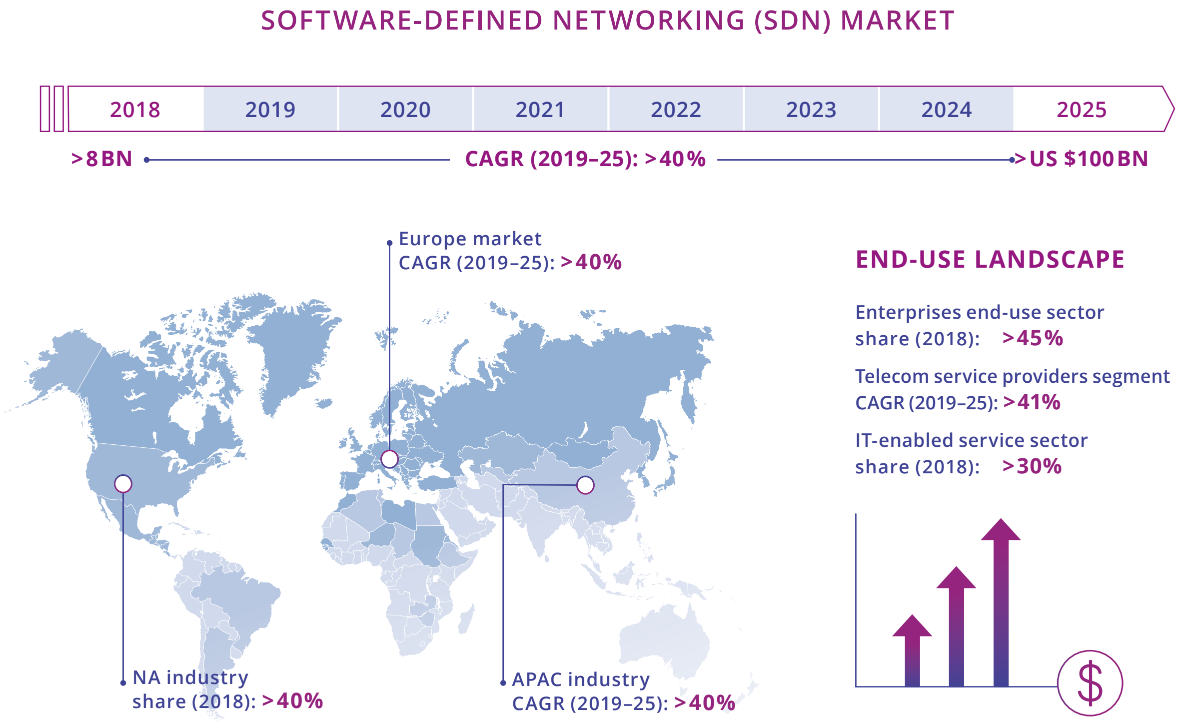
The vision is that networked systems will become as dependable and predictable for end-users as traditional industrial applications interconnected via dedicated signal lines. This means that the employed connected software components, architectures and technologies will have to be enriched to deal with dependability for their operation. Future dependable connected software will also be able to detect in advance if network conditions change – e.g. due to foreseeable transmission bottlenecks or planned maintenance measures. If outages do happen, the user or end application should receive clear feedback on how long the problem will last so they can take potential measures. In addition, the consideration of redundancy in the software architecture must be considered for critical applications. The availability of a European ecosystem for reliable software components will also reduce the dependence on current ICT technologies from the US and China.

2.4.4.2.3 Key focus areas

Dependable connected software architectures

In the past, reliable and dependable software was always directly deployed on specialised, reliable hardware. However, with the increased use of IoT, edge and cloud computing, critical software functions will also be used that are completely decoupled from the location of use (e.g. in use cases where the police want to stop self-driving cars from a distance).

- Software reliability in the face of infrastructure instability.
- Dependable edge and cloud computing, including dependable and reliable AI/ML methods and algorithms.
- Dependable communication methods, protocols and infrastructure.
- Formal verification of protocols and mechanisms, including those using AI/ML.
- Monitoring, detection and mitigation of security issues on communication protocols.
- Quantum key distribution (“quantum cryptography”).
- Increasing software quality by AI-assisted development and testing methods.



Software-defined networking (SDN) market size by 2025 (Source: Global Markets Insight, Report ID GMI2395, 2018) **F.37**

- Infrastructure resilience and adaptability to new threats.
- Secure and reliable over-the-air (OTA) updates.
- Using AI for autonomy, network behaviour and self-adaptivity.
- Dependable integration platforms.
- Dependable cooperation of System of Systems (SoS).

Dependable softwarisation and virtualisation technologies

Changing or updating software by retaining existing hardware is quite common in many industrial domains. However, keeping existing reliable software and changing the underlying hardware is difficult, especially for critical applications. By decoupling software functionalities from the underlying hardware, softwarisation and virtualisation are two disruptive paradigms that can bring enormous flexibility and thus promote strong growth in the market (see *Figure F.37*). However, the softwarisation of network functions raises reliability concerns, as they will be exposed to faults in commodity hardware and software components.

- Software-defined radio (SDR) technology for highly reliable wireless communications with higher immunity to cyber-attacks.
- Network functions virtualisation infrastructure (NFVI) reliability.
- Reliable containerisation technologies.
- Resilient multi-tenancy environments.
- AI-based autonomous testing for V&V of software reliability, including the software-in-the-loop (SiL) approach.
- Testing tools and frameworks for V&V of AI/ML-based software reliability, including the SiL approach.

Combined SW/HW test strategies

Unlike hardware failures, software systems do not degrade over time unless modified. The most effective approach for achieving higher software reliability is to reduce the likelihood of latent defects in the released software. Mathematical functions that describe fault detection and removal phenomenon in software have begun to emerge. These software reliability growth models (SRGM), in combination with Bayesian statistics, need further attention within the hardware-orientated reliability community over the coming years.

- HW failure modes are considered in the software requirements definition.
- Design characteristics will not cause the software to overstress the HW, or adversely change failure-severity consequences on the occurrence of failure.
- Establish techniques that can combine SW reliability metrics with HW reliability metrics.
- Develop efficient (hierarchical) test strategies for combined SW/HW performance of connected products.

Dependability in connected software is strongly connected with other sections in this document. In particular, additional challenges are handled in the section **Embedded Software and Beyond** in **Major challenges** (1) efficient engineering of software; (2) continuous integration and deployment; (3) lifecycle management; and (6) software reliability and trust; as well as in **Sytem of Systems** in **Major challenges** (1) "Architectures (for SoS)"; (4) SoCPS and SoES engineering; and (5) open SoCPS and SoES platforms".

2.4.4.3 Major challenge 3: Ensuring cyber-security and privacy

2.4.4.3.1 State of the art

We have witnessed a massive increase in pervasive and potentially connected digital products in our personal, social and professional spheres. Although connectivity provides better flexibility and usability of these products in different sectors, it also introduces severe issues about security and privacy. At the same time, AI is becoming a key element of these digital products, especially (but not limited to) with respect to the personalisation of mass products around individual preferences and requirements.

AI functionality is growing at speed in devices and services. Therefore, resilience to cyber-attacks is of the utmost importance. AI can have a direct action on the behaviour of a device, possibly impacting its physical life. AI systems rely on software and hardware that can be embedded in components, but also in the set of data generated and used. Cyber-attacks, such as data poisoning or adversarial inputs, could cause physical harm and/or also violate privacy. The development of AI should therefore go hand in hand with frameworks that assess (cyber)security and safety to guarantee that AI systems developed for the EU market are safe to use, trustworthy, reliable and remain under control.

The combination of connected digital products and AI highlights the importance of trustable systems that weave together privacy and cybersecurity with safety and resilience. Automated vehicles, for example, are adopting an ever-expanding combination of sensors, devices and on-board computers (sensors, Global Positioning System (GPS), radar, lidar, cameras, on-board computers, etc) that exchange data with other vehicles, infrastructures and environments. Autonomous vehicles represent a truly disruptive innovation for travelling and transportation, and should be able to ensure the confidentiality of the driver's and vehicle's information, as well as avoiding obstacles, identifying failures (if any) and mitigating them, and preventing cyber-attacks while safely staying operational (at reduced functionality) either through human-initiated intervention, by automatic inside action or remotely by law enforcement in the case of any failure, security breach, sudden obstacle, crash, etc.

Although highly complex, interconnected and strongly data-driven, for simplicity this challenge focuses on the cyber-security and privacy trade-offs. In particular, privacy is becoming a discipline in its own right and not just a part of auditing, legal and compliance. This challenge is strictly related to European data strategy and data sovereignty. An additional challenge addresses safety and resilience, and a special item is also devoted to investigating how safety and security influence each other.

2.4.4.3.2 Vision and expected outcome

The cornerstone of our vision is threefold. First, a robust root of trust system, with unique identification enabling security without interruption from the hardware level right up to the applications, including AI, involved in the accomplishment of the system's mission. Second, protection of the EU citizen's privacy. Third, proof-of-concept demonstrators that are capable of simultaneously guaranteeing (a given level of) security and (a given level of) privacy, as well as potentially evolving in-reference designs that illustrate how practical solutions can be implemented (i.e. thereby providing guidelines to re-use or adapt).

Putting together seamlessly security and privacy requirements is a difficult challenge that also involves some non-technical aspects. Consider, for example, the concerns raised in the public domain by person-tracking applications that European countries are evaluating to contain the number of new Covid-19 contagions after the end of a strict lockdown period. The awareness that the number of cyber-attacks against personal data is also continuing to rise exponentially clearly adds to that anxiety. In this regard, Risk Based Security has stated that, in June 2019, "3,813 breaches were reported, exposing over 4.1 billion records". If we compare these data to those in the same period for 2018, the report[83] found that the number of breaches had grown to 52% and the exposing records to 54%. In the first quarter of 2020, however, the number of breaches and exposed data had strongly decreased, but cybercrime had increased due to the economic recession after the Covid-19 lockdown[84]. In the meantime, the cybersecurity and privacy market in 2019 was forecast to grow by 8.7% to US $124 billion[85].

In light of this scenario, this vision challenge aims to contribute to the European sovereignty plan in terms of cybersecurity, digital trustworthiness and the protection of personal data.

2.4.4.3.3 Key focus areas

Trustworthiness

The goal is a robust and resilient system that operates in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be AI-enabled. In this aim, the main expected outcome is methods and concepts that build and test such systems:

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83 *CyberRisk Analytics, 2019 mid year, data breach report.*

84 *ref. CyberRisk Analytics, 2020 Q1 data breach report.*

85 *https://www.gartner.com/en/newsroom/press-releases/2018-08-15-gartner-forecasts-worldwide-information-security-spending-to-exceed-124-billion-in-2019*

- Ensuring cyber-security of systems, including AI.
- Defining different methods and techniques of trust for a system, and proving compliance to a security standard via certification schemes.
- Defining a method for multiple standards via the composition of certified parts.
- Enabling developers to have a flexible means to demonstrate security capabilities.
- Developing technologies, methods and techniques to ensure cyber-security at all levels.
- Definition and future consolidation of a framework providing guidelines, good practices and standards oriented to trust.

Security and privacy-by-design

The main expected outcome is a set of solutions that integrates privacy and confidentiality of data as built-in properties of systems:

- Ensuring performance and AI development (which needs considerable data) while guaranteeing general data protection regulation (GDPR) compliance.
- Establishing a secure and privacy-by-design European data strategy and data sovereignty.
- Ensuring the protection of personal data in the data-driven digital economy against potential cyber-attacks.

Ensuring both safety and security properties

The main expected outcome is to ensure compatibility, adequacy and coherence in the joint use of the promoted security solutions, and the safety levels required by the system or its components:

- Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc).
- Ensuring the nominal and degraded behaviour of a system when the system's security is breached or there are accidental failures.
- Guaranteeing a system's coherence among different heterogeneous requirements (i.e. secure protocols, safety levels, computational level needed by the promoted mechanisms) and different applied solutions (i.e. solutions for integrity, confidentiality, security, safety) in different phases (i.e. design phases, run-time phases, maintenance phases, repair and recovery phases).
- Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of trustworthiness.
- Evaluating the impact of the contextualisation environment on the system's required levels of safety and security.

2.4.4.4 Major challenge 4: Ensuring of safety and resilience

2.4.4.4.1 State of the art

Safety has always been a key concept at the core of human civilisation. Throughout history, its definition, as well as techniques to provide it, has evolved significantly. In the medical application domain, for example, we have witnessed a transformation from safe protocols to automatic medication machines, such as insulin pumps and respiratory automation, which have integrated safety provisions. Today, we can build a range of different high-integrity systems, such as nuclear power plants, aircraft and autonomous metro lines. The safety of such systems is essentially based on a combination of key factors, including: (i) determinism (the system's nominal behaviour is always the same under the same conditions); (ii) expertise and continuous training of involved personnel; (iii) deep understanding of nominal and degraded behaviours of the system; (iv) certification/qualification; and (v) clear liability and responsibility chains in the case of accidents.

Nowadays, the digitalisation of ubiquitous systems, and the embedding of AI components (hardware or software) in them, highlights the limits of traditional safety techniques. These techniques for building safe systems include fault-tree analysis, failure modes and effect analysis, evidence-based development standards (such as ISO26262 and ISO 21448), redundancy, diversification and defence-in-depth. As a result of the realities in modern systems and their usage, the safety paradigm has moved from safety as traditionally studied in embedded systems, to resilience [from resilire (lat.), to back jump]. Most of the methodical factors mentioned above fall apart. New innovations are required to increase the resilience of systems by tackling challenges involving cross-cutting considerations such as legal concerns and user abilities. For example, the inherent inscrutability of AI algorithms combined with the increasing autonomy of the system threatens liability and responsibility chains in the case of an accident. Understanding the nominal and degraded behaviours of AI-driven system is also extremely complex, and operators of several AI-driven systems are the main users of the system (for example, a child that uses an autonomous vehicle) – i.e. users not necessarily expert in the system itself, unlike the operators in the traditional high-integrity systems, such as operators of nuclear power plants.

2.4.4.4.2 Vision and expected outcome

The vision points to the development of safe and resilient autonomous cyber-physical systems in dynamic environments, with a continuous chain-of-trust from the hardware level up to the applications that is involved in the accomplishment of the system's mission, including AI. Our vision takes into account physical limitations (battery capacity, quality of sensors used in the system, hardware processing power needed for autonomous navigation features, etc). Civilian applications of (semi-)autonomous cyber-physical systems are increasing significantly. For example, drones can be deployed for monitoring social distancing and providing safety to the population (and also to deliver medicine in the UK). However, the use of drones is not accident-free. In 2015, at the Pride Parade in Seattle, a drone crashed and caused an accident that resulted in a woman being knocked out. Civilian applications thus inherently entail safety, and in the case of an accident or damage (for example, in uploading a piece of software in an AI system) liability should be clearly traceable, as well as the certification/qualification of AI systems.

The increasing trend towards the adoption of AI in civilian applications represents a great opportunity for European economic growth. However, unlike traditional high-integrity systems, the hypothesis that only expert operators can manipulate the final product undermines the large-scale adoption of the new generation of autonomous cyber-physical systems.

In addition to the key focus areas below, the challenges cited in *Section 2.3* on **Architecture and Design: Methods and Tools** are also highly relevant for this topic.

2.4.4.4.3 Key focus areas

Safety and resilience of (autonomous AI) systems in dynamic environments

The expected outcome is systems that are resilient under physical constraints:

- Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimisation.
- Resources' management of all system's components to accomplish the mission system in a safe and resilient way.
- Identify and address transparency and safety-related issues introduced by AI applications.
- Concepts and principles for trustable integration and the V&V of intelligent functions in systems/products under uncertain and/or dynamic environments.

Modular certification of trustable systems and liability

The expected outcome is a clear traceability of liability in the case of damage or accident:

- Having explicit workflows for automated and continuous layered certification/qualification, both when designing the system and for checking certification/qualification during run-time or dynamic safety contracts, to ensure continuing trust in dynamic adaptive systems in changing environments.
- Contract-based co-design methodologies, consistency management techniques in multi-domain collaborations.
- Certificates of extensive testing, new code coverage metrics (e.g. derived from mutation testing), formal methods providing guaranteed trustworthiness.

Dynamic adaptation and configuration, self-repair capabilities, (decentralised instrumentation and control for) resilience of complex and heterogeneous systems

The expected outcome is resilient systems that are able to dynamically adapt their behaviour in dynamic environments:

- Responding to uncertain information based on digital twin technology, run-time adaptation and redeployment based on simulations and sensor fusion.
- Automatic prompt self-adaptability at low latency to dynamic and heterogeneous environments.
- Architectures that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification.
- Develop explainable AI models for human interaction, system interaction and certification.
- Support for dependable dynamic configuration and adaptation/maintenance to help cope with components that appear and disappear, as ECS devices to connect/disconnect, and communication links that are established/released depending on the actual availability of network connectivity (including, for example, patching) to adapt to security countermeasures.
- Concepts for SoS integration, including legacy system integration.

Safety aspects related to the human/system interaction

The expected outcome is to ensure safety for the human, system and environment during the nominal and degraded operations in the working environment (cf. **Major challenge 5** below):

- Understanding the nominal and degraded behaviour of a system that could potentially have AI.
- Minimising the risk of human or machine failures during the operating phases.
- Ensuring that the human can safely interface with machine, and also that the machine can prevent unsafe operations.
- New self-learning safety methods to ensure safety system operations in complex systems.
- Ensuring safety in machine-to-machine interaction.
- Safely manage human interaction in complex systems, SoS and application scenarios.

2.4.4.5 Major challenge 5: Human–systems integration

2.4.4.5.1 State of the art

The massive increase of sophistication and availability of smart products and cyber-physical systems brings new challenges for engineers, designers and managers to shape them for effective, safe and acceptable use by private and professional users in real-world operations. These new products must be trustworthy, transparent and explainable to increase product acceptance and commercial success, but will challenge current technology development processes and structures. Since smart products with AI components can take over tasks that were previously performed by humans, they often require more intensive interactions and understanding by the users than "dumb" products that are completely under the users' control. Accordingly, tasks and responsibilities shift, and often unexpected operational consequences arise when disruptively innovative technologies land in daily use conditions. Often smart products that can be successfully demonstrated under test conditions fail in real-world operations because they require user knowledge, active engagement and extra work steps to enable, adapt and maintain them for effective use. This is often not considered during design and development processes, which makes implementations costly in terms of time and resources. Rather, such user knowledge and activities tend to be only implicitly assumed during design and development, and not explicitly considered or declared. For example, the facial recognition software of several large development organisations has exhibited racial biases when put to use by police departments, and therefore found unacceptable for use; use conditions and purpose had not been sufficiently considered during the design phase. Also, as AI solutions that users can understand become more common, the explainability of solutions becomes significant.

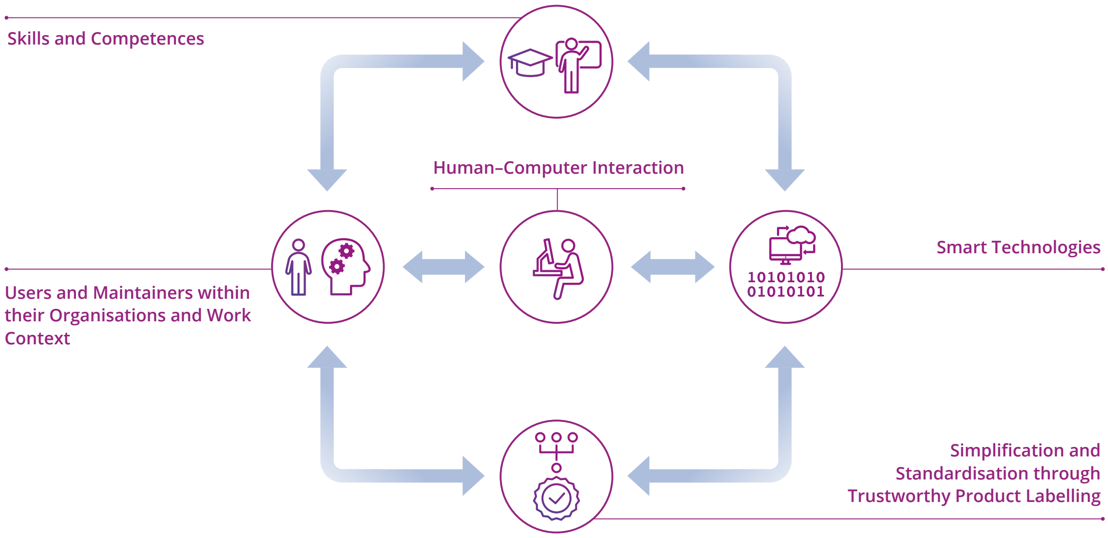
The problem of bringing smart products and human users together to create real-world effective, safe and acceptable systems that can be used by all users has been recognised by many, including the International Council on Systems Engineering (INCOSE), which is developing a new discipline of human–systems integration to address these challenges. Whereas since the 1980s traditional human–computer interaction (HCI) research has focused on the direct interactions between human and computers for displays and controls, since the early 2000s human–system integration has looked more at holistically designed systems with a thorough understanding of the user, technological constraints and context of use to define a operational concept that balances system requirements.

HCI is only one of the many aspects of human/systems integration; other critical areas include safety, health, environment, competences and training. Therefore, the trend will move away from designing human–computer interactions for the smallest common denominator user with the smallest set of skills and knowledge, as this is seen as limiting the usefulness and acceptance of technological innovations, as well as reducing their economic, operational and social impact. One-for-all solutions are in the past; new products are being tailored to adapt themselves or be adapted for specific user and use conditions.

Human–system integration is signifying a revolution in how R&D activities are orchestrated. A critical area here specifically for the consumer product market is the ability to represent and manage the competence and knowledge profiles of users to develop tailored products for them, but also to develop training and education profiles they can use.

Research and solutions are therefore needed to elicit, represent and make available design, training and education, as well as personnel selection for individual skills, competences and knowledge of users. This includes the testing for certain skills, but also the development of the knowledge frameworks required to understand the digital world of today (and tomorrow). Instead of just improving technologies, it will be increasingly important to identify what common knowledge and skills are needed for users to gain access to the technological potential. Importantly, AI solutions should be able to explain themselves to the users, and to reflect their specific background, context and expectations for effective understanding.

Bringing users closer to the technological world of tomorrow is already being practiced in some areas. For example, to improve traffic safety for automated driving systems, the Japanese strategic innovation programme for the Innovation of Automated Driving for Universal Services specifically addresses the formation of driver knowledge and competences for using advanced vehicle features.



F.38 *The fourfold vision and expected outcome of human–systems integration*

2.4.4.5.2 Vision and expected outcome

The vision is to widen the opportunities to create effective, trusted and safe digital products that are accepted by customers, and thereby enhance market potential. Many users of smart products do not currently have the prerequisite knowledge about security, privacy and functionality to make informed trust decisions about products and use them effectively. Often purchase decisions are made without consideration of such concerns, and user perceptions can become volatile, as they are susceptible to the daily vagaries of social, online and print media. In addition, smart products can require user skills, competences and knowledge that users often do not have prior to first use. In addition, companies that want to take advantage of highly connected, smart technologies do not understand how to appropriately train or select their workforce to acquire the correct skills and competences. These challenges handicap the market potential of smart digital products.

The vision is therefore fourfold: (i) to elicit the skills, competences and knowledge that users need when interacting with smart products in standardised ways; (ii) to develop multimodal means of training and education for users to acquire these skills, competences and knowledge through educational curricula, online training and tutoring; (iii) to increase the understandability of technologies through standardised and multi-dimensional product labelling systems that allow evaluations across multiple product dimensions (reliability, privacy, usability, etc) to take advantage of the common knowledge base that is created through training and education; and (iv) to develop the means to design interfaces and interaction with smart products for user classes with specified profiles of skills, competences and knowledge (see *Figure F.38*).

2.4.4.5.3 Key focus areas

Systematise assessment and sharing methods for common user skills, knowledge and competence (SKC) profiles

In the past, the necessary SKC profiles necessary for the use of products were an outcome of the development cycle rather than its starting point. This is because either SKC profiles were not available at design-time, or could not be used within the established design and development processes. SKC profiles need also to be linked to usage and environmental conditions:

- Develop standardisable methods for assessing and representing necessary user SKC for specified usage and environmental conditions.
- Develop standardisable methods for sharing user SKCs using open and managed knowledge repositories.

Develop methods to fold user SKC profiles into system design, architecture and functional allocations

Even once user SKC profiles and usage and environmental conditions have been specified, the challenge is to actively make use of these profiles during system planning and design decisions:

- Development of tools, processes and techniques to map user SKCs onto technical requirements during the product design phase.
- Development of classification of user profiles for tailored HCI concepts.
- Demonstrate the effectiveness of these tools for product design and acceptance.

Develop methods for the effective assessment and sharing of training and educational user requirement

Even if user SKC profiles are used during product design and development, users need to be enabled to effectively use these developed products:

- Develop tools and methods for deriving training and educational programme requirements for common SKC profiles.
- Evaluate training and educational programmes for product acceptance and effectiveness.

2.4.5 TIMELINE

The following table illustrates the roadmaps for **Quality, Reliability, Safety and Cybersecurity**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Ensuring HW quality and reliability	**Topic 1.1:** Quality: *in situ* and real-time assessments	• Create an environment to fully exploit the potential of data science to improve efficiency of production through smart monitoring to facilitate the quality of ECS and reduce early failure rates
	Topic 1.2: Reliability: tests and modelling	• Development of methods and tools to enable third generation of reliability – from device to SoS
	Topic 1.3: Design for (EoL) reliability: virtual reliability assessment prior to the fabrication of physical HW	• Continuous improvement of EDA tools, standardisation of data exchange formats and simulation procedures to enable transfer models and results along full supply chain
	Topic 1.4: PHM of ECS: increase in functional safety and system availability	• Condition monitoring will allow for identification of failure indicators for main failure modes
Major challenge 2: Ensuring dependability in connected software	**Topic 2.1:** Dependable connected software architectures	• Development of necessary foundations for the implementation of dependable connected software to be extendable for common SW systems (open source, middleware, protocols)
	Topic 2.2: Dependable softwarisation and virtualisation technologies	• Create the basis for the increased use of commodity hardware in critical applications
	Topic 2.3: Combined SW/HW test strategies	• Establish SW design characteristics that consider HW failure modes
Major challenge 3: Ensuring privacy and cybersecurity	**Topic 3.1:** Trustworthiness	• Root of trust system, and unique identification enabling security without interruption from the hardware level up to applications, including AI • Definition of a framework providing guidelines, good practices and standards oriented to trust
	Topic 3.2: Security and privacy-by-design	• Establishing a secure and privacy-by-design European data strategy and data sovereignty
	Topic 3.3: Ensuring both safety and security properties	• Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc) independence, geographic distribution, emergent behaviour and evolutionary development

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Establish a procedure to improve future generation of ECS based on products that are currently in the production and field → feedback loop from the field to design and development	• Provide a platform that allows for data exchange within the supply chain while maintaining IP rights
• Implementation of a novel monitoring concept that will empower reliability monitoring of ECS	• Identification of the 80% of all field-relevant failure modes and mechanisms for the ECS used in autonomous systems
• Digital twin as a major enabler for monitoring of degradation of ECS	• AI/ML techniques will be a major driver of model-based engineering and the main contributor to shortening the development cycle of robust ECS
• Hybrid PHM approach, including data science as a new potential tool in reliability engineering, based on which we will know the state of ECS under field loading conditions	• Standardisation of PHM approach along all supply chains for distributed data collection and decision-making based on individual ECS
• Set of defined and standardised protocols, mechanisms and user-feedback methods for dependable operation	• Availability of European ecosystem for dependable software, including certification methods
• Definition of softwarisation and virtualisation standards, not only in networking but in other applications such as automation and transport	• Widely applied in European industry
• Establish techniques that combine SW reliability metrics with HW reliability metrics	• Efficient test strategies for combined SW/HW performance of connected products
• Definition of a strategy for (modular) certification under uncertain and dynamically changing environments • Consolidation of a framework providing guidelines, good practices and standards oriented to trust	• Liability
• Ensuring the protection of personal data against potential cyber-attacks in the data-driven digital economy • Ensuring performance and AI development (which needs considerable data) by guaranteeing GDPR compliance	
• Ensuring the nominal and degraded behaviour of a system when the underlying system security is breached or there are accidental failures • Guaranteeing a system's coherence while considering different requirements, different applied solutions, in different phases • Evaluating the impact of the contextualisation environment on the system's required levels of safety and security	• Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of trustworthiness

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 4: Ensuring safety and resilience	**Topic 4.1:** Safety and resilience of (autonomous AI) systems in dynamic environments	• Resources' management of all system's components to accomplish the mission system in a safe and resilient way • Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimisation
	Topic 4.2: Modular certification of trustable systems and liability	• Contract-based co-design methodologies, consistency management techniques in multi-domain collaborations
	Topic 4.3: Dynamic adaptation and configuration, self-repair capabilities (decentralised instrumentation and control for), resilience of complex systems	• Support for dependable dynamic configuration and adaptation/maintenance • Concepts for SoS integration, including the issue of legacy system integration • Using fault injection methods, models-of-the-physics and self-diagnostic architecture principles to understand the true nature of the world, and respond to uncertain information (included sensor's false positives) or attacks in a digital twin, run-time adaptation and redeployment based on simulations and sensor fusion • Architectures that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification
	Topic 4.4: Safety aspects related to HCI	• Minimising the risk of human or machine failures during the operating phases • Ensuring that the human can safely interface with the machine, and also that the machine prevents unsafe operations • Ensuring safety in machine-to-machine interaction
Major challenge 5: Human–systems integration	**Topic 5.1:** Generisable competence and knowledge (C&K) profiles	• Development of C&K profile assessments for users of specific applications • Development of C&K profile representations, storage and retrieval for specific applications
	Topic 5.2: Design	• Development of proof-of-concept of tailored and adaptive systems for specific C&K profiles for specific applications
	Topic 5.3: Training	• Development of proof-of-training programmes for specific C&K profiles for specific applications
	Topic 5.4: Education	• Development of digital literacy curricula

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Automated operation • Concepts and principles for trustable integration and V&V of intelligent functions in systems/products under uncertain and/or dynamic environments • Identify and address transparency and safety-related issues introduced by AI applications • Having explicit workflows for automated and continuous layered certification/qualification, to ensure continuing trust in dynamic adaptive systems in changing environments	
• Having explicit workflows for automated and continuous layered certification/qualification, to ensure continuing trust in dynamic adaptive systems in changing environments	• Certificates of extensive testing, new code coverage metrics (mutation testing), formal methods providing guarantee of trustworthiness
• Automatic prompt self-adaptability at low latency in dynamic and heterogeneous environments	• Develop explainable AI models for human interaction, system interaction and certification
• Understanding the nominal and degraded behaviour of a system, potentially with AI • New self-learning safety methods to ensure safety system operations in complex systems • Ensuring safety in machine-to-machine interaction	• Safely manage human interactions in complex systems, SoS and application scenarios

• Standardisation of C&K profile assessments for specific applications • Standardisation of C&K profile representations, storage and retrieval for specific applications	• Standardisation of C&K profile assessments for across multiple applications • Standardisation of C&K profile representations, storage and retrieval across multiple applications
• Standardisation of C&K profile representations, storage and retrieval for specific applications	• Standardisation of methods for developing tailored and adaptive systems for specific C&K profiles across multiple applications
• Standardisation of training programmes for specific C&K profiles for specific applications	• Standardisation of training programmes for specific C&K profiles across multiple applications

2.4.6
SYNERGY WITH OTHER THEMES

The **Major challenge** "Ensuring HW quality and reliability" is a key element for any ECS, which is why it can be linked to any application area. It is directly linked to the technology section: **Components, Modules and Systems Integration**. For quality, the novel design of reliability methodologies such as PHM requires direct connection to all cross-sectional technologies (**Artificial Intelligence, Edge Computing and Advanced Control**; and **Architecture and Design: Methods and Tools**).

The **Major challenge** "Ensuring dependability in connected software" is strongly linked to the Section **Embedded Software and Beyond** as implementations will cover embedded devices to a high degree. It is also linked to the **Connectivity** section and the **Artificial Intelligence, Edge Computing and Advanced Control** section since software must reliably interact remotely, from a system to the edge and to the cloud. From a different perspective, it is also linked to the section on **System of Systems** considering that software-based systems will be integrated over distances.

The **Major challenges** "Cybersecurity and privacy" and "Safety and resilience" address robust and resilient systems in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be enabled by AI. The outcome of these challenges supports all application sections, in particular **Health and Wellbeing**, **Mobility**, **Digital Industry**, **Digital Society** and A**grifood and Natural Resources**. Moreover, they are also linked to the sections **Artificial Intelligence, Edge Computing and Advanced Control**, **Architecture and Design: Methods and Tools**, **Embedded Software and Beyond** and **System of Systems**.

3.1
MOBILITY

3.2
ENERGY

3.3
DIGITAL INDUSTRY

3.4
HEALTH AND WELLBEING

3.5
AGRIFOOD AND NATURAL RESOURCES

3.6
DIGITAL SOCIETY

3

Strategic Research and Innovation Agenda 2021

ECS KEY APPLICATION AREAS

3.1

ECS Key Application Areas

MOBILITY

3.1.1
SCOPE

Mobility is a basic human need and Europe's mobility industry is a key contributor to it. The automotive sector alone provides employment, both direct and indirect, to 13.8 million Europeans, representing 6.1% of total EU employment. 2.6 million people work in the direct manufacturing of motor vehicles, representing 8.5% of EU employment in manufacturing[86]. The automotive sector is also the driver for innovation in many other mobility sectors in Europe, including aerospace, maritime and rail.

Two major societal challenges are significantly pushing the mobility domain: the reduction of CO_2 and other emissions, and the inclusive safe and secure mobility for an ageing global society across different mobility sectors.

The first societal challenge, known as the European Green Deal, is at the forefront of the EU's priority list. As automotive traffic is currently contributing approximately 14% of global CO_2 emissions, CO_2-neutral mobility requires alternative powertrain systems for automotive vehicles, ships and flying equipment, and smart energy-charging infrastructure and systems for optimised and easy use of existing mobility infrastructure. Also required are more energy- and cost-efficient electronic and optoelectronic components, interconnected intelligent systems and (AI-based) embedded software. In addition to the strong research focus on battery electrical vehicles (vehicles here are identified as automobiles, trains, airplanes, ships, off-road vehicles, trucks, etc), research on H2-based electrical vehicles, trains, ships and even airplanes is gaining in importance due to their very good environmental performance and "cradle to grave" impact. The Key Digital Technologies (KDT) SRIA section on mobility is aligned with the proposal for the partnership "Towards zero emission road transport" (2Zero) programme proposal by Horizon Europe to achieve carbon-neutrality in road transport by 2050. There are plans to continue and strengthen this cooperation between 2Zero and KDT.

The second societal challenge focuses on the usage of smart perception, safety and automated mobility solutions and services to provide safe and comfortable inclusive mobility that is also suitable for the elderly as well as people with special needs. Research, development and innovation (R&D&I) of embedded AI-based software, sensors and electronic components and systems provide the core of automated on- and off-road vehicles, ships, trains and airplanes. A special focus requires validation of the safety and reliability of the automated mobility systems in all traffic and environmental situations as there are currently no adequate methods and tools available. Therefore, the KDT SRIA section on mobility is also closely aligned with the proposal for the partnership "Connected, Cooperative and Automated Mobility" (CCAM) under Horizon Europe.

Additional key aspects of the contribution by KDT to the future of mobility are increasing user value, security, privacy protection features, affordability and human interaction. Particularly in urban areas, intermodality and technologies supporting the shared principles will be crucial.

↑

86 *Internal Market, Industry, Entrepreneurship and SMEs, https://ec.europa.eu/growth/sectors/automotive_en*

3.1.2
MAJOR CHALLENGES – OVERVIEW

The Green Deal and digitalisation are significantly influencing the KDT SRIA in the mobility domain: the reduction of CO_2 and other emissions, and ensuring an inclusive safe and secure mobility for an ageing global society. This leads to five challenges in R&D&I for mobility.

— **There are two Major challenges in mobility derived from the Green Deal:**
- **Major challenge 1** (climate and energy): Enable electrification and sustainable alternative fuels for CO_2-neutral mobility.
- **Major challenge 2** (safety): Enable affordable, safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, small drones, etc) and mobile machinery (for smart farming).
- The results of R&D&I on these challenges will be used in green CO_2-neutral vehicles integrated into the 2Zero EU programme, and therefore roadmaps and research programmes are (and will be) aligned.

— **Digitalisation leads to three R&D&I challenges for ECS as part of the key enabling digital technologies (KDT) in mobility:**
- **Major challenge 3** (automation): Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water.
- **Major challenge 4** (validation): Provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility.
- **Major challenge 5** (real-time data handling): Achieve real-time data handling for multimodal mobility and related services.

The key digital components resulting from the work on these challenges will be used in partial or fully automated vehicles for the CCAM EU programme, and therefore roadmaps and research programmes are (and will be) aligned.

3.1.3
AUTOMOTIVE TRENDS AND SOCIETAL BENEFITS

Mobility is at the heart of European lifestyle and its economy. Efficient transportation systems are more important than ever, and also help to counteract the potential political disintegration of the Union. However, the promise of freedom offered by road transport is viewed in sharp contrast to a range of concerns about its effect on safety, health and the environment. Therefore, transport and mobility systems are in the process of a fundamental transformation towards a vision of sustainable, CO_2 emission neutrality that involves efficient, inclusive and seamless solutions.

This all implies a paradigm shift in engineering and planning. While most transport innovations in the past began with the invention of new technologies, a human-centric approach is now at the centre of the development process, such that technical, socioeconomic and legal challenges are considered in tandem with human factors.

For decades, disabled people have promoted a universal approach to the design of transport systems to make them more accessible and useful for everybody. In view of the Covid-19 pandemic, this focus on human factors of transport innovation is expected to increase; it will particularly call for smart and intelligent mobility systems enabled by KDT.

Mobility is not only a visible expression of Europe's economic and societal prosperity, it is also an important source of that prosperity. According to Europe's car manufacturers and transporters, the automotive sector employs around 12 million people (approximately 2.2 million directly and 10 million indirectly), contributing 16% of the EU's GDP[87]. Currently, the transportation sector is undergoing a fundamental and complex transformation across all modes.

Europe is ranked number one in automotive semiconductors. In the automotive value chain, Tier 1's and original equipment manufacturers (OEMs) are also top global players and intend to gain further market share through close collaboration with semiconductor and embedded software leaders in Europe.

The EU's maritime industry is characterised by high value-added expertise, rapid innovation, rigorous safety standards and a leading position in green technologies. A strategy to further build on these strengths will ensure that the EU retains its competitive position in the global maritime industry, and reaps the rewards in terms of jobs and wealth creation.

The current leading position of the European aerospace and rail industry will require a further shift to the greater autonomy of planes, trains and infrastructure, and increased trustworthiness of radio and other communication technologies. Therefore, it is also strongly dependent on progress in key digital components and AI-based real-time software.

An important priority of the European Commission in its Communication on the European Green Deal is "accelerating the shift to sustainable and smart mobility". This will require a strong boost to multimodal transport, automated and connected multimodal mobility, a ramp-up of the deployment of sustainable alternative transport fuels and less polluting transportation, especially in cities.

The electronics components and systems (ECS) community will contribute substantially to these tasks by using new technologies, components and systems to target the following topics.

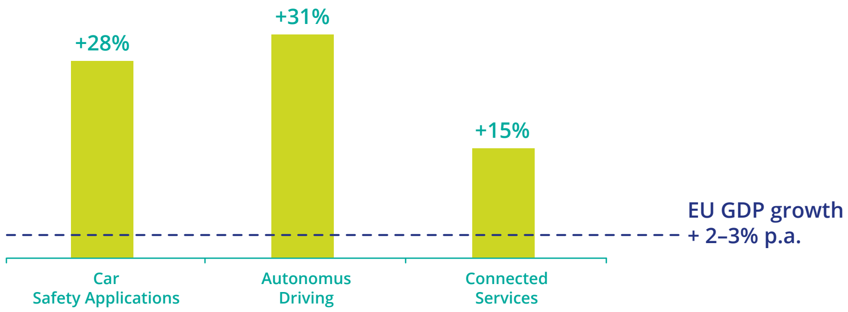
- Autonomous vehicles and coordinated mobility to make traffic more efficient and thus reduce pollution by smart and connected sensor systems, AI-based real-time software, in-vehicle controllers and networks, as well as connectivity devices and advanced embedded software solutions.

→

87 *"Internal Market, Industry, Entrepreneurship and SMEs" (available at https://ec.europa.eu/growth/sectors/automotive_en)*

FORECAST GROWTH BY MARKET VS. EU GDP GROWTH

5 years compound annual growth rate



F.39 *Forecast growth by market vs. EU GDP growth (Source: Goldstein Research)*[88]

- Electrification of vehicles and development of powertrains for carbon-free energy carriers. Enabling technologies come from the European ECS industry – for instance, energy-efficient devices, power electronic components and systems, energy (e.g. battery) management systems, and embedded software solutions for power management.
- New means of transport systems and interaction among different providers (public/private), including other transport modes (multimodal transport for passengers and goods), will be enabled through further development of new and harmonised vehicle-to-everything (V2X), logistics operation software, traffic management devices and guidance systems to enable mobility-as-a-service (MaaS). Easy access to these systems for users will guarantee the highest standards of privacy to avoid potential impacts caused by the general data protection regulation (GDPR) since information (about origin, destination, financial information, etc) needs to be shared.
- Rapid advances in AI and edge computing will ensure Europe can produce a step change in these areas. Autonomous driving, mobility and logistics are high-profile applications where the use of AI technologies is growing very rapidly, affecting both society and industry directly. The European transport industry is being revolutionised by the introduction of AI (combined with electric vehicles). However, AI applications in transport are very challenging, as they typically involve highly complex environments, a large number of possible situations and real-time, safety-relevant decision-making. Leading IT companies in the US and China in particular are providing a challenge to

88 *Sources Goldstein Research "Smart Healthcare", 2018; International Energy Agency "Energy Efficiency", 2017; Frost & Sullivan "European Smart Grid", 2016; Bloomberg New Energy Finance "Global storage market", 2017, IHS "Smart Grid Sensors", 2015; BIS Research "Global augmented and virtual reality", 2016; Gartner (IoT) 2017; MGI "The Internet of Things: mapping the value beyond the hype", 2015.*

European industry in these areas, and significant effort will be required to safeguard the leading position of the European automotive industry.

Revenues related to autonomous driving and connected cars are expected to boom (see *Figure F.39*), with safety applications (e.g. automatic collision detection/prevention) expected to reach USD58 billion (up from USD18 billion in 2017), autonomous driving (e.g. distance/park/motorway assistant, pilot, traffic sign detection/recognition) set to reach USD55 billion (up from USD14 billion in 2017) and connected services expected to reach USD43 billion in 2022 (up from USD21 billion in 2017).

3.1.4 MAJOR CHALLENGES

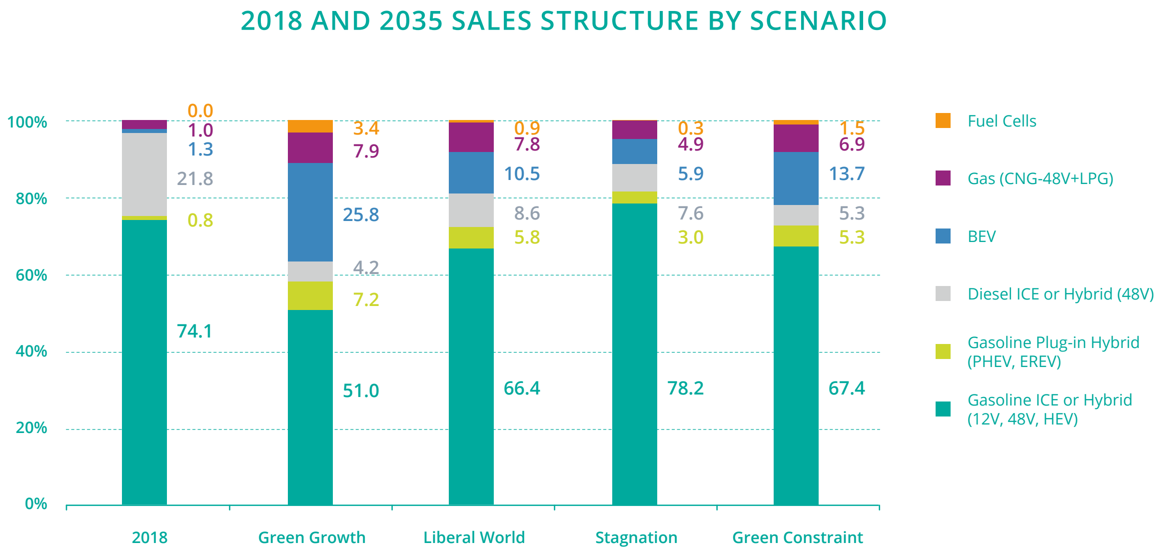
The expected achievements of the research and innovation activities for Horizon Europe on KDT for mobility – i.e. the fields of embedded AI-based software, sensor, electronics and photonics components, and systems – will be reached in cooperation with the 2Zero and CCAM programmes. The latter two will incorporate the KDT results into new CO_2-neutral vehicles, trains and airplanes to enable safe, reliable and inclusive mobility. The joint goals of these three programmes are as follows.

- Digital innovation to achieve the Green Deal for mobility with the 2Zero goals of –37.5% CO_2 by 2030 versus 2021 (according to the Worldwide Harmonised Light Vehicle Test Procedure, WLTP) and zero emissions in cities by 2040, and zero net emission by 2050 by providing the KDTs in, for example, the reduction of power electronics costs by 40% while increase power density per litre by 500% until 2035.
- Digital innovation to increase road safety (by providing the KDTs to the CCAM programme) in reducing the number of road fatalities and accidents caused by human errors to zero by 2050, as well in ensuring that no additional road fatalities are introduced by automated transport while bringing validation costs down by 50% of development costs from the current 70–80%.
- Digital innovation for the inclusiveness of mobility in ensuring inclusive mobility for persons and goods by providing mobility access to everyone, with a focus on special needs reaching 90% of the EU population (as opposed to the current 60%) from assisted vehicles by 2050 as targeted by CCAM.
- Strengthen competitiveness of the European industrial mobility digitalisation value chain by protecting global technological leadership and supply chain consistency in the automotive sector, ensuring long-term growth and jobs.

3.1.4.1 Major challenge 1: Enable electrification and sustainable alternative fuels for CO_2-neutral mobility

3.1.4.1.1 Status, vision and expected outcome

Worldwide efforts on the regulation of pollution and CO_2 emissions is leading to a strong increase in the electrification of vehicles, either with batteries (“battery electric vehicles”, BEVs), “hybrid electric vehicles” (HEVs) with petrol or diesel engines, or using fuel cells.



F.40 *Sales structure of cars 2018 and 2035 (4 scenarios) (Source: PFA France 2018)*

Possible scenarios developed by BIPE[89] in France are shown in *Figure F.40*. Depending on the evolution of regulations in particular, the split could be significantly different between the various technologies. However, the most probable scenario is that of the "Green Constraint".

Looking in more detail at the difference between low voltage systems (particularly 48V) and high voltage systems, there are six important observations that can be made.

- All cars in Europe will be electrified by 2035.
- The proportion of electrified cars in the world will reach about 70%.
- Low voltage systems will take about 60% of the market, with high voltage the rest.
- Around one-third of the market will require on-board chargers for high voltage in the range 400–800V.
- Fuel cell electric vehicles will still play a minor role by 2035, although their overall share in terms of absolute numbers might reach about 1.5 million cars per year.
- The major application of fuel cells will most likely start in truck and train applications, as well as in airplanes and drones.

The expectation is that the overall electrification scenario will lead to massive changes in the supply chains and the distribution of competences. In the field of power electronics, Europe is now in an excellent position and its industry needs to organise itself to ensure it benefits from the opportunity.

89 *https://lebipe.com/*

3.1.4.1.2 Key focus areas

- New control software is required to take full advantage of new solid-state batteries so that they have an extended lifetime, as well as their driving range in vehicles. As lifetime is key for batteries used in mobility systems, tools for accelerated lifetime testing, diagnostic systems as well as control systems that can extend the lifetime and limit degradation are essential for the success of electrified green mobility. New power electronics based on silicon carbide (SiC) and gallium nitride (GaN) devices are needed to ensure energy-efficient operation. AI and model-predictive control algorithms, supported by high-performance, multi-core, real-time operating systems, has to offer the necessary intelligence based on ultra-low power/high-performance control units.
- Similarly, control systems for fuel cell-based vehicles (mainly in trucks and buses) that minimise degradation and maximise efficiency is crucial. Adequate new sensors to measure the operating conditions within fuel cells without negatively influencing their operation are required. Also important are dynamic test systems that allow one to predict their degradation and optimise their lifetime and efficiency will be new essential base components from KDTs.
- For both electric battery and fuel cell-based mobility, new safety concepts using (AI-based) IoT diagnostics must ensure the safety of these systems, especially in accident situations.
- Efficient and fast charging and filling of alternative energy into green vehicles is another critical research topic.
- The conversion of renewable energy into green energy as electricity stored in vehicles or H2, or alternative fuels, also need efficient electronics with real-time embedded software communication with the power grid to minimise the need of new charging/filling infrastructure, which is one of the cost drivers limiting the speedy success of green mobility.

3.1.4.2 Major challenge 2: Enable affordable safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, small drones, etc) and mobile machinery (as smart farming)

3.1.4.2.1 Status, vision and expected outcome

Digital innovation is key to ensuring inclusive mobility for persons and goods by providing mobility access to all, with a focus on special needs, by reaching 90% of the EU population compared to the current 60%. As targeted by CCAM, this can be achieved through assisted vehicles by 2050.

By 2050, 67% of the population is expected to live in urban areas. As cities become bigger and smarter, this trend will lead to new opportunities for tailored and specialised vehicle design specific to urban users, including the needs and operations of commuters, as well as ride-hailing and last-mile delivery.

New vehicle concepts and ECS-enabled architectures should lead to flexibility, scalability and modularity to ensure urban-readiness (appropriate range, compatibility with charging infrastructures, ease of parking and operations, etc) in all kind of urban and suburban areas, most likely with different implementation levels of infrastructure and smart technologies. Additionally, it is assumed that these vehicles will not have to be designed for high-speed operation and long range, and can easily be charged sufficiently fast and comfortably to meet the daily needs of urban and suburban mobility usage scenarios. This aspect may also include sharing concepts, and consideration should also be given to use by the elderly and disabled.

Targeted vehicles will cover small and light land vehicles (road/off-road), but also air and water vehicles. These will all follow the design principles of tailored ECS solutions and right-sizing for their objectives. In addition, they should satisfy performance key targets such as improved efficiency during usage (e.g. using low power electronic components, smart materials or appropriate control strategies based on data from traffic flow monitoring or prediction systems) towards zero emissions, as well as integration into the mobility plans (mobility and transport as a service) of the respective areas of operation. This will be facilitated by more effective use of parking spaces, scheduling and possibly decreased congestion, including demands arising for mobility and logistics across functional urban boundaries (e.g. urban to suburban). The implementation of sensors, electronic control units and control strategies for advanced driver assistance will enable the improvement of safety, comfort and quality of life during transportation.

The challenge particularly targets the following vehicle categories.

- motor vehicles with less than four wheels (L category).
- vehicles having at least four wheels and used for the carriage of passengers (including light four-wheelers, M1/M2 category).
- power-driven vehicles having at least four wheels used for the carriage of goods (N1).agricultural and forestry tractors, and non-road mobile machinery (T).
- off-road vehicles (G).
- all kind of unmanned air vehicles (such as drones).
- all kind of manned light air vehicles.
- special-purpose light vehicles (air, land, water).

— This will have the following impact on European society.

- Urban light personal and freight mobility: the success of vehicles such as monowheels, electric scooters and drones suggests it would be useful to explore innovative micro-vehicle designs suitable for urban/suburban commuters' needs, with the option for usage within shared mobility schemes. Such micro-vehicles would also be capable of interfacing with urban collective transport systems (i.e. easy access to buses, trams and trains for last-mile transfers to achieve full intermodality).
- Light and flexible multi-passenger vehicles (e.g. collective or individual, owned or shared up to M1 category) with robust safety measures for passengers and vulnerable road users, and including specific features to facilitate shared use such as autonomous-capable vehicles with automated relocation to charging points or areas with insufficient vehicle density.
- Right-sized vehicles and tailored ECS for commercial uses, such as for last-/first-mile delivery, construction and maintenance support, which are suitable for urban scenarios. These types of vehicle will benefit local air quality and offer rapid implementation due to their holistic and design-for-purpose approach.
- Increased acceptance of single-purpose design ECS-enabled vehicles is expected due to the physical demonstration of their feasibility (both technical and economical) with equivalent or superior performance, upgradeability and operational safety in relevant environments, particularly for light and flexible transport.
- Connected and automated mobile machinery to optimise harvesting and reduce accidents.
- Real testing to demonstrate the ambitious targets of up to 10% energy-efficiency improvement compared to the existing solutions for the same vehicle classes.
- Interoperability between land, air and water vehicles in terms of ECS solutions and ECS trustworthiness (safety, security, availability, connectability, resilience).

3.1.4.2.2 Key focus areas

— The key focus areas are:

- Modular, flexible and scalable platforms and electrical/electronic (E/E) architectures.
- Reconfigurable and adaptable software architectures.

- Hardware upgradability.
- Software updateability (including over-the-air, OTA).
- Embedded intelligence:
  - Control software, real-time capable algorithms.
  - Fault-tolerance, fail-operational concepts.
- On-board technologies (devices, actuators and sensors, virtual sensors).
- Power electronics (fast-switching elements, wide bandgap materials, low power, etc).
- Predictive diagnosis and maintenance (including recovery strategies, fault detection and localisation, surveillance sensors, etc).
- Cloud/edge/fog processing approaches.
- AI-powered and AI-enabled intelligence.
- Distributed logistics systems for smart farming, movers and shuttles.
- Standards, including communication and interoperability standards, electromagnetic spectrum and bandwidth management, charging units, car access systems, etc.
- Reliable and human-like perception systems.
- Tailored ECS-enabled solutions for disabled people (supporting robots, smart wheelchairs, etc).
- Proof of robustness and trustworthiness of architectures and quantification of the operational risks.

3.1.4.3 Major challenge 3: Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water

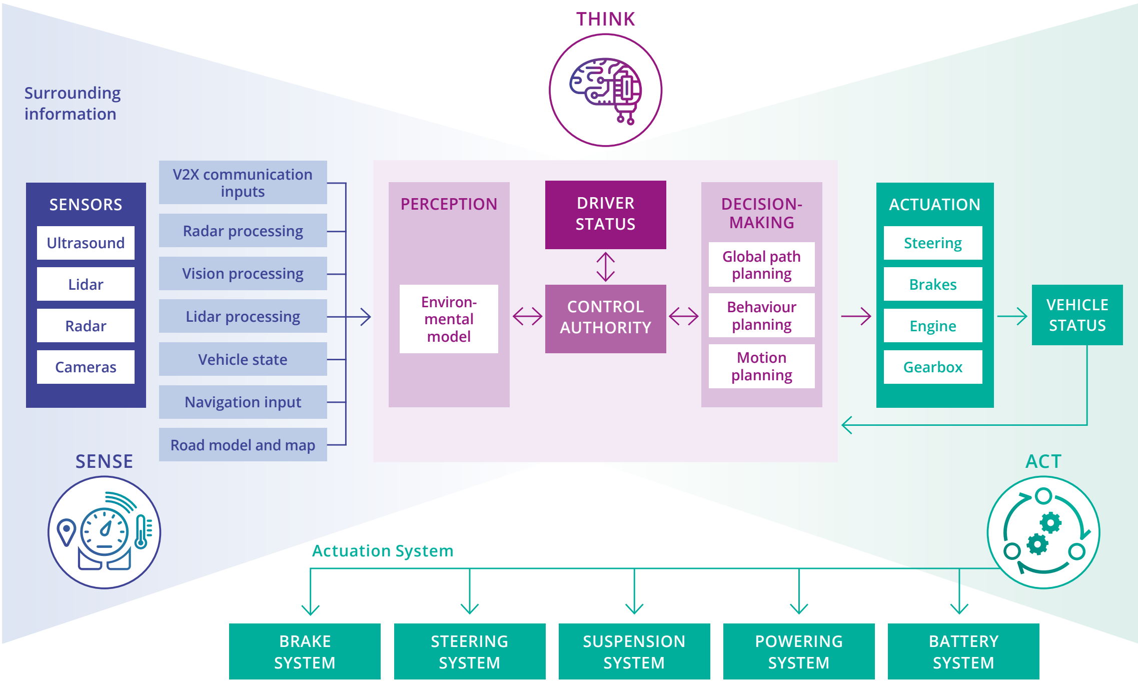
3.1.4.3.1 Status, vision and expected outcome

The European transportation industries have to strengthen their leading position to provide sustainable solutions for safe and green mobility across all transportation domains – automotive, avionics, aerospace, maritime (over water as well as under water transport) and rail. Their competitive asset is well-established expertise based on developing complex electronic components, cyber-physical systems and embedded intelligence. Nevertheless, a number of challenges in terms of autonomy, complexity, safety, availability, controllability, economy and comfort have to be addressed to harvest the opportunities coming from increasingly levels of automation and related capabilities.

The overall vision is to realise safe and secure, always connected, cooperative and automated transportation systems based on highly reliable and affordable electronic components and systems of European origin, as well as on technologies that offer new types of interaction between humans and machines.

One of the key motivators is to reduce the number of road fatalities and accidents caused by human error to zero by 2050, as well as in ensuring that no additional road fatalities are introduced through automated transport while bringing validation costs down to 50% of development costs from the current 70–80%. Key Digital Technologies will be developed to support the CCAM public/private partnerships (PPPs) in these ambitious goals. No single organisation will be able to capture these tremendous efforts in research and development. For Europe to maintain a leading position, it is therefore necessary to establish collaborations in and across industrial domains, learn from operational field data, and jointly drive the required strategic actions.

Also, in the waterborne transport sector ships will become fully connected across the globe. Remote monitoring of vessels is already possible, allowing for condition-based maintenance. Building on



F.41 *KDT components of automated vehicle*

increasing onboard automation, the remote operation of vessels will become possible, eventually moving towards full autonomy for vessels. The wider use of unmanned autonomous vessels (UAVs) – either aerial, underwater or on the surface – will increase the flexibility and energy efficiency of operations.

Connected, cooperative and ultimately automated mobility and transportation is seen as one of the key technologies and major technological advancements influencing our future quality of life. KDTs will enable different levels of partial, conditional, highly and fully automated transportation, posing new challenges for traffic safety and security in mixed scenarios where vehicles with different automation levels coexist with non-automated vehicles. Both development approaches – evolutionary (the stepwise increase of automation level: "conversion design") and revolutionary (Society of Automotive Engineers, SAE, level 5: "purpose design", e.g. a people mover in a structured environment) – should be covered, as well as cross-fertilisation with other industrial domains such as Industry 4.0.

As the proportion of electronics and software as a percentage of the total construction cost of a vehicle increases, so does the demand for the safe, secure, reliable and unhackable operation of these systems. In addition, privacy protection is a key element for car owners and drivers/operators. These requirements demand fail-operational technologies that deliver intrinsically safe operation and dependable fall-back position from component to subsystem, and provides a solution for problems in interaction with the cloud. This requires new developments in terms of multi-core-based platforms and sensing devices, combining advanced sensing in harsh conditions, novel micro- and nano-electronics sensors, advanced sensor fusion and innovative in-vehicle network technologies.

Key elements of KDTs for cars that need to be developed are shown in *Figure F.41*.

3.1.4.3.2 Key focus areas

The following research, development and innovations areas and their subtopics have been identified.

- Dependable and affordable environment perception and localisation sensors, and V2X communication.
- Centralised service/function-oriented hardware/software architectures for vehicles, ships, trains that are supported by the cloud and edge computing.
- Dependable and reconfigurable hardware and software, including OTA.
- Hardware and software platforms for control units for automated mobility and transportation (including support for AI) – e.g. IoT integration platforms for automated and connected environmentally friendly vehicles.
- New developments towards higher performance and efficiency. These are also required to ensure the reliability and safety of the power electronic components and systems for the drivetrain and charging systems, as well as for steering, break/suspension/air condition control in automobiles, trains, ships and flying equipment.
- Trustworthiness of vehicles' data.
- Interaction between humans and vehicles.
- Active safety systems.
- Vehicle hardware/software to improve comfort in parallel with safety.
- (Predictive) health monitoring for the perception system (including all required sensors, V2X systems and localisation systems) and AI components of (highly) automated vehicles used in the operational phase.
- Connected maritime systems and automated transport.
- Smart and autonomous ships.

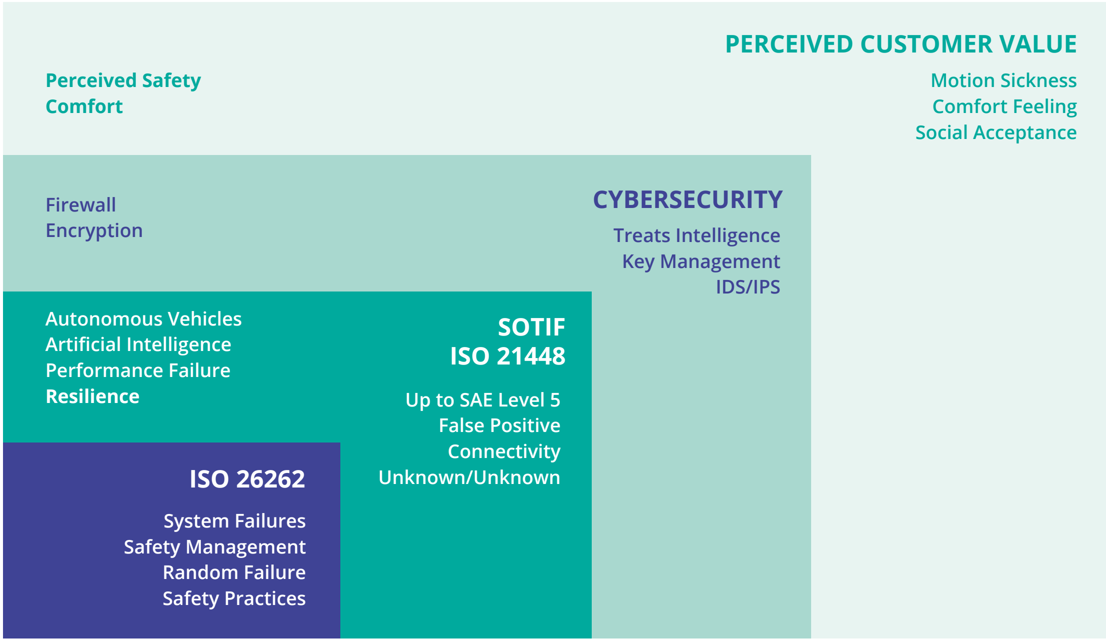
3.1.4.4 Major challenge 4: Provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility

3.1.4.4.1 Status, vision and expected outcome

To achieve the EU-wide goal of zero fatalities by 2050, active safety systems and automated vehicles are necessary (the term "vehicle" here covers mobility systems on land, water and in the air: cars, trains, ships and airplanes). Although several technology demonstrators for highly automated vehicles already exist, there is a severe lack of cost-effective, commonly accepted verification & validation (V&V) methods and tools. Winner et al predict that more than 400 million km of road driving would be required to statistically prove that an automated vehicle is as safe as a manually driven one, implying that a proven-in-use certification by performing physical tests on the road is no longer feasible. This lack of effectively applicable V&V methods has created a major barrier for the market introduction of these systems.

The main challenge is the tight interaction of these safety-critical automated systems with their environment. This means that not only does the correct functioning of the automated cyber-physical mobility system itself need be tested, but also its correct reaction to the behaviour and specifics of its surroundings. This leads to a huge number of potential scenarios that every automated mobility solution will have to handle in a safe way.

Many highly automated cyber-physical systems have adopted machine learning (ML) and AI to enable autonomous decision-making and render applications smart. While the use of ML and AI components offers great promise for improving our everyday lives in many, sometimes unimaginable, ways, it also



F.42 *Validation framework for automated vehicles (Source: AVL List GmbH)*

brings a host of very difficult verification, validation and certification challenges in the context of safety-critical applications. The opacity of ML/AI components requires the development of completely new V&V techniques, and to accordingly extend existing V&V methodologies.

Modern highly automated cyber-physical systems increasingly dynamically evolve after their deployment, and OTA updates and upgrades are becoming necessary in such systems. New methods and tools for these updates and upgrades, together with the respective re-verification and re-certification approaches, are necessary to avoid negative impacts on both safety and security.

Automation functions of vehicles rely on environment sensors, such as cameras, lidar, radar and ultrasonic sensors, as well as communication to other vehicles or infrastructures. As these safety-relevant components may degrade over time or be exposed to cyber-threats, accelerated reliability and cybersecurity test methods are required. This will need further diagnostic devices to check the reliability of hardware, sensors and their software.

The role of the driver and any additional passengers in an automated vehicle is completely changing, and therefore new test methods and tools are necessary to ensure comfort and perceived safety (societal acceptance). These are already in the early development phases in terms of new functionality and their safety.

Many of the above issues are mentioned in existing or upcoming automotive standards for cyber-physical systems – for example, Safety of Intended Functionality (SOTIF), ISO 26262 and UL4600 (see *Figure F.42*). As none of these standards are mature enough to certify fully automated vehicles with reasonable effort, close cooperation between the standardisation committees and the research consortia will be necessary.

The expected outcome is twofold:

- Digital innovation to increase road safety as specified in the CCAM programme: reduce the number of road fatalities and accidents caused by human errors to zero by 2050, as well as ensuring that no additional road fatalities are introduced by automated transport.
- Reduce validation costs down from the current two-to-five times of the implementation of automation functions in mobility by 60–80%.

3.1.4.4.2 Key focus areas

To ensure the safety, security and comfort of automated mobility systems consisting of embedded AI-based software, sensors and actuators, as well as processing platforms in vehicles, ships, trains, airplanes and off-road vehicles, several verification, validation and certification toolchains are necessary. These should ensure the safety, reliability, security and comfort for passengers and the surrounding traffic participants based on costs that do not exceed those of the design and implementation of the following functions.

- Verification of components of automated mobility systems as environment sensors/ communication systems, perception systems, environment awareness, route planning and actuator systems, diagnostics devices and black-box monitoring systems. A special case here is the use of consumer-grade components in vehicle automation.
- Validation of complete automated vehicles to perform safely and securely, and to provide comfort for passengers as well as other traffic participants in the specified operation design domain (geolocation area, weather conditions, road/sea/air conditions, etc).
- Validation of the reliability of all components as well as their interaction as a complete automated cyber-physical system in the specified operation period.
- Validation of the safety, security, reliability and comfort for the deployment of OTA update packages for automated on-road or off-road vehicles, trains, ships and airplanes.
- Verification of the completeness and reliability of training datasets for machine-learning and AI algorithms used in automated cyber-physical systems.
- Validation of the accuracy of simulation models in the specified operational design domain (ODD) used in virtual validation toolchains.

Validation toolchains, their components and underlying methods should lead to safe, reliable and secure argumentation describing why the performed tests resulted in the estimated residual risk for automated cyber-physical systems for on-road or off-road vehicles, ships, trains and airplanes. Optimisation methods can be used to balance multiple design objectives – e.g. that the residual risk remains below a certain limit (such as that stipulated by regulatory bodies) while meeting financial design targets. The verification, validation and certification tools and methods may be used for cyber-physical systems with different levels of automation.

A special focus is on the verification, validation and certification of embedded AI-based systems, and the required training data for the respective machine-learning algorithms. Ecosystems for the creation and maintenance of reliable labelled data are envisioned. To integrate with different legacy systems, eco-systems supporting open platforms are required.

Virtual validation, or more concretely scenario-based virtual validation, is considered a cornerstone for the verification, validation and certification of vehicles. Two aspects are essential here: (i) scenarios representing the most relevant situations; and (ii) reliable simulation models.

Scenarios may be derived from requirements of safety analyses, extracted from naturalistic driving or synthetically created using gaming theory-based methods with a defined relevance. Statistical safety evidence from scenario-based verification and validation derived from naturalistic driving is needed. Also, here the establishment for open platforms and ecosystems for the creation and maintenance of reliable scenarios is encouraged. The definition of performance (safety, security, reliability and comfort) indicators for different automation functions and SAE levels (in the case of road vehicles) is necessary. Again, eco systems to share these data are useful.

Reliable simulation models for environmental sensors, vehicles, drivers and traffic participants, as well as traffic, are vital. The development of these models, and the corresponding test systems, are essential. To test safety-critical scenarios using real vehicles in a safe environment requires the creation of stimulators for the different environmental sensors under different weather, traffic and road conditions. The verification, validation and certification of vehicles will be carried out with a combination of virtual test environments using model-in-the-loop (MIL) and software-in-the-loop (SIL), mixed virtual/real environments (vehicle-in-the-loop, VIL, and hardware-in-the-loop, HIL), as well as a proving ground for real-world public road testing. Road testing will result in amounts of data larger than 20TB per hour per vehicle, and therefore adequate data acquisition, management and (cloud or on-premise) evaluation systems capable of handling the specific data types of the sensors are critical (although these do not exist yet). Additionally, OTA data collection from in-use operations is required to continuously collect unknown scenarios that can be fed back into development to improve the quality of the systems.

Additional challenges covering this topic can also be found in *Section 2.3* (**Architecture and Design: Methods and Tools**) and *Section 2.4* (**Quality, Reliability, Safety and Cybersecurity**) of this SRIA.

3.1.4.5 Major challenge 5: Achieve real-time data handling for multimodal mobility and related services

3.1.4.5.1 Status, vision and expected outcome

To help provide better health and quality of life for their citizens, European municipalities will continue to ban cars with conventional powertrains from city centres, and promote more equal urban land use. At the same time, the demand for individual accessibility, flexible transit and fast delivery is on the increase. Therefore, multimodality is a cornerstone of the EU's strategy on transport. This combines collective and individual solutions, ranging from micro-mobility such as e-scooters via car-sharing and ride-pooling fight up to long-haul transport systems through common hubs, platforms and systems for booking, customer services and payment. In the future, Europe will also aim to offer more sustainable and systemic transport solutions besides road transport, such as high-speed rail or electric aircraft. Concurrently, limited peak capacities, missing last-mile connections and self-contained mobility-as-a-service systems will remain somewhat of a bottleneck when it comes to shortening travelling times, keeping supply chains clocked, and reducing single occupancy trips, with the accompanying reductions in congestion, environmental concerns and cost of travel. Therefore, sharing services are the key element to maximising the flexibility of public transport systems, and new technologies such as taxi and delivery drones or guided transport (hyperloop) solutions can be expected to fill the gaps in the time, cost and green environment map.

The Covid-19 pandemic seemed to have put some elements of this future vision in question for a while. Transportation demand dropped almost completely for many weeks, and only started to recover slowly. Public transport, as the cornerstone of a multimodal mobility system, was particularly affected as the desire for readily available, trustworthily hygienic and health-protecting ways of getting from A to B became paramount. It will remain a challenge for mobility service providers to develop and deploy novel solutions, such as self-sanitising and protective mobility shells (physical or virtual), for a vulnerable society that combine the flexibility of a multimodal system with the required infection safety. In another sense, multimodal mobility could also mean putting services and deliveries on wheels, which so far would have required people to travel to places where they risk being exposed to the virus.

As pointed out by the EU-funded Coordination and Support Action "Action Plan for the Future of Mobility in Europe"[90], the vision of a truly integrated and seamless transport system for people and freight must be developed and implemented, and the full potential of transformative technologies has to be exploited. This can only be achieved if user-centredness, cross-modality and technology transfer become the focus of efforts for all stakeholders in transport.

3.1.4.5.2 Key focus areas

- Design a low/zero emission, safe and accessible transport system tailored to user needs by exploring user needs and expectations, defining user profiles and mobility patterns, and identifying technology options.
- Enable mobility everywhere for everyone through the technological development of, for example, sensors, AI, machine learning, predictive maintenance, safe and secure vehicle software and electronics.
- Enhance efficiency and capacity in rail projects for automated maintenance and transfer of goods between modes.
- Create intelligent decision-support systems for passengers and transport operators that enable smart travel demand management.
- Achieve real-time data handling for multimodal mobility and related services.
- Develop convenient sharing concepts through automated maintenance of vehicles, and define approaches for implementation.
- Develop a framework for cybersecurity in passenger and goods transport across all modes, and provide IT connectivity that allows plug and play data sharing.
- Increase data security and privacy in authentication and payment processes for mobility services (through the concepts of trustee roles, blockchain, etc), and support the respective initiatives.
- Employ robots, drones and shared public transport services for logistics.
- Infection-risk detection, self-sanitising and protective functions for public transport use.
- Multimodal navigation systems providing travellers with efficient, safe and healthy transfer options.
- Development of modular mobility platforms for the on-site provision of services and goods delivery.
- Integrate cross-modal hubs and interfaces into the urban structure, and connect them by harmonised infrastructure to smart sustainable corridors.
- Provide open application programming interfaces (APIs) and user data and statistics for all modes and providers, enabling demand-oriented and demand-responsive cross-modal transport offers.
- Ensure accessibility of shared services, and incentivise shared fleets of personal mobility devices at hubs to facilitate mode change for those with disabilities and reduced mobility.

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90 *Mobility4EU, www.mobility4eu.eu*

3.1.5
REQUIREMENT OVERVIEW

In addition to the availability of technology, components and systems as described in other parts of this document, it is important that a number of societal needs are met, particularly the following.

- Legislation for automated vehicles throughout Europe: some initial pilot sites have been identified, but an overall legislative framework is required to achieve full deployment of highly automated driving (HAD). To date, there has been no regulatory approach to define a security/privacy framework for the IoT that involves billions of identities and devices being connected with each other. Technological stakeholders and the political arena have to share findings and derive recommendations to EU's and national regulatory bodies concerning the minimal regulatory framework needed to assure the security and privacy of citizens and companies.
- Social acceptance of the technology by citizens and users: society (governments, media, press, citizens, educational institutes, etc) has to be prepared for the introduction of some of this technology (such as by human factor-based questionnaires) and their thinking monitored to help define what actions can be taken on how new technologies and related services can be more easily accepted.
- It is crucial that future systems meet the expectations of end users, and that their underlying technology and platforms can be operated by service providers with appropriate business models; end users will expect flexible, reliable and cost-efficient services that can be personalised for them. For both end users and service providers, GDPR compliance is essential to ensure maximum transparency and user acceptance.

— Some examples of attention areas are:

- Evolving from regional/national policies to a European-wide supported common policy with respect to HAD.
- Evolving from regional/national pilot test sites to European-wide deployment.
- Ensuring privacy protection in connected cars, and how this should be communicated to citizens.
- Ensuring business perspectives for MaaS operators, seamless mobility to end users and the reduction of emissions and urban congestion.

3.1.6
TIMELINE

The roadmap for the key digital technologies in mobility are aligned with European roadmaps for terrestrial, water and aerospace transport:

- A new European Road Transport Research Advisory Council (ERTRAC) roadmap entitled "Sustainable Energies and Powertrains for Road Transport – Towards Electrification and other Renewable Energy Carriers".
- Urban mobility roadmap.
- Long-distance freight transport roadmap.
- Towards zero logistics emissions by 2050.

- The joint European Technology Platform (ETP) common paper published in 2019.
- The European roadmap on connected and automated driving published in 2019.

The roadmap combines the objectives in the application research programmes 2Zero and CCAM with the derived KDT mobility challenges. The following roadmap indicates when R&D&I activities are required to ensure the key digital technologies are available for use in the different mobility domains. In areas that already have ongoing electric mobility, the focus is more on improvements to existing concepts (for example, optimisation of costs), while for others (such as electric aircrafts) it is more about focusing on lower technology readiness levels (TRLs). These are both going on in parallel, and are also influencing each other.

This roadmap is a preliminary estimate in regard to when the KDTs will need to be ready for the various technology fields. It will be continuously updated as new domain roadmaps become available.

3.1.7
SYNERGY WITH OTHER THEMES

Mobility is a domain that needs multiple key enablers, as described in other sections of this document. It is transversal to almost all chapters, from components to systems.

For instance, semiconductor technologies are evolving rapidly. In the past, silicon was the dominant material, but its performance is now being outpaced by wideband materials such as SiC and GaN. These materials allow reduced packaging, increased operation temperatures, higher switching frequencies and therefore new concepts of compact power electronics modules. This is a major disruption that changes the market for electric mobility.

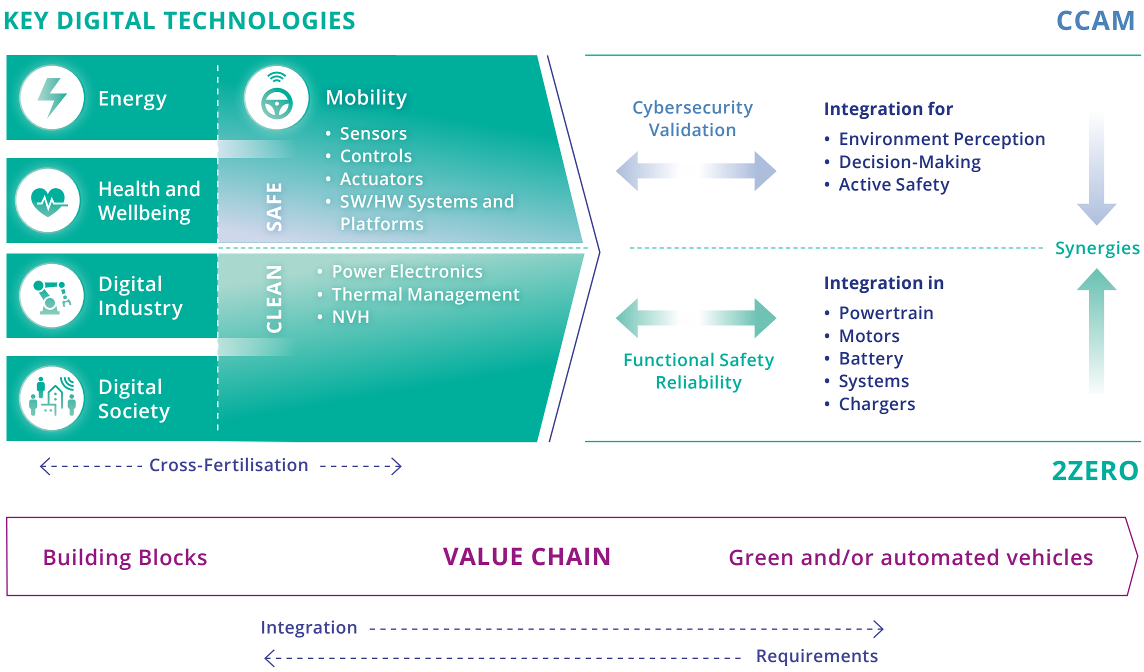
Closely linked to these semiconductor technology updates are packaging technologies. Moving from standard industrial modules to full integration is the second major disruption. Only adapted packaging can permit the full exploitation of the benefits of such new semiconductor technologies.

Other components that are of strategic importance are passives, such as capacitors and coils that can withstand higher temperatures and switching frequencies. For these, it is necessary to look at innovative materials that bring improved performance at a lower cost and a high rate of recyclability for the whole system.

A further aspect of mobility is the increasing level of automatisation, which is also having a huge influence on other in-vehicle components in the area of digital technologies for embedded software, AI, sensors, actuators and trustworthy communication. In this respect, there is a strong need for cybersecurity to protect cars, drivers and the environment. OTA updates of rapidly improving complex software for the upgrade of car systems are therefore mandatory. This requires a safe, secure and available infrastructure in cities as well as rural areas.

This infrastructure includes 5G/6G communication to allow massive transfer of data to cars. In the background of such operations, a performant (and GDPR-compliant) cloud data system needs to support the mobility of each individual. The overall management of such an infrastructure should include smart grid operations to minimise energy waste and losses through inefficiencies, as is further elaborated upon in the **Energy** section. It is clear that this requires system developments, from small sensor systems to micro and large grid control, including all aspects of cohabitation of modules and sub-systems. (electromagnetic compatibility, EMC, and thermal considerations).

The relations between KDTs and the application-oriented partnerships in the mobility domain (2Zero, CCAM) are following the value chain, and are creating new links between the ecosystems of enabling technologies and applications. While the focus of KDT is on electronic components and systems as enabling technologies for multiple application fields (including mobility), the customised integration, verification and optimisation of hardware/software systems and platforms for certain powertrain or vehicle control functions would be a matter for 2Zero or CCAM. Reversely, requirements and standards for the electronic components and systems within KDT should be derived from 2Zero and CCAM project results. This logic is show in *Figure F.43*.



Synergies with European partnerships

F.43

It should also be noted that synergy potentials exist between the domains of safe and clean mobility, not just at the level of the application in a multimodal urban mobility system but also at the level of the enabling technologies. Examples include electronic architectures for fail-safe power distribution and control within the vehicle, the functional safety and reliability of systems and cybersecurity, and control in power systems. Additional alignment is already in progress with existing or planned programmes for rail (Transforming Europe's Rail System), maritime (Zero Emission Waterborne Transport) and aerospace (Clean Aviation).

3.2

ECS Key Application Areas

ENERGY

3.2.1
SCOPE

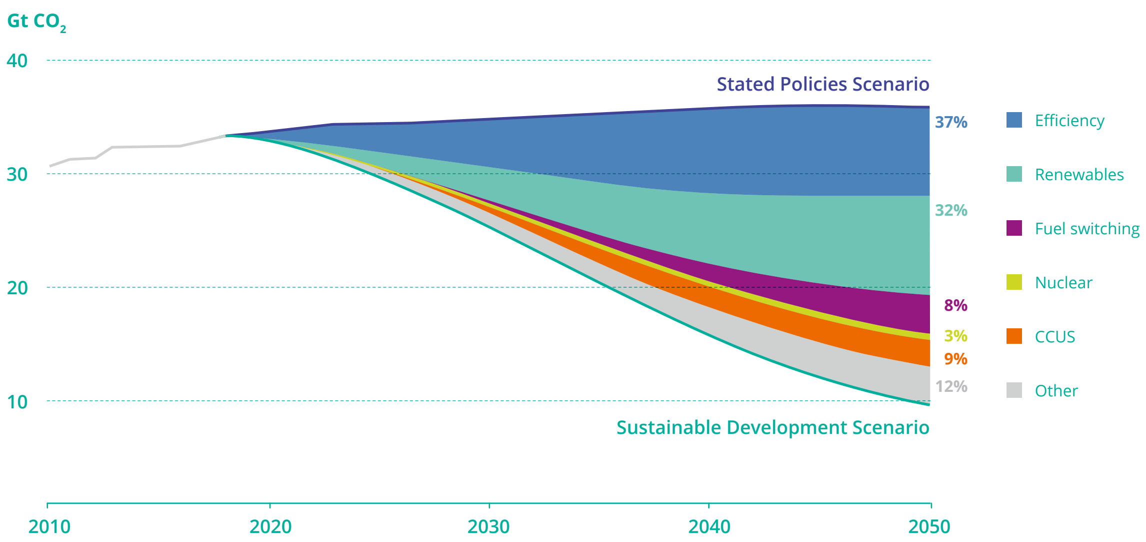
Change towards a carbon-neutral society and challenges for ECS

Energy systems, "supplying clean, affordable and secure energy" are the focus of the European Green Deal. The European power sector must therefore undergo further transformation from fossil fuels to renewable generation, while also evolving to enable the decarbonisation of mobility, industry and thermal energy supply. Due to the increasing residual load resulting from the local mismatch between decentralised renewable generation and load, a digitally controlled transmission and distribution infrastructure is required. Thus, electronic components and systems (ECS) are key to future energy systems being optimised, in both design and operation, for high-efficiency, low CO_2 emissions, cost and security of supply. The development of energy systems is driven by action against climate change, booming decentralised renewable generation (solar, wind), digitalisation and artificial intelligence (AI) technologies, and cyber-security issues.

This section highlights the **Major challenges** in the changing energy landscape, one that is increasingly based on electrical energy: generation, supply, conversion and use. Greater efficiencies and secure, highly reliable solutions are required to achieve the transition to a carbon-neutral society by 2050.

3.2.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

ENERGY-RELATED CO_2 EMISSIONS AND REDUCTIONS BY SOURCE IN THE SUSTAINABLE DEVELOPMENT SCENARIO



Efficiency and renewables provide most CO_2 emissions reductions (Source: IEA World Energy Outlook 2019) **F.44**

The energy world is undergoing a radical transformation, partly driven by EU and national roadmaps. The global installed capacity of renewable generation has doubled over the past decade[91], an increase dominated by wind and solar energy, a move characterised by strongly intermittent, distributed generation with plant capacities ranging from domestic solar (≤ 10 kW), commercial solar and wind (≤ 500 kW) to power stations at the utility scale (≥ 1 MW). At the same time, the levelised cost of electricity (LCOE) from photovoltaic (PV) sources dropped by factor of 10[92]. Thus, grid parity between renewable (wind and PV) and fossil fuel-based generation has been achieved in several areas of the world. However, future renewable generation capacity must grow by at least four times compared to today's conventionally generated capacity to enable the substitution of fossil fuel-based transportation, domestic heating, and commercial and industrial processes, as well as to address the strong economic growth of non-OECD countries. Since the pursuit of all economically viable opportunities for efficiency improvement can reduce global energy intensity by over 3% per year, increasing energy efficiency may be accountable for 37% of CO_2 emission reduction by 2050[93] (see *Figure F.44*). Energy supply to all sectors in an affordable and reliable way (reliability, resilience) needs to match demand (availability) as effectively as possible (energy and resource efficiency).

Therefore, the power grid architecture developed for centralised, demand-driven power generation needs to be transformed into multimodal energy system (MM-ENS) architecture (*Figure F.45*). This will comprise distributed renewable generation, energy conversion units for sector coupling, transmission and distribution grids that permit bi-directional power flow, and energy storage for all modes of energy (electric, thermal, chemical). Energy management systems (EMS) must optimise ENS operation to match load and demand at all levels, ranging from the nanogrid[94] (behind the meter, building level) and the microgrid[95] (district or community level), to the regional distribution grid, which is connected to the cross-regional transmission infrastructure. Fossil fuel power plants that used to operate on schedules driven by demand will be transformed into back-up power supply facilities.

The overall reduction of energy consumption, along with the efficiency measures mentioned above, will always be a target since all energy usage that can be avoided also implies a reduction in emissions. This can be achieved through control elements for switching off energy use and zero power stand-by functionality, or moving to new technologies similar to the impact that progressing to LED illumination has had over the last decade. Upcoming threats are energy-consuming information and communications technology (ICT) technology related applications such as blockchain, AI, data traffic or digital currencies. The challenge will be to develop highly efficient algorithms and methodologies.

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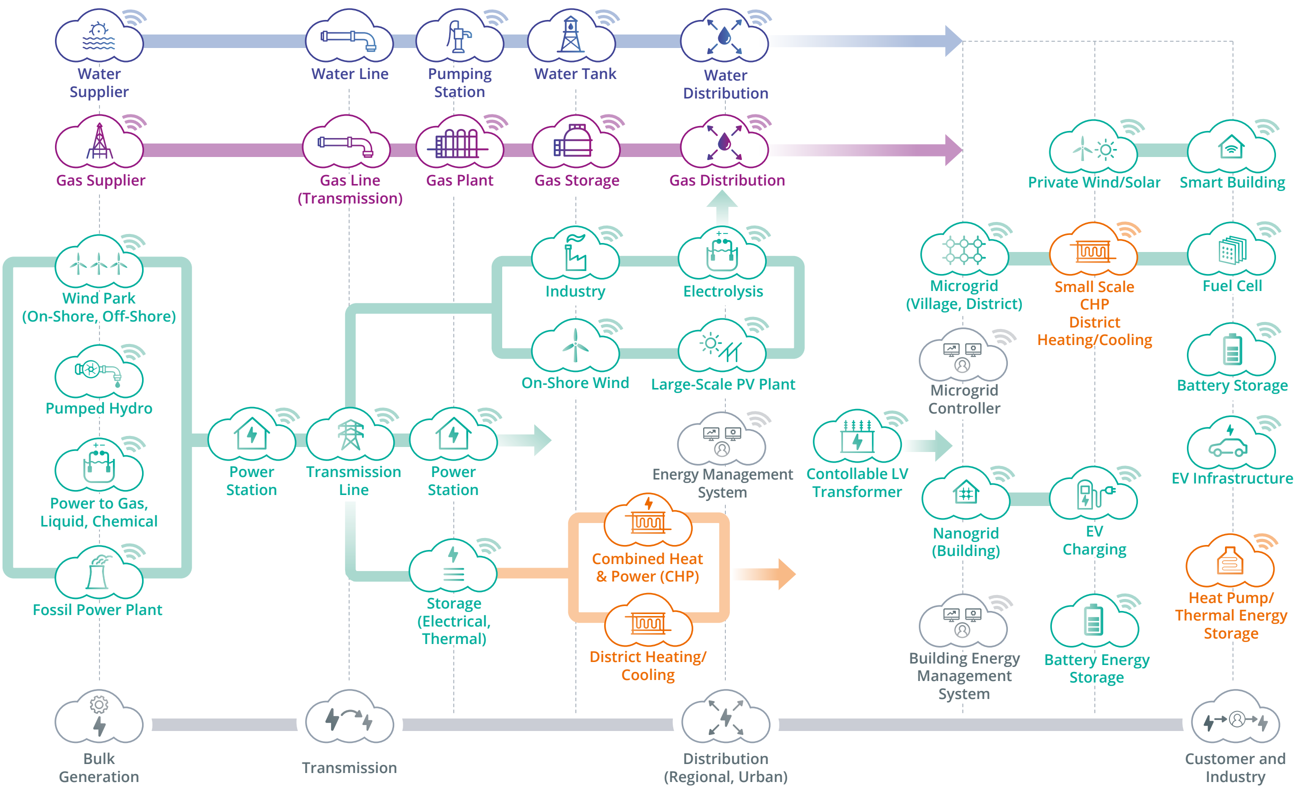
91 *IRENA (2019), Renewable capacity statistics 2019, International Renewable Energy Agency (IRENA), Abu Dhabi*

92 *IRENA (2019), Renewable Power Generation Costs in 2018. International Renewable Energy Agency (IRENA), Abu Dhabi*

93 *IEA World Energy Outlook 2019, p.25*

94 *Nanogrid: A single domain for voltage, reliability and administration. Typically used behind the meter, at the building level.*

95 *Microgrid: A small network of electricity users with a local source of supply that is usually attached to a centralised national grid, but is able to function independently. Typically used at the district or community level.*



Interconnected energy infrastructure (Source: Siemens Corporate Technology)

F.45

Key to these new energy applications will be smart sensors, networks of sensors, and smart actuators that enable status monitoring on each grid level, as well as smart converters (for all voltage levels). Such converters need to use highly efficient and fast semiconductor power devices and modules that enable real-time control of energy system components and grids for optimised operation based on forecasts of generation and demand, but also for any potential critical event. Future grid operation requires a sophisticated information and communication infrastructure that includes cloud services, IT security and AI technologies. Together, they will contribute to a significant reduction of energy consumption, and consequently CO_2 emissions.

To achieve the targets of the Green Deal, and ensure a competitive advantage for European-based technologies and solutions, research has to be performed in the following areas:

- Significant reduction and recovery of losses (application and service-oriented architecture (SoA) related).
- Increase of power density (e.g. through exploitation of new materials) and decrease of system size by miniaturisation and integration at the system and power electronics level.
- Increased functionality, reliability and lifetime (including sensors and actuators, ECS HW/SW, semiconductor power devices, AI, machine learning (ML), monitoring systems, etc).
- Manufacturing and supply of energy-relevant components, modules and systems.
- Transitioning to renewable energy sources and decentralised networks, including management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility.

F.46 *Energy from renewable sources: Wind turbines and photovoltaic (Source: © Mariana Proenca/Karsten Wurth – Unsplash [M])*

- Energy supply infrastructure for e-mobility, digital life and Industry 4.0.
- "Plug-and-play" integration of ECS into self-organised grids and multimodal systems, real-time digital twin capability.
- Safety and security issues of self-organised grids and multimodal systems through high-level IT security, etc.
- ECS for storage solutions.
- Optimisation of applications and exploitation of existing technology advances in all areas where electrical energy is consumed.

External requirements and societal benefits

To align with the Paris Agreement, the EU has committed to substantial reductions in CO_2 emissions. In particular, the EU aims to make Europe the first climate-neutral continent by 2050 (EU long-term strategy) while also boosting the competitiveness of its industries. The intention is that carbon pricing throughout the EU economy will be implemented more strictly and further climate legislation will be introduced, while also working to clarify existing policies. In addition, the "Clean Energy for all Europeans" package was finalised by the EU in 2019 as a comprehensive update of its energy policy framework. This focuses on a range of actions in renewable energy, the energy performance of buildings, energy efficiency, governance regulation and electricity market design. Smarter buildings with greater automation and control systems for effective operation will be promoted, as will an enhanced e-mobility infrastructure. Energy efficiency targets and energy labels were also tightened to encourage innovation in the industry.

However, to achieve the European Green Deal objective of clean, affordable and secure energy in all sectors, new laws and regulations will be required. While subsidies and regulations will promote sustainable developments in all application domains of ECS (energy, industry, mobility, communication, consumer goods and cities), the energy domain is the foundation.

Electrification of the transport sector (Source: © Gerd Altmann/Pixabay)

F.47

Additional perspectives are provided by the UN's "Roadmap 2050", which addresses sustainable development solutions and implementations towards a carbon-neutral global population.

All these factors are considered for the roadmaps on research, development and innovation of ECS for applications in the energy sector. Potential targets comprise the implementation of electricity storage solutions (e.g. vehicle2grid, battery grid storage), further increases in efficiency and a reduction in lifecycle costs of energy generated from renewable sources (*Figure F.46*), the electrification of transportation (*Figure F.47*), and the thermal processes in industry, as well as the development of secure, self-learning EMS for buildings and industrial sites. ECS as enablers support the EU and national energy targets to achieve sustainability (*Figure F.48*), and are essential for a highly developed energy landscape as part of a fair, democratic, healthy and prosperous society.

Energy efficiency through ECS fosters economic development towards a circular economy and new employment opportunities. These will have a huge impact on job generation and education if they are based around the complete supply chain and fully developed in Europe. With more than 11 million jobs in the field of renewable energies[96] and indirectly involved technologies, this is a visible and significant factor for economic and societal stability. The capability of maintaining an understanding of the complete systems, as well competences regarding small-scale solutions right up to balanced regional energy supply solutions, are key to Europe's competitiveness and success in the global market of energy solutions.

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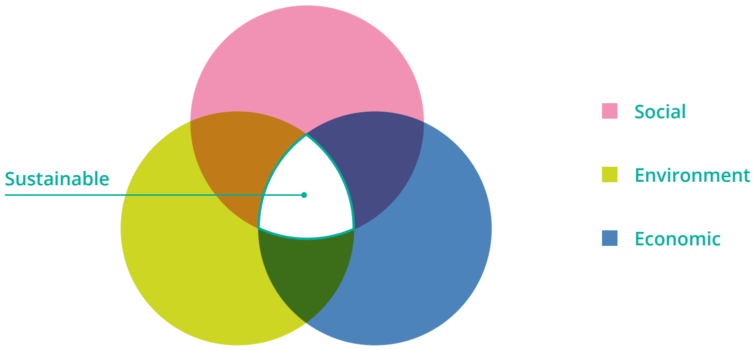
[96] *IRENA, Renewable Energy and Jobs – Annual Review 2019.*



F.48 *Three pillars of sustainability*
(Source: Purvis, Mao, Robinson 2018: Three pillars of sustainability: in search of conceptual origins)

Societal benefits here include access to knowledge, development of modern lifestyles and the availability of energy all the time and everywhere based on a minimum of wasted energy and greenhouse gas (GHG) emissions. Therefore, ECS and its application domains enable Europe to meet existing needs without compromising the ability of future generations to meet their own requirements.

3.2.3 STRATEGIC ADVANTAGE FOR THE EU

European ECS companies are among the leaders in smart energy-related markets, such as in electrical drives, grid technologies and decentralised renewable energy sources. For instance, four European-based power semiconductor suppliers are among the top 13 in the world, having a combined market share of over 21% in 2019. Three power modules suppliers are also found among the top 10, with one global leader in the automotive, discrete power device and security integrated circuit (IC) sectors, respectively, with a combined market share of over 35%. Overall, the share of European suppliers in this growing market is increasing, underlining their competitiveness. However, this position needs to be strengthened to ensure further employment is secured by innovative research across Europe. Such technological progress will have a multiplying effect by creating a convergence between semiconductor and other promising future technologies, such as 5G, the Internet of Things (IoT), AI and cloud-edge computing. As a result, EU ECS market prospects are viewed as very strong[97]. A seamless line from ECS research and development and innovation (R&D&I) to production, covering future energy businesses

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97 *KPMG GSA Global Semiconductor Industry Outlook 2020 Part 2.*

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98 *EA Energy Efficiency 2019.*

99 *In-depth analysis in support of the commission communication, A clean planet for all, European Commission 2018: 773.*

from generation over conversion to distribution and transmission, will ensure Europe's technological non-dependence.

ECS enable affordable energy conversion efficiencies of 93–99%, which enhances the push towards greater use of renewable energy resources. Involving new materials such as wide-bandgap semiconductors, new device architectures, innovative new circuit topologies, architectures and algorithms, help ensure the total system cost can be reduced. A focus on ECS development secures the smooth implementation of renewable energy power plants into the EU grid, a step towards the long-term goal by 2050. To ensure greater competitive, self-sufficient and energy-efficient transmission and consumption in the EU, the energy highway through Europe, as well as decentralised intermittent energy sources, bi-directional grid and storage systems, and distributed AC/DC network and grid technologies need to be implemented. These measures will support the EU in achieving its goals of a connected, breakdown- and blackout-protected, market-based energy market that is also more consumer-oriented. Consequently, EU's energy systems will serve as a blueprint for global application.

3.2.4
MAJOR CHALLENGES

3.2.4.1 Major challenge 1: Smart and efficient – managing energy generation, conversion, and storage systems

3.2.4.1.1 Status, vision and expected outcome

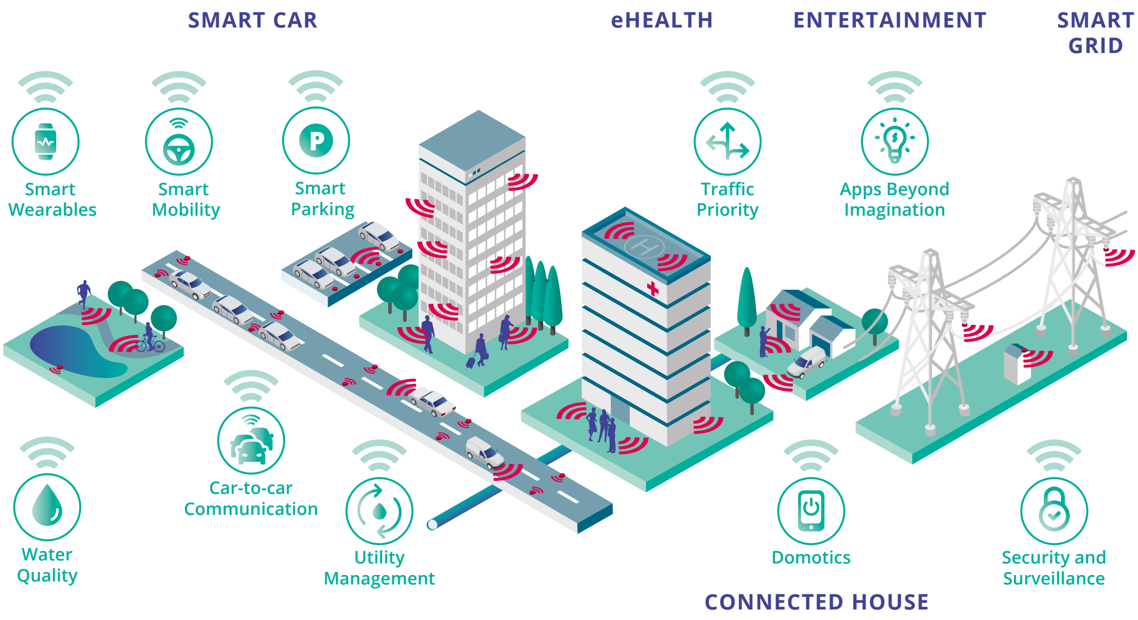
According to the Efficient World Strategy scenario of the International Energy Agency (IEA), digitalisation enhances energy efficiency gains in the transportation and industry sectors[98]. Smart and efficient energy systems are drivers of energy savings. Therefore, they are in full alignment with the European Green Deal. Alternative approaches to energy generation (hydro, photovoltaic and wind), and the electrification within the industry, transport/mobility, and the construction/building sectors will result in meeting the challenge of creating smart, efficient and reliable energy generation, conversion and storage components.

Smart energy systems

For operating smart energy systems, all the relevant energy conversion and storage components need to be equipped with smart actuators and sensors for status and health monitoring. The integration of sensor, connectivity and edge processing in supplementary/additional parts will enable the creation of intelligent facilities through retrofitting. The creation of secure electronic control units also requires the development of specific hardware and software. Consequently, smart control units need to be produced for all types of energy production, conversion and storage components, comprising smart electronic converters, actuators, sensors, security systems and reference communication interfaces. They should have plug-and-play functionality and real-time digital twin capabilities.

Conversion

The electrification of industry is one of the main implications of attaining the 2050 decarbonisation targets, mainly through the move from fuel-based heating processes to electro-heating solutions. In addition, direct electrification of industrial production processes (such as the electro-synthesis of chemicals or electrolysis)



F.49 *5G as enabler of an interconnected smart network (Source: European Commission, Towards 5G)*

is also crucial for replacing present CO_2-emitting solutions[99]. In the case of heating, ventilation and air conditioning (HVAC) systems, significant reductions in consumption can be achieved by optimising the systems that handle all the processes of energy management, or by evolving the use of the machine-to-machine (M2M) technologies. For both strategies, efficient ECS are required to obtain optimal control functionality based on sensing, collecting, processing and evaluating device-related data[100].

Although ICT energy consumption, and that of data centres in particular, is expected to increase exponentially over the next few years, it can be limited by improving energy efficiency[101]. DC power supply requirements based on advanced semiconductor power devices will provide lower power consumption, and thus provide greater efficiency. Investments in next-generation computing, storage and heat removal technologies will be required to avoid a drastic increase in energy demands, and to minimise the implications of unavoidable data centre energy use for the global climate[102]. In data centres and 5G networks, photonic ICs can route information streams from fibre to fibre without having to be converted into electronics in the process. This move will be highly efficient and energy saving.

The advanced features of 5G will help innovate the use of the technology (see *Figure F.49*), but will result in larger data rates and throughputs, and cost and energy demand will increase substantially. Therefore, the energy harvesting capability of sensors and devices in the 5G environment will be crucial to making 5G both green and cost-efficient[103].

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100 *Energy Management in Smart Buildings by Using M2M Communication, IEEE Xplore.*

101 *European Commission Joint Research Centre JRC, Directorate Energy, Climate and Transport. Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency.*

102 *Masanet, Eric, Arman Shehabi, Nuoa Lei, Sarah Smith, And Jonathan Koomey. "Recalibrating Global Data Center Energy-Use Estimates." 367, No. 6481 (2020): 984-986.*

103 *S. K. Routray and Sharmila K. P., "Green initiatives in 5G," 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, 2016, pp. 617–21.*

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104 *IEA Tracking Energy Integration, 2019.*

Power electronics circuits based on semiconductor power devices are used in all conversion processes. However, silicon-based power devices are approaching their limit in terms of breakdown voltage, current, switching frequency and temperature capabilities. Next-generation power semiconductor devices will rely on wide bandgap (SiC, GaN) and ultra-wide bandgap (diamond, Ga_2O_3) technologies. Due to this irresistible trend, research on device reliability, packaging and assembling methods suitable for very high electric fields and high temperature is strongly required.

Storage

Energy storage deployment provides much-needed energy system flexibility[104]. In terms of further storage possibilities, different options for various capabilities will require greater efficiency improvements. For example, optimised converters, sensor solutions for monitoring, and battery management systems will have to be developed for these storage options, all of which will include ECS.

3.2.4.1.2 Key focus areas for increased efficiency and smart energy generation, conversion and storage components

— **Increased efficiency at all levels:**

- Power conversion and semiconductor power devices.
- Power supply.
- Energy harvesting.
- Energy management.

— **Residential, commercial and industrial demand-side management (scheduling and load adaption)**

- Sensors, actuators, drives, controls and innovative components.
- Full monitoring in adaptive and controlled systems.
- High-efficiency electric drives, heat pumps, cooling, HVAC, data centres and other consumers of electricity for variable load operation.
- Solutions for increasing power demand of 5G systems.

— **Development of EMS, including:**

- Optimisation modules.
- Demand and generation forecasting.
- Customer preferences.
- Weather forecasts.
- Price/tariff information and forecast for scheduling controllable loads and generators.
- Smart sensor networks, with internal and external physical parameters that influence energy conversion efficiency.

— **Conversion of industrial processes:**

- “Industrial electrification” (i.e. replacement of CO_2-emitting processes with others based on “clean” electricity).
- Electric drives for commercial and industry applications.
- Industry 4.0 with combination of cyber-physical systems (CPS), IoT and AI.
- DC subsystems for industrial production /data centre applications.
- Photonic routing in data centres from fibre to fibre without conversion to electronics.

— **Development and application of storage optimised for residential, commercial and industrial utilisation:**
- Control, interfaces to batteries, fuel cells, hydrogen storage, electrolysers.
- Integrated battery-driven applications (e-car charging, PV-system local-charging, etc).

3.2.4.2 Major challenge 2: Energy management from on-site to distribution and transmission systems

3.2.4.2.1 Status, vision and expected outcome

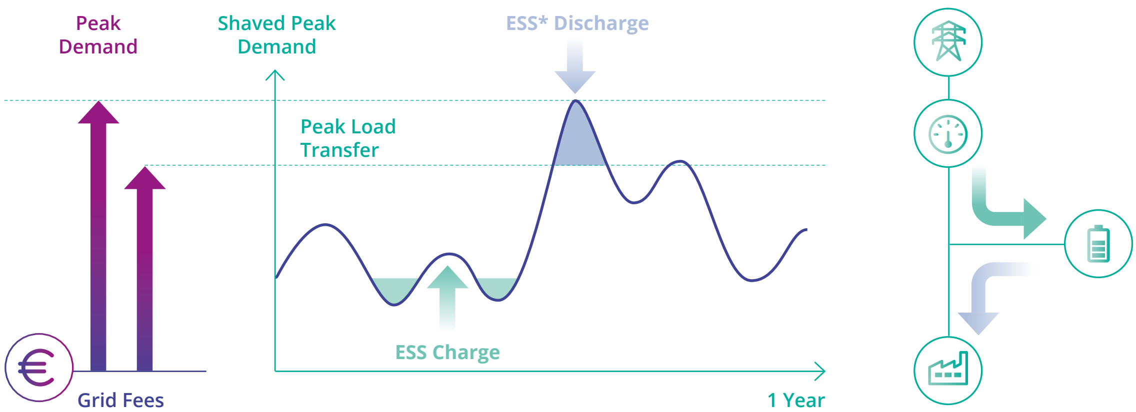
The distribution grid comprises commercial-scale renewable generation as well as private and smaller renewable power generation units, conversion between different energy modes, storage, control, and protection systems for grid infrastructure, combined with all types of consumption.

Autonomous control systems

In future distribution grids, generation and consumption by power electronics systems will surpass the share of synchronous generation. This will lead to potential grid instabilities due to lack of inertia, and therefore autonomous control systems need to be implemented to control the high demand loads. These control systems should be organised hierarchically to adjust the heavy loads according to actual local production and storage capabilities so that the import or export of power is minimised. Price control systems such as time of use (TOU) can help to prevent grid violations. Storage devices can be charged when the price is low and discharged when the price is high, to provide flexibility as well as ensure stability and reliability in the grids.

For industry or larger groups of buildings, control methods can increase the flexibility of the total system, and can be set up using hierarchical and intelligent control methods to minimise costs and provide peak-shaving (see *Figure F.50*). For larger power production facilities, hybrid generation and storage solutions should also be promoted as they can integrate power production facilities with storage devices to offer the best arbitrage cost. Novel grid architectures for manufacturing will strive to increase topological and energy flexibility within production cells to enable adaptive production optimisation.

ALGORITHM-CONTROLLED EMS TO SHAVE PEAK LOADS



F.50 *Visualisation of an algorithm-controlled EMS to shave peak loads.*
An EMS predicts load peaks and charges/discharges a battery accordingly. (Source: EDF Renewables)

Security, reliability and stability of energy systems

For stable, resilient on-site energy systems, multimodal EMS allowing integration of electricity, heating and cooling, as well as transport (e-vehicle charging), will be developed. Their features should comprise high-level IT security, energy trading via local energy market platforms, renewable energy certification, development of solutions for low voltage electronic systems that are easy to set up, and also support self-learning in terms of evolving needs.

EMS for industrial and residential customers include optimisation modules, demand and generation forecasting, customer preferences, weather forecasting and price/tariff information/forecasting. They require beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to effectively forecast the weather to produce accurate generation profiles. Furthermore, the interface to the grid could be used for additional power-quality services based on innovative power electronics converter technologies for reactive power compensation.

Future transmission and distribution grids will remain integral to energy distribution. The coupling of different domains (electricity, thermal, gas, etc) will enable new business opportunities based on technological solutions for ICT power electronics.

3.2.4.2.2 Key focus areas for on-site or behind-the-meter systems

— **Security, reliability and stability of total energy systems:**
- Automation of grids.
- Storage of data.
- AI and ML for optimised operation of the grid.
- ML-based forecasting algorithms for generating accurate generation profiles of expected power production and consumption.

— **Stable and resilient on-site energy systems – multimodal energy management:**
- Integration of electricity, heating and cooling, and transport (e.g. e-vehicle charging systems).
- Coupling with energy trading systems (e.g. local energy market platforms).
- High-level IT security.
- Renewable energy certification.

— **Hybrid solutions:**
- Integrating power production facilities with storage devices.
- Arbitrage cost, keeping level of production according to market bid.

— **Virtual markets:**
- Flexibility in demand and supply.
- Aggregation of energy consumption and production.

— **Electric energy supply for manufacturing:**
- Higher uptime using novel industry grids and uninterruptible power supplies (UPS).
- Stable power supply using novel electronic converter technologies.

— **Plug-and-play capability for components, self-learning:**
- Integration of low voltage systems using flexible planning rules.
- Cost-effective solutions to minimise set up time and manual parametrisation.

— **Reduced physical size and weight of individual transformer stations with equivalent power ratings by the development of solid-state transformers**

- New functions for the operation of power systems.
- Avoidance of infrastructure extensions caused by increasing share of distributed generation.

3.2.4.3 Major challenge 3: Achieving clean, efficient and resilient urban/ regional energy supply

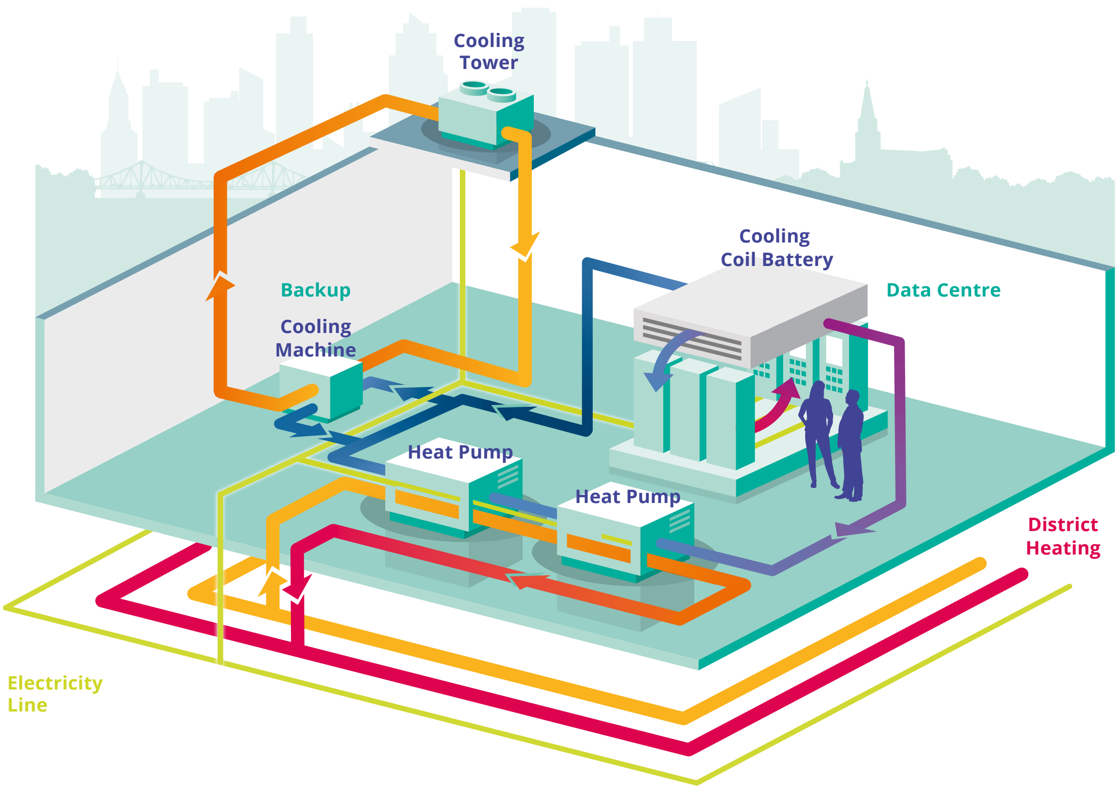
3.2.4.3.1 Status, vision and expected outcome

Achieving a 45% renewable energy share in the electricity sector in Europe by 2030 will necessitate decentralised, intermittent energy sources, bi-directional grids and storage for energy supply in transport, industrial and smart cities applications.

Multi-energy systems (MES)

MES can help to achieve optimised energy management, with all sectors being integrated to maximise overall system efficiency. Energy flows between sectors and their storages will ensure the highest use of renewable energy while balancing fluctuations.

Heating supply can use district heating, supported by heat pumps and boilers, using thermal storage in the district heating system (*Figure F.51*). Integration with industry makes use of waste process energy using heat pumps to boost from low (40–50⁰) to high temperatures in the pipe (80–90⁰). Electrolysers add to the gas system or transport, while water treatment will use excess power from renewables, adding further flexibility.



F.51 *A combination of heat pumps and district heating*
(Source: IEA HPT, New ways of combining heat pumps and district heating)

Local communities use MES concepts at the regional level. Different local inputs can also be gathered for overall aggregated control for the larger regions. Autonomous controllers are used behind the meters to support overall control. A clear hierarchical set-up, control structure and knowledge of market interactions are therefore a prerequisite. Complex integrated control systems will use AI, ML and comprehensive communication grid/IoT platforms to receive all data for control and optimisation. Risk and security analysis will provide resilience and ensure the stability of MES.

Urban transformation

Emission-free cities could use electrification and decentralised storages to improve both efficiency and reliability. ECS as indispensable components will ensure efficient management of data and data storage, and AI approaches and the ECS supply chain for integrated applications in energy will become key enablers for smart power grids.

The electrification of urban mobility supports individual and public transport (including utility electric vehicles, EVs). The former will require household and public charging, while the latter will use well-defined charging points on (bus) lanes or at terminals. Power varies from 10 kW (low voltage, LV) to 600 kW (medium voltage, MV). Reservation and optimisation will be based on ICT.

Other crucial aspects of emission-free cities are an efficient urban energy infrastructure, low-carbon and smart residential and service buildings, low-carbon mobility, smart water systems and smart waste management. Even a shift to LEDs with no smart functions can result in energy savings of ~50% in an industrial setting[105].

Storage solutions

In households, battery energy storage devices can be used to increase self-consumption. Some regions will use heat/cooling storage. Algorithms/models for the optimal use of storage (community/ private/ industrial) are based on technical parameters, demand and generation forecasts, and customer preferences to reduce power peaks and support integration of renewable energy systems (RES) into the existing infrastructure.

MES in larger communities with different kinds of storage possibilities (electrical, thermal, gas, water, etc) will play an important role. V2G has the potential to offer huge distributed electrical energy storage. Systems with electrolysers might also make use of storage tanks for gas production. The development of grid-supporting control algorithms and supporting regional energy management for communities (e.g. peer-to-peer (P2P) trading via storage systems, self-consumption optimisation) is also needed.

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105 *Muneeb A, Ijaz S, Khalid S, Mughal A (2017) "Research Study on Gained Energy Efficiency in a Commercial Setup by Replacing Conventional Lights with Modern Energy Saving Lights". J 6: 202.*

3.2.4.3.2 Key focus areas for achieving efficient community and regional energy management

- **Electric energy supply for urban mobility:**
  - Development of household and public charging infrastructure.
  - Creation of charging points along the (bus) lane or at fleet terminals, for public transportation.
  - Reservation and optimisation services implemented with ICT solutions.

- **Electric energy supply for urban life:**
  - Increase share of renewable generation, self-consumption (mainly heating/cooling and EVs) and building optimisation.
  - Local DC-coupling of various technologies for fast charging at home.

- **Regional energy distribution infrastructure:**
  - Communication infrastructure to support self-organised local energy communities.
  - Sustainable off-grid supply with power electronics based around grid-forming capabilities.
  - Virtual power plant functionality optimising the match between generation and demand.

- **Secure cross-regional transmission infrastructure:**
  - High-voltage transport grids.
  - Multi-terminal high-voltage direct current (HVDC) systems connecting remote energy-generation sites.
  - Interaction between distribution systems at the community and district level.

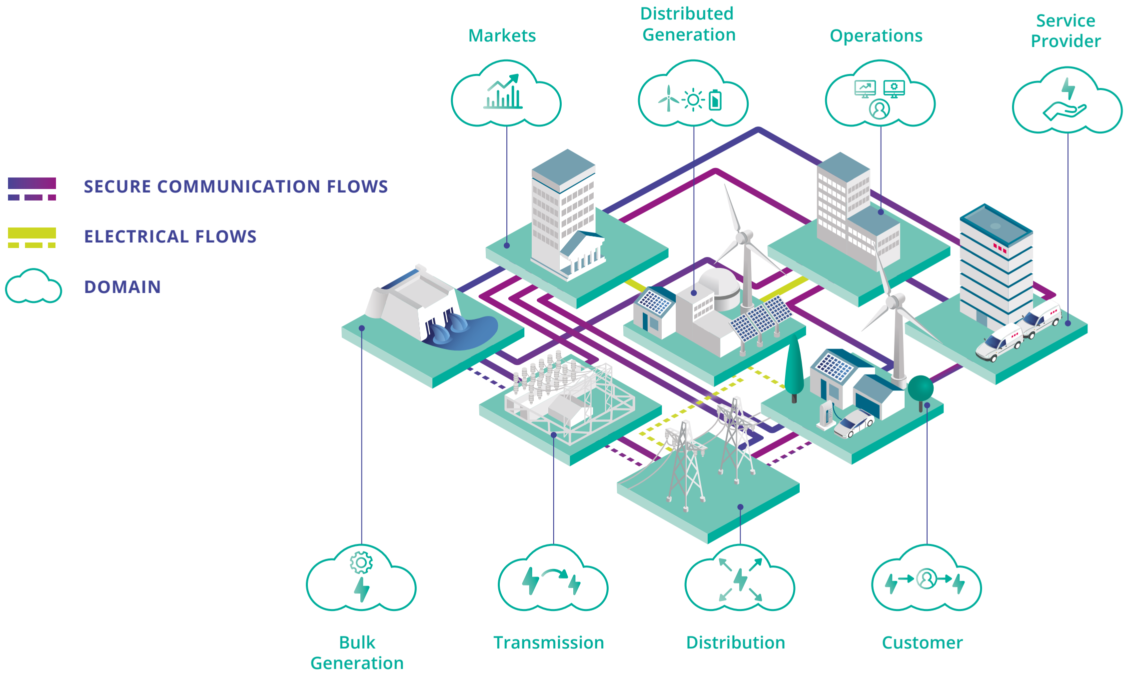
- **Operation of connected energy systems:**
  - Connectivity, security, integrity, resilience, variability.

- **Storage systems:**
  - Development of grid-supporting and peak-shaving control algorithms.
  - Support for regional energy management for communities.
  - P2P trading using storage systems.
  - Self-powering systems for small IoT nodes must be developed. The objective here is that local energy harvesting will substitute battery-powered devices, and eliminate the high demand in energy for battery manufacturing and distribution logistics.

3.2.4.4 Major challenge 4: Cross-sectional tasks for energy system monitoring and control

3.2.4.4.1 Status, vision and expected outcome

In terms of current energy management platforms, these still have shortcomings in automation, interaction and intelligence. Thus, as the traditional energy grid evolves into a smart grid, it should integrate ICT and power electronics in a massive way. ECS can empower electrical utility providers and consumers, and improve efficiency and availability, while constantly monitoring, controlling and managing demand. Such enormous and complex networks need cross-sectional approaches for monitoring and control to achieve efficiency, security and reliability of communication and electrical flows (*Figure F.52*), all based on new ECS technologies.



Interaction of actors in different smart grid domains through secure communication flows and electrical flows (Source: NIST Framework and Roadmap for Smart Grid Interoperability Standards)

F.52

Optimisation in monitoring and control

To ensure security, reliability and stability of the total energy system, it is important to be aware of the current state of the system at all times. Therefore, observability and state estimation, together with the forecasting of expected production and consumption, play a key role. This requires automation of the grids, use of sensors at different levels, storage of data, AI and ML to operate the grids in an optimised way, while at the same time remaining committed to ensuring data security and conforming to the general data protection regulation (GDPR). Data collection within the grid needs to be limited to chosen parameters to avoid unnecessary costs and complexity.

IoT technology as applied to the smart power grid can help achieve sustainable energy, low latency and reliability[106]. Machine learning used to forecast energy demand in smart grid environments can contribute to both the medium-term and long-term prediction of consumption and production, and can solve energy management issues through improved accuracy of prediction[107]. It allows administrators to optimise and plan their resources, and to manage energy inconstancies and variations. Nevertheless, security concerns and vulnerabilities need to be identified in existing electricity grids, and sufficient solutions implemented to reduce the risks to an acceptable secure level[108].

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106 *Jaradat, M., Jarrah, M., Bousselham, A., Jararweh, Y., & Al-Ayyoub, M. (2015). The Internet of Energy: Smart Sensor Networks and Big Data Management for Smart Grid, https://hdl.handle.net/10356/81241*

107 *Ahmad, Chen 2018: Potential of three variant machine-learning models for forecasting district level medium-term and long-term energy demand in smart grid environment. https://www.sciencedirect.com/science/article/abs/pii/S0360544218313811*

108 *Aloul, Al-Ali, Al-Dalky,Al-Mardini,El-Hajj 2012: "Smart grid security: Threats, Vulnerabilities and Solutions".*

Transmission system operators

European transmission system operators (TSOs) are entities operating independently from other electricity market players, and which are responsible for the bulk transmission of electric power on the main high-voltage electric networks. TSOs provide grid access to the electricity market players according to non-discriminatory and transparent rules. To ensure security of supply, they also guarantee the safe operation and maintenance of the system. In many countries, TSOs are also in charge of the development of the grid infrastructure[109].

Energy management platforms for integrated energy systems

In a notable research programme, Chinese engineers and scientists have designed an energy management platform for integrated energy systems. This platform can carry out the control of underlying facilities, visual monitoring, data storage and the energy-optimised planning of the system using AI. Finally, this energy management platform can also be used to optimise daily summer loads for the full 24 hours, something that helps to verify the practicability of the platform[110].

Hardware

Electrical grids aim to become more distributed, smart and flexible to meet the increasing demand for electricity. For new grids, the trend is to design energy generation and consumption areas together, in a distributed form. Therefore, power electronic devices play an especially crucial role in regulating distributed generation and dispersing energy-storage devices together and into the grid. The intensive use of power electronic converters in the microgrid brings their control methods to the forefront, which should achieve an effective dynamic response and high reference tracking characteristics[112]. However, combining low-power and high-power components in this way requires fundamentally new HW solutions. In addition to necessitating heterogeneous integration at the highest and most diverse levels, leading to unprecedented electromagnetic compatibility (EMC) and thermo-mechanical concerns, It may also open the door to developments not possible in any other application field. For example, sensors (e.g. for self-monitoring) placed directly into power switches can control energy flow to an entire city, a breakthrough that involves two heterogeneous worlds in conjunction (e.g. kV and pW, MA and nA). Such sensors must withstand strong magnetic field changes and temperature fluctuations (+300^0), and thus require further research and innovation.

3.2.4.4.2 Key focus areas in the cross-sectional tasks

— **Self-adaptive control based on AI/ML:**

- Data-driven analytics (descriptive, diagnostic, predictive and prescriptive) in smart grids.
- Fraud detection.

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109 *Source www.entsoe.eu.*

110 *Article: "Design of energy management platform for integrated energy system".*

111 *Bin JIA,Fan LI,Bo SUN* School of Control Science and Engineering Shandong University Jinan, China.*

112 *Bayhan, Abu-Rub (2020). "Smart Energy Management Systems for Distributed Generations in AC Microgrid". Quatar Environment and Energy Research Institute, Hamad Bin Khalifa University; Texas A&M University at Qatar, Doha, Qatar.*

- Design, development and application of deep learning in smart grids.
- AI in an advanced metering infrastructure.
- Predictive maintenance concepts that result in reduced maintenance costs and increased lifetime for equipment and infrastructure.

— **Algorithms for status, prediction and demand:**

- Multi-objective optimisation algorithms in smart grids (e.g. forecasting of generation and consumption).
- State-estimation based on measurement values, simulation values, trained models (ML).
- Optimal utilisation of storage systems (community storage, private storage, industrial storage systems) based on technical parameters, demand and generation forecasts and customer preferences.
- Short-/long-term demand and generation forecasting algorithms for different energy domains (electricity, warm water consumption, etc) and integration into overall systems.
- New theories and applications of ML algorithms for smart grids.
- Data management, weather forecasting, energy use forecasting with a time horizon of 24 hours and with resolutions of at least 15 minutes (prevalent use of renewable solar, wind, hydroelectric sources according to demand profiles and use cases).

— **Flex offer to address flexibility (mathematical tool) – how much energy can be produced in a certain time – aggregated and delivered to the market (as an alternative to blockchain, etc):**

- Demand response in smart grids.
- Peak load management approach in smart grids.

— **IT security, connectivity, integrity:**

- AI techniques for security.
- Smart and secure edge devices for secure data management and control.
- EMS for low-power/low-cost devices.

— **Hardware innovation:**

- H-bridge quasi-impedence source inverter (qZSI) for PV systems.
- Three-phase back-to-back inverter for wind energy conversion systems.
- Ultra-capacitor with high efficiency (95%) and high-power density.
- New generation of smart meters.
- Status/health monitoring (e.g. ice sensor/detection) for transmission lines.

3.2.5
TIMELINE

The following table illustrates the roadmaps for **Energy**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Managing energy generation, conversion and storage systems smartly and efficiently	**Topic 1.1:** Smart electronic control systems for energy conversion and storage	• High-efficiency converters, smart actuators and sensors, plug-and-play functionality, real-time digital twins, integrated security systems, status and health monitoring, integrated reference communication interfaces, self-powered systems for off-grid operation
	Topic 1.2: Optimised storage possibilities	• Control interfaces to batteries, fuel cells, electrolisers • Optimised converters • Sensor solutions for cell and module monitoring • Battery management systems • Self-powered electrochemical energy storage systems (SEESs)
	Topic 1.3: Electric drives for domestic, commercial and industry applications	• Heat pumps, cooling devices, HVAC development, innovation and installation
Major challenge 2: Energy management, distribution and transmission systems on-site or behind the meter	**Topic 2.1:** Stable and resilient multimodal EMS	• Distributed generation, interconnectivity, renewable energy sources and grid connection
	Topic 2.2: EMS for industrial and residential customers	• Development of beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles • Handle uncertainties at industry sites through ECS
	Topic 2.3: Autonomous control systems	• Control of high-demand loads for efficient energy distribution
Major challenge 3: Achieving efficient community and regional energy management	**Topic 3.1:** Regional energy distribution infrastructure	• Secure cross-regional transmission infrastructure • Communication infrastructure to support self-organised local energy communities
	Topic 3.2: Electric energy supply for urban life and mobility	• Development of household and public charging infrastructure; charging points on bus lanes or terminals • Reservation and optimisation services implemented with ICT solutions
	Topic 3.3: Storage systems for urban communities	• Development of grid-supporting and peak-shaving control algorithms • Battery energy/heat/cooling storage devices for households
Major challenge 4: Cross-sectional tasks for energy system monitoring and control	**Topic 4.1:** AI, ML and algorithms for status, prediction and demand	• Data-driven analytics and deep learning in smart grids; AI in advanced metering structures; smart sensors with improved data processing; stream processing for real-time applications
	Topic 4.2: IT security, connectivity, integrity	• Smart, secure edge devices for secure data management and control
	Topic 4.3: Hardware	• Improvements in robustness of HW devices to withstand strong magnetic field changes and temperature fluctuations

MEDIUM TERM (2026–2029)	LONG TERM (2030–2035)
• Storage devices providing flexibility, stability and reliability in the grids • Further energy efficiency improvements	• Getting closer to zero emissions (due by 2050)
• Grid integration • Storage devices providing flexibility, stability and reliability in the grids	• Development of excellent storage possibilities to balance energy generation volatility; efficient energy distribution and usage
• Supplying clean, affordable and secure (made in Europe) energy to these applications	• "In all cases, the 2050 target is to electrify these [...] processes with technical solutions based on renewable ("clean") sources" (Green Deal)
• Integration of electricity, heating, cooling and transport • Virtual power plant functionality optimising the match between generation and demand • Secure gateways allowing energy trading • Coupling with energy trading systems (e.g. local energy market platforms) • Renewable energy certification (labelling through ECS)	• Efficient energy distribution and usage; cost-efficiency; high-level IT security
• Optimisation modules, demand and generation forecasting, customer preferences, weather forecasting and price/tariff information/forecasting • Demand-side management for buildings • Virtual energy market	• EMS optimising operation of components for lifetime and revenue
• Price control systems • Storage devices providing flexibility, stability and reliability in the grids	• Minimise costs, provide peak shaving; hybrid solutions; novel grid architectures for manufacturing to enable adaptive production optimisation
• Sustainable off-grid supply with power electronics based on grid-forming capabilities	• Energy flows between sectors and their storages to ensure the highest use of renewable energy while balancing fluctuations
• Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimisation • Local DC-coupling of various technologies for fast charging at home	• Emission-free cities with electrification and decentralised storage to improve efficiency and reliability
• P2P trading using storage systems • Self-consumption optimisation	• Support for regional energy management for communities
• Innovative approaches ensuring clean, secure and affordable energy for EU citizens; multi-objective optimisation algorithms in smart grids; optimal utilisation of storage systems; short-/long-term demand and generation forecasting algorithms for different energy domains	• Save, interconnected smart grid network; cross-sectional approaches for energy monitoring and control, integrated energy system
• AI techniques for security	• Eliminate security vulnerabilities as much as possible
• Good dynamic response and high reference tracking characteristics of power electronic converters; new HW solutions to combine low-power and high-power components	• Optimal regulation of distributed generation and dispersed energy storage devices; robust devices able to control high energy flows

3.2.6
SYNERGY WITH OTHER THEMES

Energy supply and energy efficiency are fundamental to all other applications, from mobility and industry to societal sectors. The requirements of ECS for energy applications strongly drive technological developments in (high-)power electronics, as well as for sensors, photonics, signal processing and communication electronics, along the full supply chain – i.e. from design to processing to integration. Hence, the **Energy** section has close links to the **Architecture and Design**, **Process Technologies, Equipment, Materials and Manufacturing** and **Components, Modules and Systems Integration** sections. Energy applications have specific and often particularly high requirements in terms of reliability, safety and security, which means they are instrumental to the definition of research work in the transversal section on **Quality, Reliability, Safety and Cybersecurity**.

Due to recent progress in automotive propulsion concepts based on batteries, fuel cells and hybrid engines, the synergies to the **Mobility** section are particularly high. The new technologies needed for such applications require greater efficiency and reliability, which shows a strong connection to the high-priority R&D&I areas listed in *Section 3.2* **Energy**. The strongest interface is seen in coverage of charging and storage infrastructures.

Finally, the power supply scenario, along with the availability and integration of several renewable sources with variable power generation profiles, can be considered an example of System of Systems (SoS), enabling synergy with the related transversal **System of Systems** section. Power management is fundamental to modern and future factories driven by the Industry 4.0 concept, where digitalisation plays a key role. Industrial IoT (IIoT), big data and AI are enabling factors for energy-aware systems based on the full exploitation potential of synergy across several sections.

3.3

ECS Key Application Areas

DIGITAL INDUSTRY

3.3.1
SCOPE

To be able to manage everything in a machine, factory or company network, industries have divided the necessary ECS technologies into levels or technology stacks. In these levels or stacks, sensors and actuators are closest to processing materials or handling items, and therefore seen as the lowest in the hierarchy. Moving up the levels, you find devices, unit processes, production or manufacturing lines, operations control, company or enterprise business processes, and an increasing amount of machines, lines, company boarders, as manufacturing has become more networked and global.

This SRIA addresses the digitalisation of the major European industrial sectors. These include discrete manufacturing (e.g. manufacturing of automobiles, white goods, furniture, toys, smartphones and airplanes), process industries (e.g. chemical, petrochemical, food, pharmaceuticals, pulp and paper, and steel), and machines and robots. Emphasis is also given to factories and operating sites, value chains, supply chains and lifecycles.

Digitalisation continues to be regarded as a key enabler for the future success of European industry. This section will address the potential for the development of topics such as responsive, smart and sustainable production, Artificial Intelligence (AI) in digital industry, industrial services, digital twins and autonomous systems. As discussed at the end of the section, nearly all of the topics in the **Technology** chapter of the SRIA are of vital importance to industrial applications. These include standardisation, engineering tools, cybersecurity and digital platforms. To digitise European industry, potentially all enabling technologies will need to be employed to realise the required competitive edge, and of course a focus on digital industry would not be complete without the enabling technologies.

3.3.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

External requirements

As stated in the new industrial strategy for Europe ("Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: A New Industrial Strategy for Europe", Brussels):

> Europe needs an industry that becomes greener and more digital while remaining competitive on the global stage. The twin ecological and digital transitions will affect every part of our economy, society and industry. They will require new technologies, with investment and innovation to match. They will create new products, services, markets and business models. They will shape new types of jobs that do not yet exist which need skills that we do not yet have. And they will entail a shift from linear production to a circular economy.

The digital sector will also contribute to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint. Scalability is key in a digitalised economy, so strengthening the digital single market will underpin Europe's transition. Europe must also speed up investment in research and the deployment of technology in areas such as AI, 5G, data and metadata analytics.

European factories and machines already have a high level of automation and digitisation. Many of the leading end-user companies are European based, and Europe also has a number of significant system and machine building, engineering and contracting companies that have a competitive edge in automation and digitisation. The business environment is changing. Through specialisation in new or niche end products, production is becoming more demand-driven and agile, while production is increasingly geographically distributed. In addition, the outsourcing of auxiliary business functions such as condition monitoring and maintenance is gaining in popularity, leading to highly networked businesses. There are many opportunities for energy, waste, material, recycling optimisation, etc, over the value chains and across company boundaries. Such advantages can only be realised by having a significant increase in digitisation.

This transition should include the adoption of applications that do not require to be kept internal or confidential, as solutions based on web/cloud services allows for the mediation of key factors such as their use by non-AI professionals, and off-line development of advanced criteria models and inferential engines through the expertise of specialised centres.

The exploitation of AI for core business functions generally requires a complete rethinking of data management and their use and tracking inside the supply chain. Instead, the implementation of a system of system (SoS) framework enables the data to be to capitalised on through appropriate actions, in which analysis and analytical tools usually reach their limits.

The actual value chain will come from existing installations, as it is unusual for new factories to be built. As new, fast and secure communication protocols will provide easy connectivity and interoperability across systems, this will enable the potential for integration. Easy access to a secure internal network will provide all existing information to users at any time and anywhere within the plant. Moreover, new interesting features could be accessed through cloud or edge-based computing systems. However, this will require new hardware infrastructure to be added to the plant, along with greater processing power to handle larger amounts of data.

Digital infrastructure and micro services will help evolve business models towards selling added value as a service. Investment in projects will create networks between vendors and providers. In modern business-to-business (B2B) relationships, ongoing R&D and industrial pilots will aim to deliver a range of after-sales services to end customers. Typically, such services will include condition monitoring, operations support, spare parts and maintenance services, help desks, troubleshooting and operator guidance, performance reporting, as well as the increasingly required advanced big data analytics, prognostics-based decision support, and management information systems. However, the actual market for these types of service is still in its infancy. Many end customers are still hesitant to outsource their condition monitoring business processes, although significant combined benefits have been demonstrated by organising such business processes as commercial services, allowing end users to pay more attention to their core businesses.

Industrial services often represent 50% or more of industrial business volume, and this share is steadily growing. The share of services is generally higher in high-income countries than in low-income countries. The importance of service businesses in the future is obvious, since they also enable sustained revenue after the traditional product sales, with the service business being typically many times more profitable than the actual product sale itself.

3.3.3
STRATEGIC ADVANTAGE FOR THE EU

It is important here to note the view of manufacturing from the recent Science Europe report, "Guidance Document Presenting a Framework for Discipline-specific Research Data Management":

> Europe is home to a competitive, wealth-generating manufacturing industry and of extremely comprehensive manufacturing ecosystems which accommodate complete manufacturing supply chains. Europe's manufacturing industry is the backbone of the European economy, bringing prosperity and employment to citizens in all regions of Europe.

The EU is a global market leader for high-quality products, and European Industry is the world's biggest exporter of manufactured goods, which represent 83% of EU exports. Thanks to the strengths of its manufacturing industry, the EU annually achieves a considerable trade surplus in the trade of manufacturing goods, which amounted to €286 billion in 2018. This healthy surplus generated by the manufacturing industry allows the EU to finance the purchase of other, non-manufactured goods and services, such as raw materials, energy (oil and gas), and services. The surplus in manufactured goods thus compensates the deficits which are generated by purchasing non-manufactured goods. However, the surplus generated by EU's manufacturing sector cannot fully compensate these deficits anymore: the overall EU trade balance (counting both manufactured goods and non-manufactured goods) changed from a surplus of €22 billion in 2017 to a deficit of €25 billion in 2018. From a macro-economic perspective, this is not a healthy situation in the long run, and shows the importance of a strong manufacturing industry.

Although Europe's industry is a worldwide technology leader in most manufacturing market segments, this position is constantly being challenged by international competitors. While being highly competitive, statistics show that EU manufacturing industries constantly need to keep up with international competition. Competitors, especially from Asian economies, have reached advanced levels, often supported by state-supported programmes. Furthermore, industrial structures are changing with significant foreign investments, including those by emerging economies, in Europe and in the US. And finally, large-scale digitalisation, changes in trade rules, and global environmental concerns create new challenges.

In addition, it is worth noting the perspective of the recent P4Planet 2050 Roadmap of SPIRE, "Transforming the European Process Industry for a Sustainable Society":

> Process industries are an essential part of the European economy. Process industries are crucial components of numerous value chains that deliver goods and services to our society and to European citizens. The materials produced by the process industries ultimately aid in providing shelter and housing to families, transporting passengers or freight, offering comfortable working spaces, producing and preserving food and beverages, and producing the sophisticated devices needed in modern healthcare and high-tech digital world. In other words, process industries enable the life we are living. Currently the process industry provides about 6.3 million jobs directly and 19 million indirectly. Process industries continuously attract talent and incite academia to train the next generation of experts. Process industries contribute about €565 billion/year to GDP, drive innovation, and develop solutions for societal problems.

Focused innovation efforts will transform the European process industries. The process industries will adapt existing processes and develop disruptive new processes to fulfil the needs of this society in transition, both in the short and the longer term. New solutions (both technical and non-technical) are crucial. As major technological challenges are similar across process industries, increased collaboration is needed. Europe and its process industries can only succeed in solving the puzzles of climate change and circularity if they jointly define and implement ambitious research, innovation, industrial and financing policies enabling fast and smooth transitions.

As many process industries compete on a global playing field, the competitiveness of these industries needs to be safeguarded throughout the transition. The transformation of EU process industries requires unprecedented levels of investments. If new technologies come at higher cost, there is a risk that European process industries lose their competitiveness. This needs to be avoided through an effective policy framework, but competitiveness can also be boosted by innovation and scale (e.g. driving down cost of process technologies or of inputs).

3.3.4
MAJOR CHALLENGES

3.3.4.1 Major challenge 1: Responsive and smart production

3.3.4.1.1 Status, vision and expected outcome

The ability to quickly react to changes, efficient work allocation, predictable quality, fair circulation of tasks, and to tailor tasks for individuals are important targets for responsive and smart production.

Agile factories and networks are required to deliver products with a high degree of personalisation (high-mix, low-volume, lot size one, highly customised manufacturing), Therefore, to ensure manufacturing plants are more constructible, adaptable and dependable, a new and scalable approach to adaptivity and resilience is needed. This approach must be general, cohesive and consistent across all the interconnected lifecycles of the system components. Many European initiatives and reports cover this topic:

- European Factories of the Future Research Association (EFFRA) calls for "agile value networks [to] design, manufacture and deliver innovative products with a high degree of personalisation".
- SMART-EUREKA mentions "intelligent and adaptive manufacturing systems" as a main research and innovation domain.
- ManuFuture claims that "factories will adapt and become resilient to foreseen and unforeseen changes in the market and in technology".
- In their 2018 report, World Manufacturing indicated that rapidly responsive manufacturing is a disruptive trend, to "… react quickly to and take advantage of changes in market conditions, customer preferences, manufacturing conditions and social demands".

The main expected outcomes of more responsive and resilient production are:

- capability to rapidly change production.
- efficiency to become profitable with high-mix, low-volume production.
- capacity to operate, even with decreased operational capability.
- enable rapid innovation.
- limit deterioration in performance, reliability, maintainability and interoperability when plants face disturbances.

ECS and Key Digital Technologies (KDT) will play a lead role in this evolution to more responsive, robust and resilient factories. From sensors integrated in wearables and prosthetics, to SOS that enable self-healing and self-reconfiguration, responsive and resilient manufacturing has always been an important challenge.

The impact of Covid-19 has highlighted many of the reasons why an agile factory needs to adapt better in times of change to be a more useful part of the European response to such crises by:

- modifying production based on medical needs and exogenous inputs.
- scheduling production with less human resources and social distancing constraints.
- empowering agile working and telepresence.
- adapting to changes in the supply chain, promoting European independence.
- developing capacity for in-kind, or inside a shorter supply chain for the production of components that usually come from the worldwide market-based supply chain.

In terms of standardisation, standards are a significant and necessary part of all industrial applications. The modern digitalisation of industry could not exist without standards, as without standards interoperability would not be possible. They enable extensive industrial projects while ensuring quality, safety and reliability. Many engineering methods are standardised, and provide textbook consistency across professional engineering. However, standards must also be supported by the relevant engineering tools, etc, as those required for design or development are different from those required at the operation stage.

3.3.4.1.2 Key focus areas

- Robust optimal production, scalable first-time-right production: Future manufacturing plants should become more robust in the sense they can continue production even when facing a disturbance. This will require advances in, for example, self-healing and redundant automation systems, first-time-right, zero-defect manufacturing, and predictive maintenance.
- Mass customisation and personalised manufacturing, customer-driven manufacturing, mastering the complexity of products, processes and systems: Progress in recent years towards lot-size-one manufacturing and personalised product design will continue to grow in the next few years.
- Resilient and adaptive production, including the shortening of supply chains and modular factories: Resilience is a critical property for systems that can absorb change and adjust their functional organisation and performance to maintain the necessary operations for accomplishing their objectives under varying conditions.
- Cognitive production: This involves deploying both natural and artificial cognition to enable new analyses and learning that can enable responsive and sustainable adaptable production. For example, real-time monitoring against lifecycle assessment (LCA) criteria can be facilitated by the implementation of AI. More generally, it is important for cognitive production to support the emergence of simplicity rather than the combinatorial growth of complexity when complex cyber-systems are combined with complex physical systems.
- Manufacturing as a service: Technological advances have the potential to expand the geographical distribution of manufacturing and facilitate manufacturing as a service (a well-known example of that is 3D printing). Another interesting opportunity for manufacturing as a service is moveable factories, which can bring production resources to locations far from fixed factories, including to locations where there is no industrial infrastructure. Hence, although they are not necessarily hi-tech, moveable factories circumvent the need for new industrial infrastructure. The scope for moveable factories is enhanced by the range of manufacturing machines and power sources that are becoming increasingly small and light enough to fit into trucks, trailers, carry cases, etc.

- Standardisation: Due to the ongoing legacies of the many existing standards and their installed base (number of units of a product or service that are actually in use), focus should be on bridging the systems of the various standards. This should involve developing semantic technologies as a means to master these diverse and numerous standards, including software or platforms that enable effective connectivity at a high application level, as well as respective digital testing, development environments and licencing. This is key to ensure there is wide acceptance and support of software vendors, engineering offices and end-users.

3.3.4.2 Major challenge 2: Sustainable production

3.3.4.2.1 Status, vision and expected outcome

This **Major challenge** focuses on how Industry 4.0 should address the future regulation or market requirements emerging from the European Green Deal and zero-carbon (or below carbon-neutral) operations.

Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2ºC. The rapid transformation of all sectors is therefore required. In fact, many European countries have set even more ambitious targets, and ECS/KDT could have a great bearing in reducing environmental impact through sustainable manufacturing, including energy- and resource-efficiency and by applying circular economy strategies (eco-design, repair, re-use, refurbishment, remanufacture, recycle, waste prevention, waste recycling, etc).

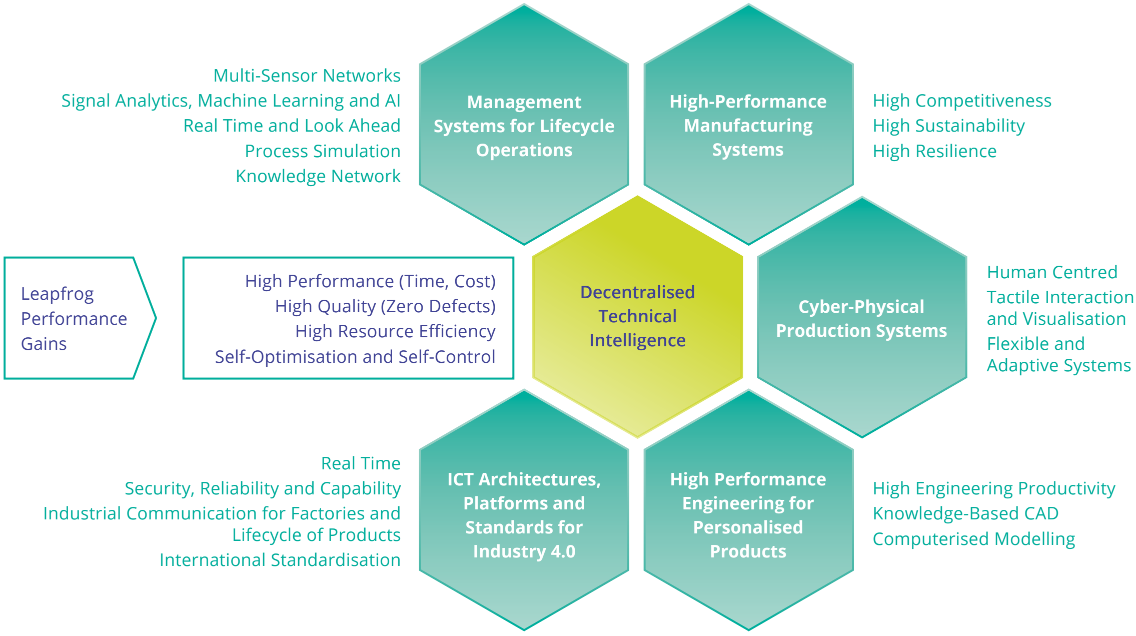
The vision of Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) categorises the high-level goals discussed above into more practical action, as follows.

- Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
- Re-use waste streams and energy within and between different sectors, including recovery, recycling and the re-use of post-consumer waste.
- Replace current feedstock (raw material to supply or fuel a machine or industrial process) by integrating novel and renewable feedstock (such as bio-based) to reduce fossil, feedstock and mineral raw material dependency while reducing the CO_2 footprint of processes or increasing the efficiency of primary feedstock. Replace current inefficient processes for more energy- and resource-efficient processes when sustainability analysis confirms the benefits.
- Reinvent materials and products to achieve a significantly increased impact on resource and energy efficiency over the value chain.

ManuFUTURE Vision 2030 combines these objectives as shown in *Figure F.53*.

3.3.4.2.2 Key focus areas

- Lifecycle assessment: LCA is a prerequisite for holistic environmental evaluation, and is a simple but systematic method that requires extensive and comprehensive models and data. In practice, mixed combinations often need to be employed – for example, missing measurements must be compensated for by models or standard data. LCA software must also be better integrated into other automation systems.
- Monitoring flows of energy, materials and waste: It is already commonplace in many industry sectors (food, medicine, etc) that material and energy streams need to be fully traced back to their starting point. As more and more products, raw materials, etc, become critical, this implementation strategy must be expanded. Flows need to be monitored. Sustainable manufacturing needs



The visionary manufacturing system for adding value over the lifecycle with decentralised technical intelligence (Source: ManuFUTURE, "Strategic Research And Innovation Agenda (SRIA) 2030")

F.53

comprehensive environmental and other measurements that may have been in place when the relevant manufacturing or production was initiated. On the other hand, this is a very typical application for many types of IoT sensor and system that can be informed by careful LCA.

- Discharges or losses mostly happen when production does not occur as planned, due to mistakes, the bad condition of machinery, unskilled operation, and so on. Human factors cause most of the variation in the running of continuous processes. There should therefore be a focus on how an AI assistant or AI optimiser could be used to help operators by providing advice and preventing less than optimal changes.
- Human-centred manufacturing: A higher level of formal training may be required for workers in production and maintenance. Greater specialisation is constantly introducing products and processes that require greater company-specific training.
- Extended human capabilities enabled by big data and AI: AI will impact nearly every industry, and service businesses around AI will emerge, something that will provide new opportunities for small and medium-sized enterprise (SMEs).
- Human operators in more autonomous plants and in remote operations.
- Human safety: With the localisation of personnel, machines and vehicles, situation-aware safety (sensing of safety issues, proximity detection, online human risk evaluation, map generation, etc) will become increasingly vital.
- Competence and quality of work: At a strategic level, the European automation and industrial IT industry depends on its ability to attract skilled personnel to maintain their competence over time.
- Human–machine interfaces and machine-to-machine communications: Augmented reality (or virtual reality) will be used to support a number of tasks. Enhanced visualisation of data and analytic results will be required to support decision-making.
- Green Deal: Policy initiatives aimed at putting Europe on track to reach net-zero global warming emissions by 2050 are key to the European Commission's European Green Deal. The Commission plans to review every EU law and regulation to align them with the new climate goals. To achieve

the highly challenging objectives of the Green Deal, all industries must focus on high efficiency, low energy usage, carbon-neutrality or zero-carbon usage, zero waste from water, soil and air – all measured, calculated or estimated on product, factory, global and lifecycle levels. European industry must research and discover new materials while paying a great deal of attention to recycling, re-use, and de- and re-manufacturing.

Many of these advances will require extensive development in the other engineering, business or social domains, even at the individual level, that are outside of the ECSEL/KDT focus. However, it is also obviously the case that a growing part of these approaches will be implemented through the significant help of electronics and software technologies. The need for ECSL/KDT technologies is diverse, and it is not useful to indicate one single technology here. High performance, high precision, careful and professional engineering and decision-making are needed – often at a much higher level than today.

3.3.4.3 Major challenge 3: Artificial Intelligence in digital industry

3.3.4.3.1 Status, vision and expected outcome

Major challenge 3 focuses on cyber-physical systems (CPS)/industrial internet, big data, machine learning and AI. Local edge-based intelligence is seen as an opportunity for Europe. This **Major challenge** extends toward AI-enabled, adaptable, resilient factories, including the human as a part of a "socio-technical" system. AI in combination with (predictive) condition monitoring and maintenance will be applied to not only support reconfigurable first-time-right/zero-defect manufacturing, but also to support human decision-making (considering uncertainties), as well as enabling resilient manufacturing ecosystems based on new business models. An important challenge here is to lead not only the digital transformation of Industry 4.0, but the next generation of ECS platforms supporting AI-driven human-centric autonomous Industry 4.0 operations.
Condition monitoring techniques can be applied to many types of industrial components and systems, although often at additional cost. Commonly, the business value required from condition monitoring depends on the higher availability of equipment and, for production processes, information provision to be able to plan and act on maintenance proactively instead of reactively, as well as to offer decreased cost and improved on-time delivery. Other business values that may be of interest are safety and the optimal dimensioning/distribution of spare parts and maintenance staff. Thus, serious breakdowns and unplanned interruptions to production processes can largely be avoided using condition monitoring.

AI will impact several main areas, all of which are relevant to **Digital Industry**:

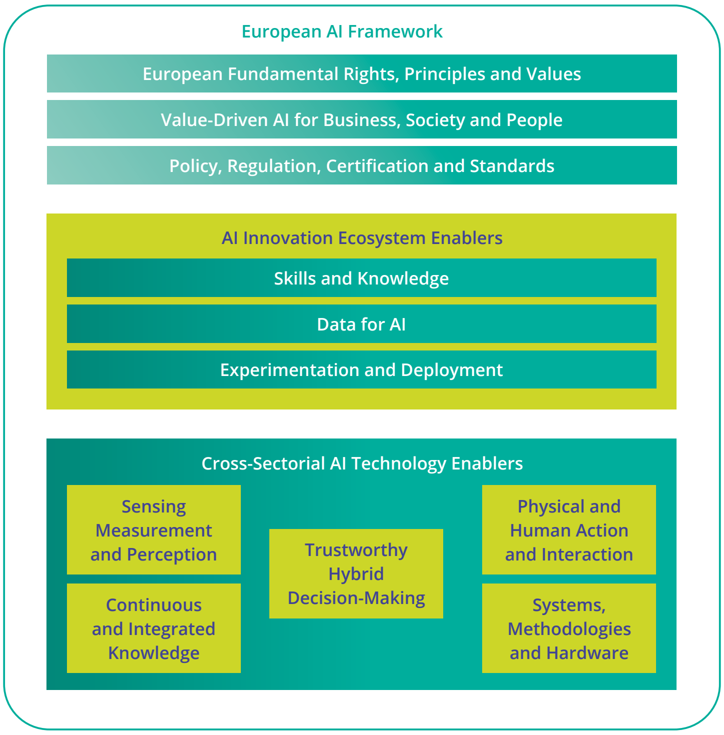
- By weaving AI into the design, manufacturing, production and deployment processes, productivity can be improved.
- By using AI to increase autonomy, higher operational flexibility can be achieved.
- By using AI to improve usability of products and services (e.g. by allowing greater variations in human–machine interaction), the user value can be increased and new customer segments addressed, thereby creating new markets.
- By using AI to support complex decision-making processes in dynamic environments, people can receive assistance in circumstances of rising complexity (e.g. technical complexity, increasing volatility in markets).

These fundamental impacts will be experienced in all areas of every market sector. In manufacturing and production, AI will deliver productivity gains through more efficient resource, energy and material use, better design and manufacturing processes, and inside products and services, enhancing their operation with more refined contextual knowledge.

The agenda here is cross-sectorial, focusing on AI applied in any domain. However, the impact of AI in **Digital Industry** is of particular significance. A joint paper by the Big Data Value Association (BDVA) and euRobotics has noted that roughly 50% of the opportunities for exploitation of AI are in manufacturing ("Strategic Research, Innovation and Deployment Agenda for an AI PPP: A Focal Point for Collaboration on Artificial Intelligence, Data and Robotics", Second Consultation Release, September 2019).

3.3.4.3.2 Key focus areas

a) European AI framework

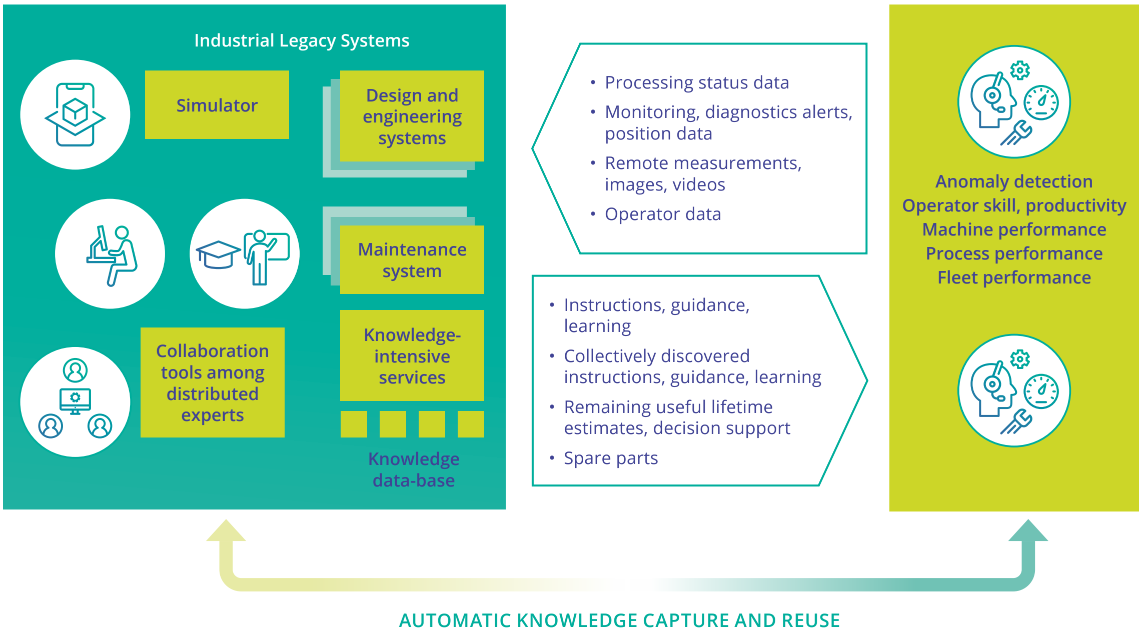


European AI framework and enablers F.54

Figure F.54 sets out the context for the operation of AI public/private partnerships (PPPs), as well as other PPPs or joint undertakings (JUs). It clusters the primary areas of importance for AI research, innovation and deployment into three overarching areas of interest. The European AI framework represents the legal and societal fabric that underpins the impact of AI on stakeholders and users of the products and services that businesses will provide. The AI innovation ecosystem enablers represent essential ingredients for effective innovation and deployment to take place. Finally, the cross-sectorial AI technology enablers represent the core technical competencies that are essential for the development of AI systems.

b) AI in manufacturing

- AI for production planning and management: This involves dynamic production systems and shop floors, production ramp-up, task planning and scheduling, etc.
- Virtual models spanning all levels of the factory life and its lifecycle: A holistic and coherent virtual model of the factory and its production machinery will result from the contribution and integration of modelling, simulation and forecasting methods and tools that can strategically support manufacturing-related activities.



F.55 *Industrial service business between a machine or system vendor or service provider and an end-customer. Services or lifecycle businesses deal with, for example, anomaly detection or condition management, operator skills development, productivity issues, machine or system performances, and fleet performances.*

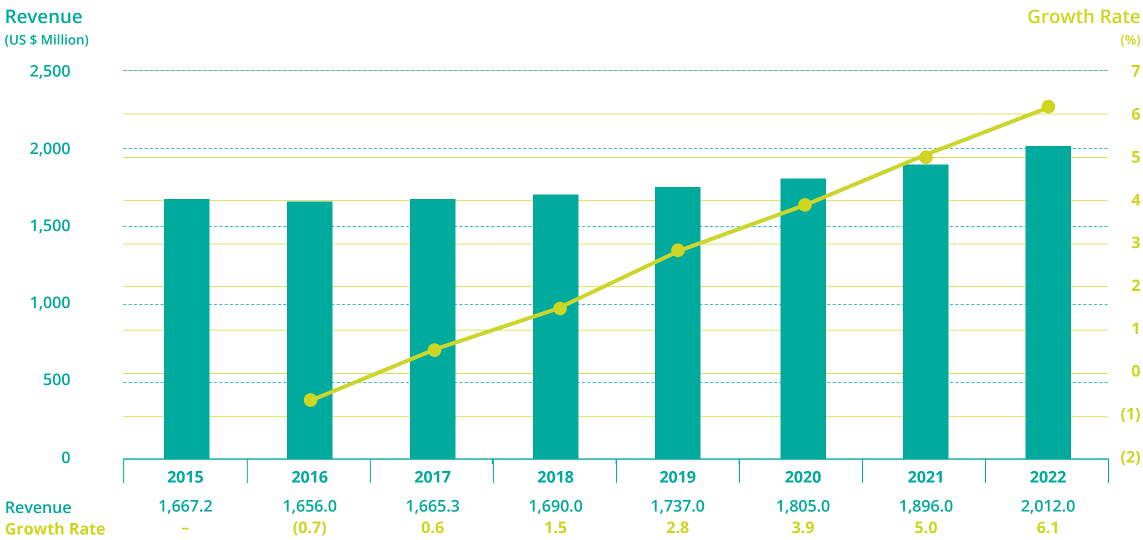
- AI for green/sustainable manufacturing: The development of software-based decision-support systems, as well as energy management, monitoring and planning systems, will lead to overall reduced energy consumption, more efficient utilisation and optimised energy sourcing.
- AI applied in supply chain management: Planning and managing logistics for real-time operations, collaborative demand and supply planning, traceability, and execution, global state detection, time-to-event transformation, and discrete/continuous query processing would therefore be a challenge in view of the distributed nature of these elements.
- AI for sales.
- AI for advanced manufacturing processes: The ability to design functionality through surface modifications, functional texturing and coatings, enabling improved performance, embedded sensing, adaptive control, self-healing, antibacterial, self-cleaning, ultra-low friction or self-assemblies, for example, using physical (additive manufacturing, laser or other jet technologies, 3D printing, micromachining or photon- based technologies, physical vapor deposition, PVD) or chemical approaches (chemical vapor deposition CVD, sol–gel processes) will deliver high functionality and hence high-value products.
- AI for adaptive and smart manufacturing devices, components and machines: Embedded cognitive functions for supporting the use of machinery and robot systems in changing shop floor environments.

c) AI for decision-making

- AI can supporting complex decision-making processes, or help develop hybrid decision-making technologies for semi-autonomous systems. Decision-making is at the heart of AI.
- Human decision-making, machine decision-making, mixed decision-making and decision support.
- Sliding or variable decision-making.
- Dealing with uncertainty.
- AI for human interaction with machines.

TOTAL EAM SOFTWARE MARKET: SERVICES REVENUE FORECAST, GLOBAL, 2015–2022

CAGR, 2017–2022 = 3.9%



Global Enterprise Asset Management Software Market, Forecast to 2022
(Source: Global Enterprise Asset Management Software Market, Forecast to 2022. Frost & Sullivan, January 2018)

F.56

d) AI for monitoring and control

- AI for control technologies.
- AI for monitoring services.
- AI for maintenance systems for increased reliability of production systems.
- AI services for continuous evaluation and mitigation of manufacturing risks.
- AI for quality inspection.

3.3.4.4 Major challenge 4: Industrial service business, lifecycles, remote operations and teleoperation

3.3.4.4.1 Status, vision and expected outcome

The volume and value of industrial services are increasing by between 5% and 10% every year. The share of services has exceeded the share of machinery for many machine, system and service vendors – not just for a final assembly factory, but also for companies in supply chains. Companies are willing to take larger shares of their customers' businesses, initially as spare part suppliers, but increasingly for remote condition monitoring, as well as extending this to a number of those tasks previously considered as customer core businesses. From a customer point of view, such a shift in business models lies in the area of outsourcing.

While many businesses have become global, some services are still provided locally, at close to customer's locations, while other services are provided centrally by the original vendor or companies specialised in such services. Similarly, as there may be extensive supply chains underpinning the vendor companies, the respective services may also extend to supply chain companies. The industrial era is becoming a service era, enabled by high-end ECT/KDT technologies. This distributed setting conveniently fits into modern edge/cloud architectures as computing and communication platforms.

The importance of service businesses to the future is evident as they enable a revenue flow beyond traditional product sales, and more importantly they are typically much more profitable than the product sales itself.

The service business markets is becoming more and more challenging, while high income countries are focusing on the high-skilled pre-production and lifecycle stages. Fortunately, in the global service business market, Europe can differentiate by using its strengths: a highly skilled workforce, deep technology knowledge and proven information and communications technology (ICT) capabilities. However, to ensure success it needs new innovations and industry-level changes.

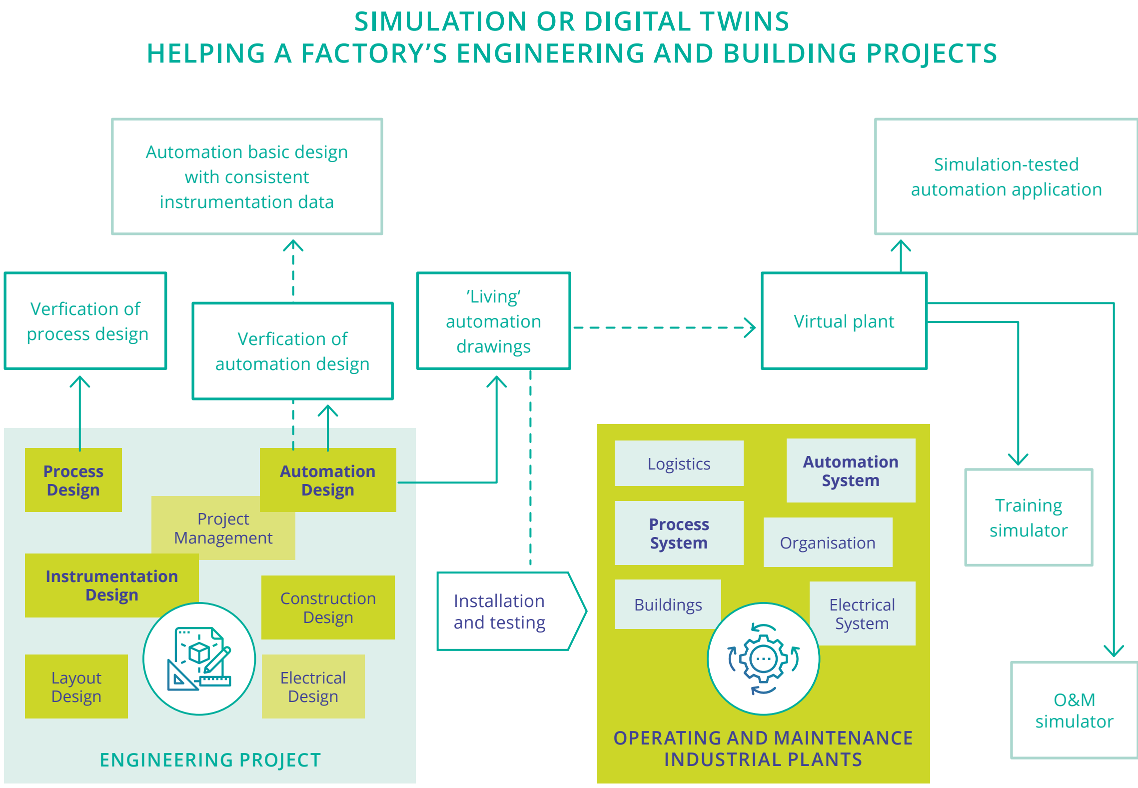
3.3.4.4.2 Key focus areas

- Collaborative product-service engineering, lifecycle engineering: Extending R&D to take into account how products and systems will be integrated into the industrial service programme of the company. This should possibly be enhanced by obtaining further knowledge to provide services for other similar products (competitors!) as well their own installed base.
- Training and simulation: Complex products such as aircrafts, drones, moving machines and any teleoperated machineries need a simulation environment for proper training of the human driver/operator.
- Condition monitoring, condition-based maintenance, anomaly detection, performance monitoring, prediction, management: The traditional service business sector is still encountering major challenges in practice. It will therefore require an extension to the above, as targets of services are expanded to other topics in customer businesses in addition to spare parts or condition monitoring.
- Remote engineering and operations, telepresence: Operating or assisting in operations of industrial systems from remote sites.
- Decision and operations support: In most cases, decision-making is not automatic, whereas in the future it could be based on remote expert assistance or extensive diagnosing (AI-based, etc), engineering, and knowledge management systems.
- Local and global services: Organising services locally close to customers and centrally at vendors' sites.
- Fleet management: This could benefit on the basis of sold items, by obtaining knowledge and experience from range of similar components and machines in similar or different conditions.
- Edge/cloud solutions: Implementing distributed service applications on effective edge cloud systems.
- Full lifecycle tutoring: Monitoring activities, level of stress and performance-oriented behaviour during the product's life, from anticipating its end of life to properly handling its waste and recycling, including improved re-design for the next generation of products.

3.3.4.5 Major challenge 5: Digital twins, mixed or augmented reality, telepresence

3.3.4.5.1 Status, vision and expected outcome

A "digital twin" is a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance and behaviour of their machines, and also to find new revenue streams. Currently, connectivity to the cloud allows an unprecedented potential for the large-scale implementation of digital twin technology for companies in various industries. A physical asset can have a virtual copy running in the cloud, increasing revenue through continuous operational data.



Simulation or digital twins helping a factory's engineering and building projects **F.57**

Simulation capability is currently a key element in the European machine tool industry's attempt to increase its competitiveness. In the Industry 4.0 paradigm, modelling plays a vital role in managing the increasing complexity of technological systems. A holistic engineering approach is therefore required to span the different technical disciplines and provide end-to-end engineering across the entire value chain.

In addition to virtual commissioning, modelling and simulation can more widely respond to many digitalisation challenges:

- visualising physical or real-world phenomena of products, production, businesses, markets, etc.
- helping designers to perform their core tasks – i.e. studying alternative designs, optimising solutions, ensuring safety, and providing testing for automation and Internet of Things (IoT) solutions.
- The effects of changes can be safely and more comprehensively assessed in advance in a virtual domain rather than using real plants, equipment or even mock-ups.
- Simulators offer versatile environments for users or operator training.
- It is evident that former computer-aided design (CAD)-driven digitalisation is shifting the focus towards simulation-based design.

Simulators may be used online and in parallel with its real counterpart to predict future behaviour and performance, provide early warnings, outline alternative scenarios for decision-making, etc, Although they have years of research behind them, such tracking simulators are still in their infancy, at least for industrial use.

Telepresence technologies can also be considered as the predecessor for an extended reality (XR) presence. The combination of XR and 5G offers significant potential for innovation, which would benefit the evolution of European digital industry. Broadly speaking, XR is a combination of virtual and augmented reality, and an XR presence is a continuum between a physical reality presence and a virtual reality presence. The main driver here is improving competitiveness through better productivity, more effective worker safety and better quality. The industrial applications have followed the prospects offered by the gaming industry and consumer applications. One of the reasons for its increased take-up is the declining cost of electronic components and sensors.

3.3.4.5.2 Key focus areas

- Virtual commissioning: Digital twins applied to virtual commissioning to bring collaboration between different disciplines and models from domains of engineering (mechanic, electronic, automation) in the same environment.
- Interoperability is a major challenge: Applications cannot yet be used across platforms.
- Heterogeneous systems remain a challenge: Information sharing and standards and means to ensure interoperability of digital twins and their information sources are important to facilitate information synchronisation. Having all relevant engineering disciplines (processes, assembly, electronics and electrical, information systems, etc) evolving together and properly connected over the lifecycle phases is therefore crucial. This also involves multi-domain simulation, joint simulation of multi-simulation systems coupling.
- Tracking mode simulation: Model adaption based on measurements. Generating simulators automatically from other design documentation, measurements, etc. Generation of simulators from 3D, data-driven models, etc.
- Simulator-based design: Digital twin for testing the designed model by replacing the required physical components with their virtual models. This offers continuous design improvement (the digital twin provides feedback and knowledge gained from operational data), design optimisation, etc.
- Digital twins combined with data-driven models (knowledge and data fusion): Combination of data-driven and knowledge-based models along the complete lifecycle (product and production). The real challenge is to combine physics and knowledge-based models (digital twins) with data-driven models (models created using AI from massive acquired experimental data), capitalising on the strength of information present in each of them.
- Digital twins applied to sustainability and circular economy: Simulate the usage of energy, use of raw material, waste production, etc, with the goal of improving energy efficiency and circular economy performance.
- Human-in-the-loop simulations: Methods and simulations for human-in-the-loop simulations and integration of digital twins in learning systems for workers.

3.3.4.6 Major challenge 6: Autonomous systems, robotics

3.3.4.6.1 Status, vision and expected outcome

Machines are usually more precise and efficient than humans when carrying out repeatable tasks. Thus, replacing or aiding work processes susceptible to human errors, quality defects and safety issues with machines will have an impact on quality and redundant waste. In some industries (such as construction, aerospace and automotive), the critical infrastructures of complex systems, and utilities, quality issues and the prevention of hidden defects in structures and/or any mechanical and electrical components are extremely serious. Therefore, substantial losses in terms of legal aspects, safety, potential stresses under critical situations of vehicles and aircrafts, substandard end products, and quality costs in general, are potentially damaging.

There are many kinds of autonomous systems, robots and working machines. These can be categorised by purpose, as follows.

- **Industrial machines and robots:**
  - manufacturing (e.g. welding, assembling, spray gun robots).
  - material handling (e.g. conveyors, warehouse robots, trucks).
- **Consumer robots:**
  - domestic (e.g. robotic lawn mowers or vacuum cleaners).
  - care (e.g. lifting or carrying robots).
- **Healthcare and medical robots:**
  - robotic surgery, hospital ward automation.
  - medical tests and hospital care, remote healthcare.
  - medical imaging, exoskeletons.
- **Moving machines:**
  - mining machines (e.g. drilling machines, dumpers, conveyors).
  - forestry (e.g. forest harvester), agriculture (e.g. tractors, appliances).
  - construction (e.g. excavators, road graders, building robots).
  - logistics and sorting centres (e.g. cranes, straddle carriers, reachers, conveyor belts, sorting machines, trucks).
  - military robots and machines.
- **Transport:**
  - vehicles, trucks and cars, trains, trams, buses, subways.
  - aviation (e.g. aeroplanes, helicopters, unmanned aerial vehicles, UAVs).
  - marine (e.g. vessels, ships, auto-piloted ships), submarine (e.g. auto-piloted submarines).
- **Utilities and critical infrastructures:**
  - extraction (e.g. drills for gas, oil).
  - surveillance (e.g. quadcopters, drones).
  - safety, security (e.g. infrared sensors, fire alarms, border guards).
  - energy power plants sensors and actuators (e,g, production and distribution).
  - transportation (e.g. moving bridges, rail exchanges).

The main aims and evolution trends of robots and autonomous systems in digital industry are oriented toward:

- production efficiency, speed and reduced costs.
- higher precision and quality.
- safety in working conditions.

As is evident from the above, robots and machines are involved in several application sections of this SRIA in addition to **Digital Industry** – i.e. **Digital Society**, **Health and Wellbeing**, **Mobility**, and **Agrifood and Natural Resources**.

There is undoubtedly a move to increase the level of automation and degree of digitalisation in industry, which will ultimately lead to fully autonomous systems. Moreover, there are some outstanding flagship programmes already launched (for autonomous driving, for example). Also, some mature manufacturing phases, or even entire production lines, are already practically fully autonomous.

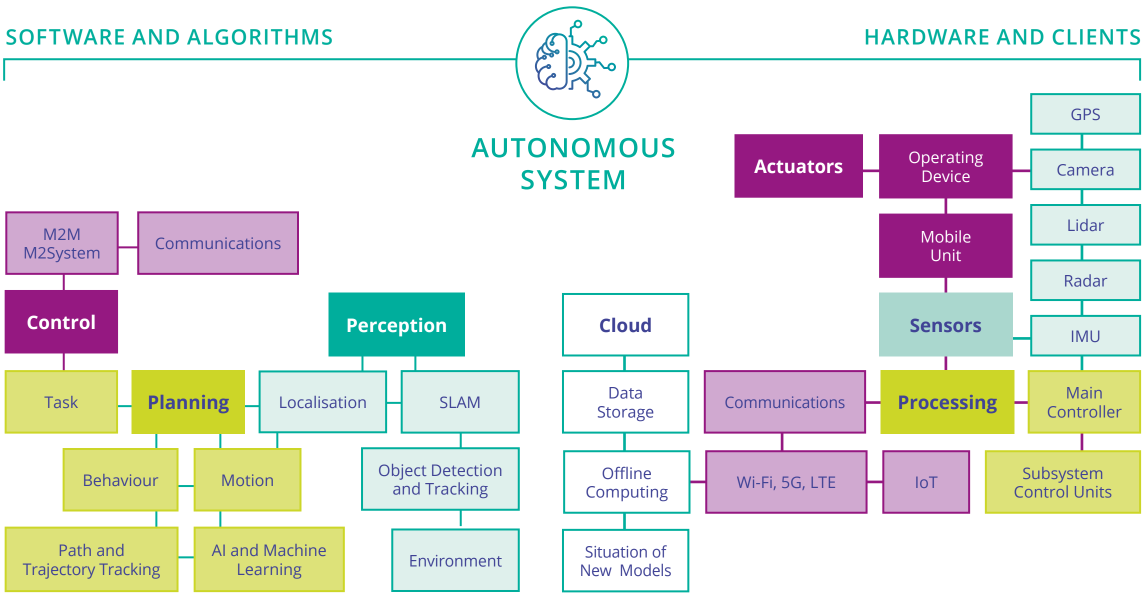
However, between the two extremes of entirely manual and fully autonomous there will always lie a large area of semi-autonomous equipment, units, machines, vehicles, lines, factories and sites that are worth keeping somewhat below 100% autonomous or digitised. The reasons for this include:

- a fully autonomous solution may simply be (technically) near to impossible to design, implement and test.
- if achievable, they may be too expensive to be realised.
- a fully autonomous solution may be too complex, brittle, unstable, unsafe, etc.
- a less-demanding semi-automatic solution may be easier to realise to a fully satisfactory level.

When the extent of automation and digitalisation are gradually, reasonably and professionally increased, often step by step, they may bring proportionally significant competitive advantages and savings that strengthen the position of digital industries overall. However, since the extent of automation and digitalisation remains well below 100%, any potential negative effects to employment are still either negligible or non-existent. On the contrary, an increased market position could enhance the need for more people in the respective businesses.

3.3.4.6.2 Key focus areas

a) Autonomous functions of systems



F.58 *A generalised overview of autonomous system (AS) technologies and functionalities. Adapted from Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). "Perception, Planning, Control, and Coordination for Autonomous Vehicles. Machines", 2017.*

b) Safety and security in autonomous systems

Current standards of safety requirements for autonomous machines categorise safety into four approaches.

- On-board sensors and safety systems for machines that work among humans and other machines but is restricted to indoor applications.
- An isolated autonomous machine that works in a separated working area, mostly an intensive outdoor environment where other machines or humans are monitored.

- Machine perception and forecast of expected and/or unexpected human activities aimed at: (i) assisting human activities and movements with a proactive behaviour; (ii) preserving human health and safety; and (iii) preserving the integrity of machinery.
- An operator is responsible for reacting to a hazardous situation encountered by the autonomous machine when being provided with enough time between alert and transferring responsibility.

c) Requirements management and conceptual modelling of autonomous systems

d) Human–ssmachine interaction in autonomous systems

- Human–robot interaction or human–machine cooperation.
- Transparency of operations between human and advanced machine systems (AMS) in uncertain conditions.
- Remote operation and advanced perception, AS oversight and tactical awareness.
- Autonomy intended to enhance human capabilities.
- Natural human interaction with autonomous systems.
- Assisted, safety-oriented and proactive robot interaction with humans.

e) Verification and validation, digital verification and validation (V&V)

- Automatic or semi-automatic V&V.

f) Digital design practices

- A digital design environment, digital twins, physical mock-ups.
- Sub-task automation development, generation of training data and testing solutions and field data augmentation, according to a handful of global machine manufacturers.
- Machine state estimation (assigning a value to an unknown system state variable based on measurements from that system).

g) Simulators and autonomous systems

- 3D models of the product with solid bodies, environment and object models and simulation tools.
- Early design phase simulators.
- Robotic test environments.
- Empirical or semi-empirical simulators, making use of both real and simulated data collected from previous experiments.
- Off-road environments.

h) Autonomous capabilities development in a digital environment

3.3.5 SYNERGY WITH OTHER THEMES

About engineering tools

Digital twins are commonly characterised by modelling and simulation (the finite element method, FEM, computational fluid dynamics, CFD, etc) or virtual or mixed reality techniques, and their numerous applications. However, the product processes, manufacturing design and management of the operative lifetime of a product or factory is much broader. Typical examples of these are: managing the multi-technologies (mechanical, electronics, electrical, software); safety, security and reliability engineering; managing interactions with the contexts of the target (humans, environment); managing testing and quality; the various types of discharges or footprints; managing projects, logistics, supply chains, etc. These tasks are increasingly being managed by software tools and systems, and through the use of standards, regulations and engineering handbooks, which generally require extensive domain knowledge and experience.

The respective engineering disciplines are well distinguished, developed and understood. Key examples here – such as factory design, electronics design, engine design and car design – are well known and significant as regards success. These disciplines are going through a tremendous and demanding digitalisation process, and are sometimes called the "other twins" to underline their importance and high value. A narrow focus on digital twins will certainly play a growing role in implementing the concomitant increase in types of "other twin".

There is also a notable discipline called "systems engineering", which describes both aspects and the whole of the instantiated subfields such as factory design and engine design. Similarly, many notable software tools – such as product lifestyle management (PLM), supply chain management (SCM) and CAD – are actually families of tools with significant versions for the actual subdomains:

- parallel joint engineering of products, processes, safety, security, cybersecurity, human factors, sustainability, circular factors, etc.
- mastering the deep linkage and complexities in multiple engineering domains and technologies, along with product and process lifecycles in the digital domain.
- multiplying the engineering extent, efficiency and quality in the digital world.

About trust, security, cybersecurity, safety, privacy

Increasingly, industrial technologies are being regarded as critical applications by law, meaning that extensive validation, verification, testing and licensing procedures must be in place. Security must also be embedded in all engineering tools, which strongly suggests that safety is not achieved by testing alone, but should be built or integrated into every lifecycle stage.

Security and cybersecurity are the other side of the coin in the distributed, remote or networked applications that contemporary communication technologies effectively enable. Lacking useful security could easily be a showstopper.

Since safety or security is difficult to achieve and prove, industries prefer to talk about trust and how they expect (and assume) safety and security will be in place for their business partners. Nevertheless, there must be no nasty surprises between trusted partners in terms of security issues.

As regards privacy, there is much idealistic urging by researchers, software enthusiasts, etc, for open data and open software from industrial actors. However, certain data must be kept private by law. In addition, critical applications have be sealed and protected once they have been finalised, otherwise their safety, security, functionalities, etc, cannot be guaranteed. Most industrial applications also involve a great deal of engineering effort and creativity, are very extensive and constitute the core asset of companies that must be protected. Competitive business situations could therefore result in a cautious attitude towards open data and software. Nonetheless, industries sometimes do not entirely know what data, etc, it is beneficial to keep private and what should be open. In the era of AI, it may be a challenge to know in advance what could be discovered, for example, in the vast amount of factory or machine data available. It is better be safe than sorry! Open interfaces, standards, etc, are good examples of practical openness.

About digital platforms, application development frameworks and SoS

Analysis of the different roadmaps confirms that the platform landscape is still very fragmented, with open and closed, vertical and horizontal platforms, in different development stages and for various applications. There is a strong need for interoperability/standardisation and the orchestration/federation of platforms. The trend is towards agile, composable, plug-and-play platforms (also that can also be used by SMEs), and more decentralised, dynamic platforms supporting AI at the edge. In addition, future (ledger-based) technologies could provide common services on trusted multi-sided markets/ecosystems.

Existing gaps can still be found in the following topics.

- Moving the focus to industrial and engineering applications. It is important to win the global platform game in various application sectors (which are strong today), and to effectively develop high-level outperforming applications and systems for actual industrial and business requirements.
- Preparing for the coming 5G era in communications technology, especially its manufacturing and engineering dimension.
- Long-range communication technologies optimised for machine-to-machine (M2M) communication and the large numbers of devices – low bit rates are key elements in smart farming, for instance.
- Solving the IoT cybersecurity and safety problems, attestation and security-by-design. Only safe, secure and trusted platforms will survive in industry.
- Next-generation IoT devices with higher levels of integration, low power consumption, more embedded functionalities (including AI capabilities) and at a lower cost.
- Interoperability-by-design at component, semantic and application levels.
- IoT configuration and orchestration management allowing for (semi)autonomous deployment and operation of large numbers of devices.
- Decision support for AI, modelling and analytics, in the cloud but also in edge/fog settings.

3.4

ECS Key Application Areas

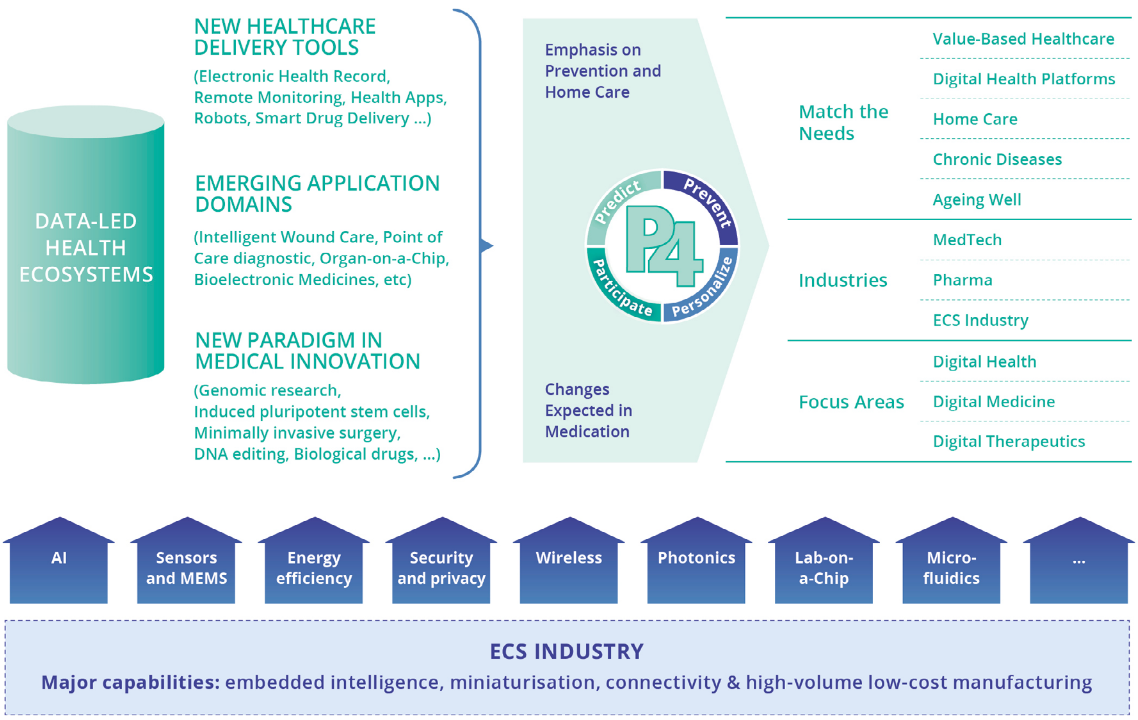
HEALTH AND WELLBEING

3.4.1
SCOPE

The healthcare industry is facing radical change, enabled by its current digital transformation. These developments will progressively generate a new ecosystem. New players will come to the fore, either from within the industry or through newcomers accessing the healthcare industry ecosystem.

Data will play an increasingly important role in providing a better understanding of consumer needs in terms of health, and to enhance and tailor a more cost-efficient health offering that delivers the right care at the right time and in the right place. The interconnections made possible by being able to access pools of data not previously available (worldwide database, data clouds, apps, etc) are creating a major shift in healthcare provision.

A few years ago, the big techs (especially Google, Apple, Facebook, Amazon and Microsoft, GAFAM) attempted to move into healthcare, which is a heavily regulated industry. At that stage they might have underestimated the challenge, but the spread of digitalisation and innovative information technology (IT) is giving them a second chance, and they are taking it. Data are everywhere, and healthcare practitioners need to cope with new and emerging digitalised delivery tools. Health tech companies, whether large corporations, small and medium-sized enterprises (SMEs) or start-ups, bring extensive expertise in using data and analytics, will be the dominant catalyst of these trends and are likely to drive change in the healthcare industry. Also, in a post Covid-19 era, regulators – usually seen as the main inhibitors – are also expected to be more favourable towards accelerating the current healthcare digital transformation.



ECS Industry impact in Healthcare Digital Transformation **F.59**

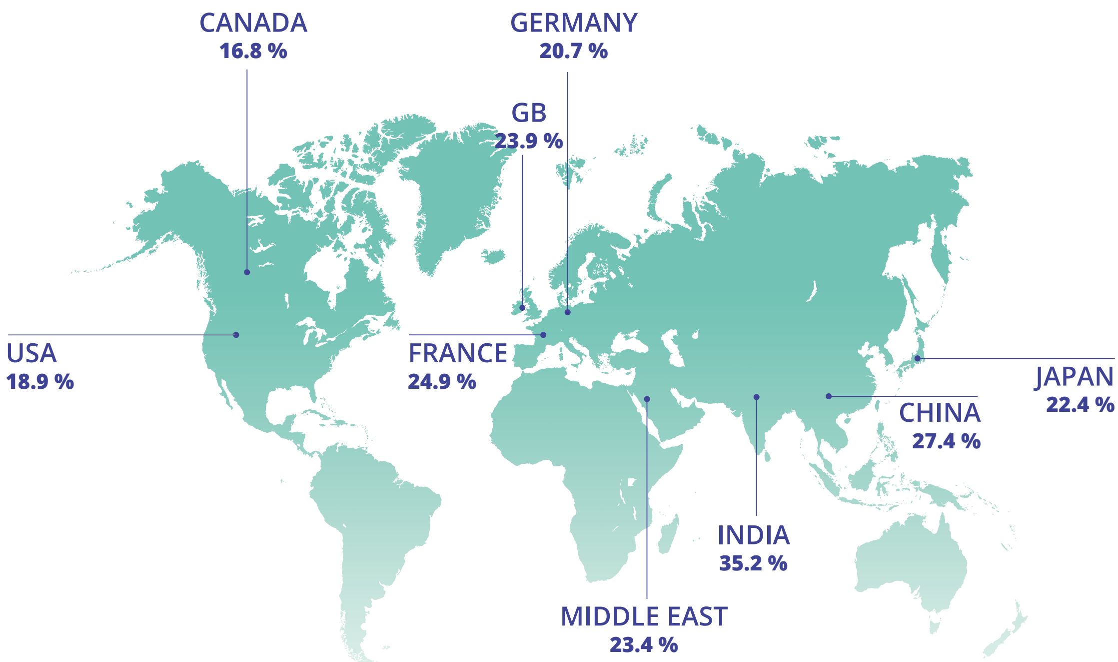
The Covid-19 pandemic is accelerating the adoption of telemedicine, initially at the most basic level (i.e. consultation by telephone), something that governments are also taking the opportunity to roll out, and this type of consultation is likely to further enable the digitisation of auscultations for medical diagnoses.

The emergence of P4 healthcare – predictive, preventive, personalised, participatory – as opposed to reactive healthcare, is blurring the lines between medical technology (medtech), the pharmaceutical industry and electronic components and systems (ECS) industry, opening the way for healthcare innovation. This is a huge opportunity for the European ECS industry, its worldwide medtech and pharma market leaders, as well as the 25,000 SME medtech companies across Europe, since the new healthcare ecosystem will rely on digital instruments, advanced electronic sensors and photonics, micro-electromechanical systems (MEMS), and the large volume, high-quality, low-cost production capabilities of the ECS industry.

3.4.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

External requirements

Healthcare electronics represents approximately 5% of global electronic equipment production, amounting to €91 billion in 2017 versus a total of €2,000 billion for the industry as a whole (according to Decision Etudes et Conseil, "Study on the Electronics Ecosystem": Annex 4, Health & Care). This report shows that healthcare is now the seventh biggest market in terms of electronic production worldwide, and is expected to benefit from a robust growth rate of over 5% over the next few years.



F.60 *Healthcare Data CAGR 2017–2025*
(Source: Bis Research-2020)

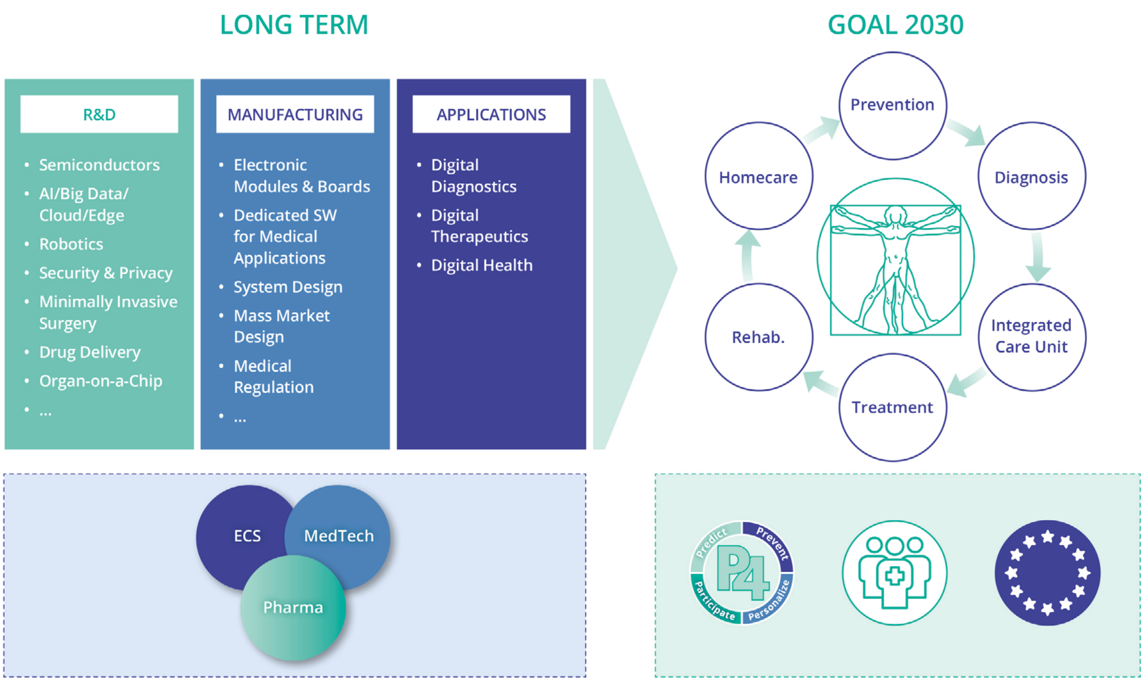
Within the industry, the current major innovation is the "big data" healthcare market. The market is exploding: the volume of generated data in healthcare is predicted to more than triple from 2017 (700 exabytes, e.g. 700 1018) to 2025 (2300 exabytes), according to a survey by BIS Research. This is supported by other studies, such as the "Stanford Medicine 2020 Health Trends Report", which identifies the rise of the (digital) data-driven physician as a direct consequence of how data and technology is transforming the healthcare sector.

Of course, this big data trend in healthcare relies on government initiatives to encourage the adoption of digital health, and it is interesting to note that Europe – represented in the map above by three countries behaving similarly – is well in line with the global trend.

These trends in healthcare electronics, healthcare data and healthcare technologies will continue to impact the healthcare value chain. The graphic below highlights how the healthcare digital transformation is gradually positioning the "healthcare consumer" at the centre of the value chain. It also shows how healthcare electronics – from research and development (R&D) to design and manufacturing – will digitalise the application segments, and how the care pathways – from prevention to treatment – will be transformed. As a consequence, healthcare will increasingly occur at the "point-of-need", in most cases at home, whether for wellbeing, preventive measures or post-hospital intervention (e.g. rehabilitation) centred around the patient and taking place away from a clinical environment. Such a transformation will be enhanced by less of an obvious division between the ECS industry and the medtech and pharma ecosystems.

Societal benefits

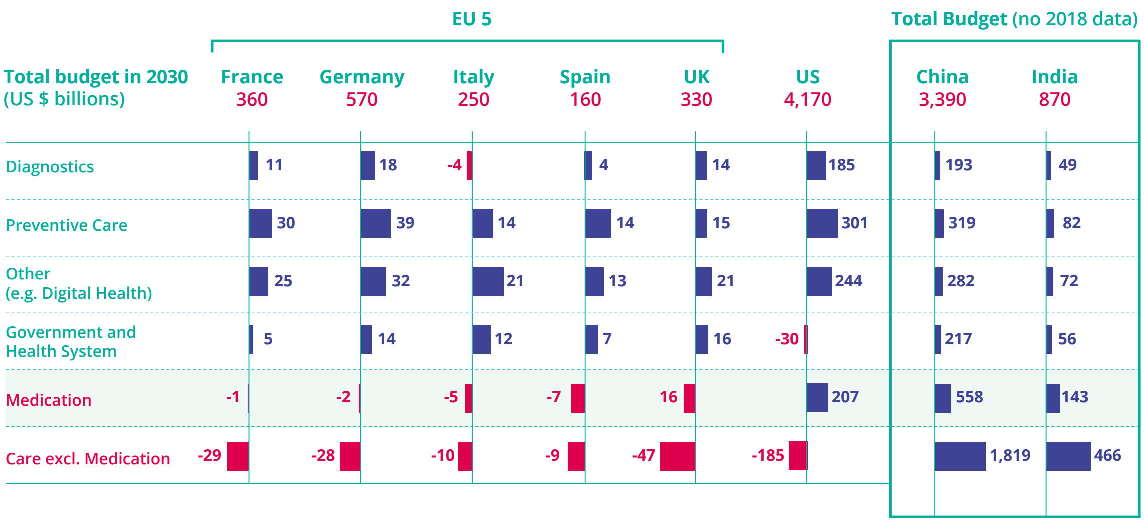
According to different projections, healthcare budgets around the world are expected to increase by 10% in aggregate by 2030. Healthcare spending will be driven by ageing and growing populations, rising labour



Continuum of Care Value Chain

F.61

HOW NATIONAL HEALTHCARE BUDGETS WILL SHIFT BY 2030 (2018 VS. 2030)



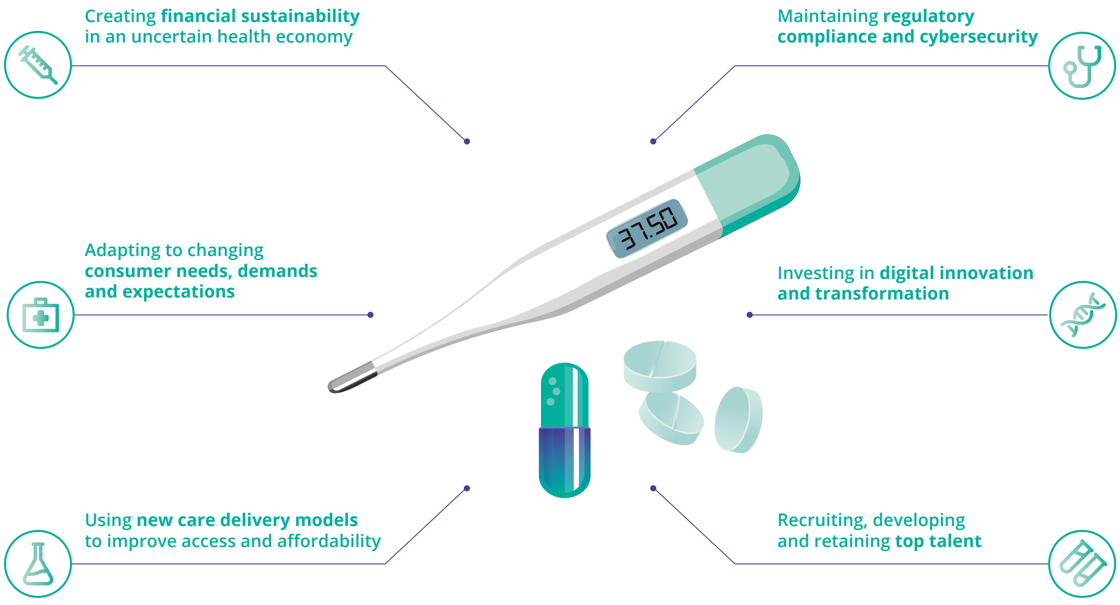
F.62 *How national healthcare budgets will shift by 2030 (2018 vs. 2030)*
(Source: OECD data; The Lancet; Strategy & analysis)

costs, and also by clinical and technology advances. Consequently, by 2030 healthcare is expected to be centred on patients being empowered to prevent disease rather than seek treatment, as highlighted above. Healthcare consumers will receive personalised health solutions provided within a healthcare system that is organised and regulated in an entirely new way (see *Figure F.62*).

Healthcare budgets in Europe will therefore shift towards novel areas such as digital health and more advanced prevention and rehabilitation options, for which homecare will play a key role. Money is expected to be redirected toward personalised medicine for the most complex diseases, and preventive, early stage treatments. This split is likely to lead to significant changes and require new R&D strategies for many industry players. The expectations will lie in those areas summarised in the *Figure F.63,* which is taken from a Deloitte report.

Another societal benefit relates to medical education, an area rapidly progressing due to computer-assisted learning, student medical apps, digital games, simulation and wearable technologies increasingly being embedded in the curriculum, although the pace has not yet been fast enough to meet the clinical need. The Covid-19 crisis has exemplified the need for greater investment in technology to facilitate this. For example, recent events have highlighted the crucial role of anaesthesia in airway management to reduce fatalities, yet clinical airway management is constrained by insufficient training time. Simulation training in airway management is recommended by the Royal College of Anaesthetists, but in recent years less than half of NHS consultants in the UK have access to adequate training.

In addition to technical skills such as attention and manual dexterity, some non-technical skills (including situation awareness and cognitive communication) have been highlighted as contributory factors in airway management. Multidisciplinary team training has been advocated, but Covid-19 has highlighted the need for rigorous preparation for airway management through the inclusion of checklists and cross-checks, in addition to the need for highly skilled experienced airway operators to perform first-pass tracheal intubations. Although team-based training and simulation are critical to maximising successful outcomes,



F.63

Source: "2019 Global health care outlook – Shaping the future", Deloitte

training that was previously considered to be occasionally necessary has gained in importance in critical care. Clinical engineering, simulator training and objective performance measures through non-invasive wearable sensors in training and practice is becoming progressively important for patient safety, with further key roles being in extended realities, robotics, Internet of Things (IoT) and Artificial Intelligence (AI). The clinical need and potential applications extend across clinical skills in areas such as needle intervention, surgery and radiology, as well as in non-technical skills in all areas of medicine.

These societal benefits related to the healthcare domain are not specific to the European healthcare community, but impact the global healthcare community. The European challenge lies in how best to lead the way.

3.4.3 STRATEGIC ADVANTAGE FOR THE EU

Like the rest of the world, Europe is going through a healthcare digital transformation, creating a fundamental evolution in care delivery mechanisms. Digital innovation based on the EU's ECS, medtech and pharma industries can support Europe's response to some of the key technological challenges that will be discussed later in this section, as well as the societal challenges lying ahead, as summarised above.

Europe is well-positioned in terms of electronic equipment dedicated to health and care (with 19% of global production in 2017). The European healthcare industry has a number of competitive advantages in a range of economic sectors related to health and social care, as well as digital technology. For example, two of the three largest market leaders in medical equipment (Philips, Siemens and GE Healthcare) are Europe-based companies. The pharmaceutical industry is a major contributor to the European economy, with an estimated 1.4% of the EU's combined GDP and 0.9% of the region's employment (Source: EFPIA, 2019).

Programmes such as "EU4Health", which is based in Brussels, are designed to ensure that the EU remains the healthiest region in the world, offering tools promoting innovation in the health sector – making medicines, medical devices and other crisis-relevant products available and affordable, supporting innovation and addressing other important long-term challenges for health systems. This particularly includes obstacles to a broader uptake and the best use of digital innovations, as well their scaling up, as Europe needs to become faster in the translation of ideas and valid technology into economically viable solutions.

Regulators are approving a growing number of digital health therapies, unleashing innovation in digital medicine and also in AI, which has the potential to transform the key steps of clinical trial design – from study preparation to execution, towards improving trial success rates – thus lowering the pharma R&D burden. For instance, in November 2019 Germany passed a law to allow doctors to prescribe health apps, with costs being reimbursed by insurers.

The European Commission has also recently adopted a Recommendation on a European Electronic Health Record (EHR) exchange format. This Recommendation seeks to facilitate the cross-border interoperability of EHRs in the EU by supporting members states in their efforts to ensure that citizens can securely access and exchange their health data wherever they are in the EU.

However, as we have recently seen, Europe still faces difficulties in managing the shortage of ventilators and personal protective equipment (PPE). This calls for a better integration of medical resources for pandemics, as the Covid-19 crisis has provided a big impetus for enabling digital health, prompting changes that are helping tech companies and data innovators play a greater role in service delivery. Nonetheless, the digital transformation of healthcare is only at its beginning.

Europe needs to maintain this momentum and build upon digital health technologies that will support this healthcare transition to reach market maturity and wide acceptance. They can help the EU to become faster in translating ideas into economically viable solutions, and which can be further scaled up in daily health practice. These are some of the main questions that have to be addressed to achieve this:

- How can the EU prepare its healthcare system to undertake digital transformation, managing a shift in focus from acute, hospital-based care to early prevention?
- How can the EU contribute to delivering cost-effective and high-quality healthcare, maximising the patient's overall outcomes?
- How can the EU contribute to strengthening where and how healthcare is delivered, supporting home-based care?
- How can the EU support a much stronger participation of citizens in their own care process, enhancing patient engagement?
- How can the EU contribute to supporting its clinical workforce and healthcare consumers to embrace technology-enabled care?

This section on the ECS health applications of the ECS-SRIA will provide recommendations to answer these questions from the perspective of technology, with the aim to establish Europe as a global leader:

- in P4 healthcare deployment, enabling digital health platforms.
- in the healthcare system paradigm transition from treatment to health prevention, enabling the shift to value-based healthcare.

- in building a more integrated care delivery system, supporting the development of the home as the central location of the patient.
- in enhancing the access to personalised and participative treatments for chronic and lifestyle-related diseases.
- in ensuring a more healthy life for an ageing population.

3.4.4 MAJOR CHALLENGES

3.4.4.1 Major challenge 1: Enable digital health platforms based upon P4 healthcare

3.4.4.1.1 Status, vision and expected outcome

- The medtech industry is in the process of transitioning from an industry primarily producing high-end hospital equipment to one that will increasingly serve point-of-care (PoC) professionals and "health consumers", thereby moving from a product-based approach to the provision of "integrated services".
- Electronic medical technology, such as the Internet of Medical Things (IoMT), minimally invasive implants, energy-efficient devices, advanced analytics, cognitive computing for advanced clinical decision support, cybersecurity, enhanced network capabilities for continuous data access (to mention only a few of those listed below in the section "Key focus areas"), will support the deployment of P4 healthcare in a data-led environment.
- The P4 healthcare vision is therefore not only placing doctors and other health professionals at the centre of the care process, but all those relevant to the health consumer. Even if the healthcare ecosystem is operating in a highly regulated environment, by 2030 we can expect this trend to progressively become the norm. The ECS community should participate in the development of dynamic healthcare systems that learn in real time from every result, achieve a better understanding of treatment response and prognostic heterogeneity, and introduce more refined, patient-tailored approaches to disease detection, prevention and treatment.
- The P4 healthcare vision, enabling for instance early diagnostics based upon merged data and machine-learning techniques through the detection of weak signals, allows preventive treatments that are far less intensive than acute treatments and increase the chances of survival and quality of life.
- The medtech industry is not alone on this journey. New pharmaceuticals and treatments will be developed for personalised medicine settings by embedding connected devices and exploiting the potential of the IoT and AI.
- This is all creating a new industry, one that revolves around digital health platforms. This platform-based new-market disruption will enable the emergence of specialised platforms, and new players will enter the health domain. This will impact current business models in healthcare, using aggregated data to create value rather than devices – supporting, for instance, proactive services, facilitating outcome evaluation for the treatment of different therapies, and paving the way for outcome-based or pay-per-use reimbursements. This is a potential path to reducing the burden of healthcare expenditures. Electronic medical technology enabling digital health platforms based upon P4 healthcare is an enabler for the required societal shift, as highlighted by the Covid-19 crisis.

3.4.4.1.2 Key focus areas

- The addition of AI capabilities – person-centred AI-based consumer devices/embedded AI-based medical devices and systems – to Smart Things will significantly enhance their functionality and usefulness, especially when the full power of such networked devices is harnessed – a trend that is often called "edge AI". AI enables much more efficient end-to-end solutions by switching from a centralised to a distributed intelligence system, where some of the analysis carried out in the cloud is moved closer to the sensing and actions.
- This distributed approach significantly reduces both the required bandwidth for data transfer and the processing capabilities of cloud servers. It also offers data privacy advantages, as personal source data is pre-analysed and provided to service providers with a higher level of interpretation. It also offers greater reliability and safety.
- A high level of digital trust – for privacy and security by design, hardened and embedded AI models – is of course required for executing transactions in healthcare and wellbeing. Securing the IoT ecosystem is a multiple level problem. Privacy should be "by design". In general, integrating security features into an existing system can become very complex, sometimes impossible, and often increases the cost of the final product significantly. A more efficient approach is to consider those security requirements at the very beginning of a project, and then integrate them in the design and development phase. The ECS industry can assist with end-to-end solutions by providing on-chip security, supplying comprehensive hardware and software services, including authentication, data encryption and access management.
- Next-generation connectivity – better performing, more ubiquitous, accessible, secure and energy-efficient networks – will contribute to unleashing the potential of digital health. One of the main characteristics of future networks will be their increased intelligence to improve the performance of the networks, and offer sophisticated and advanced services to the users, due to edge computing and metadata, for instance.
- With the explosion of wearables and other small form-factor, battery-operated devices, very low power consumption is probably one of the biggest concerns and technology challenges for product designers. The transition from linear to circular economy will require innovative designs for the lifetime of electronic components and systems, and disruptive changes in ECS supply chains, to reduce the ecological footprint. The ECS industry will contribute to improving energy efficiency – including new, sustainable and biocompatible energy harvesting – to locally process data and the transmission of pre-processed data as opposed to the transmission of high-volume data (such as imaging data).
- As a result of improved integration and analysis of multimodal data, new tools for clinical decision-making and precision medicine will emerge, supporting early diagnostics, personalised medicine and potential curative technologies (e.g. regenerative medicine, immunotherapy for cancer).

3.4.4.2 Major challenge 2: Enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies

- A major trend in healthcare is the transformation of large healthcare systems to optimise hospital workflow: a shift from general hospitals treating any diseases towards integrated practice units that specialise in specified disease types. These units, organised around a medical condition, aim to maximise the patient's overall outcomes as efficiently as possible, increasingly through remote access, for patients anywhere in the world.

- Pay-for-cure rather than pay-for-treatment can be an effective way to increase the efficiency of healthcare by avoiding unnecessary tests, therapies and prescriptions. Combined with empowered patients, care-givers should be able to make better informed and more effective choices for treatment. To achieve this, outcomes need to cover the full cycle of care for the condition, and track the patient's health status aftercare is completed.
- This first involves the health status, relying for instance on EHRs supporting precise communication between different care-givers' PoC diagnostic systems or AI-based clinical decisions. Early diagnosis is key for the successful treatment of both modest and challenging medical conditions.
- Health outcomes are also related to the recovery and the sustainability of health. Readmission rates, level of discomfort during care, and return to normal activities should be taken into account for both providers and patients. Humanoid robots applying interpreted human body language and emotion in care delivery, sensors, the deployment of companion devices anticipating and contextualising acute or chronic conditions in EHRs involving health models describing the outcome health values for the patients, both in the short term and long term, will have a direct positive effect on readmission prevention.
- To achieve this transformation, a supporting IT platform is necessary. Historically, healthcare IT systems have been siloed by department, location, type of service, and type of data (for instance, diagnostic imaging). An innovative and efficient healthcare information infrastructure – integrating IoT with big data learning for optimising workflow, usage, capabilities and maintenance, and of course digital trust – will aggregate the different areas for efficient value-based healthcare, combining prevention tools, early detection and treatment. This will enable better measurement, and facilitate the design and implementation of new bundle-based reimbursement schemes, reducing costs while improving health outcomes.
- By 2030, value-based healthcare will enable the adoption of optimisation practices already supported by ECS technologies in the industry.

3.4.4.2.1 Key focus areas

- By 2030, clinical decision-making will be augmented by electronic medical records. Digital centres will enable advanced capabilities for clinical decision-making where AI, real-time data from portable devices (e.g. wearables and microfluidic sensors), 3D printing for surgeries, continuous clinical monitoring – including robotics to improve treatments either in the operating room, minimal invasively inside the body, at the general practitioner or at home – will support the integration of specialised care units. A large number of images will be combined with other sensor data and biomedical models to obtain precise, quantified information about the person's health condition, preventing and providing, for instance, early warnings for (combined) diseases supported by patient health models on complex health conditions. Low–latency, massive image processing is the main information source for AI-based automation, visualisation and decision support within the whole care cycle. Precise quantified imaging is needed at many levels: from molecular imaging up to whole body imaging. The development and use of accurate digital twins of the human body will enable *in silico* clinical trials, individualised computer simulations used in the development or regulatory evaluation of a medicinal product, device or intervention. While completely simulated clinical trials are not yet feasible, their development is expected to have major benefits over current *in vivo* clinical trials, which will drive further research on the subject. Moreover, "digital twins" will help in combining all the data on a personal level, and enable personalised clinical decision-making.
- Europe is a leading producer of diagnostic imaging equipment. In diagnostic imaging, to promote safety the ECS industry has begun to place great emphasis on accurate radiation dose monitoring and tracking. Healthcare providers are already applying dose management as a

part of the quality programme in their radiology departments, and patient-specific computed tomography (CT) imaging and personalisation of scan protocols will be a key aspect of patient-centred care in radiology departments, facilitating the management and control of both image quality and dose with the optimisation of 3D X-ray imaging protocols.

- The enormous capabilities of the ECS industry in miniaturisation, integration, embedded intelligence, communication and sensing will have a major impact on the next generation of smart minimally invasive devices.
  - Historically, the first revolution in minimally invasive surgery was in the early 1980s after a real-time, high-resolution video camera was developed that could be attached to an endoscope, allowing the first laparoscopic cholecystectomy in 1987 (in France, by Philippe Mouret).
  - Highly miniaturised electrical and optical systems realised using advanced cost-effective platform technologies will bring extensive imaging and sensing capabilities to these devices, and enable the second minimally invasive surgery revolution, with smart minimally invasive catheters and laparoscopic instruments for faster and more effective interventions.
  - Sensing and diagnostics solutions need to achieve appropriate sensitivity, specificity and time-to-result.
  - Reducing waste is possible through sensors made of biological materials, combining a biological component with a physicochemical detector.
  - The fusion of diagnostics and surveillance will help reducing system and operational costs.
  - To realise next-generation smart catheters, a broad spectrum of advanced ECS capabilities will need to be brought together, foremost in dedicated platforms for heterogeneous miniaturisation and integrated photonics. These can be complemented with platforms for embedded ultrasound, low-power edge computing, and AI and digital health platform integration.
  - Optical coherence tomography (OCT) is another example where ECS technologies make a critical impact, in shrinking devices and reducing costs, allowing devices to be used in wider fields beyond ophthalmology.
- Finally, it should be noted that the development of the next generation of smart minimally invasive instruments will go hand in hand with the development of new navigation techniques.
  - Breakthrough innovations in photonics are enabling optical shape-sensing techniques that can reconstruct the shape of a catheter over its entire length.
  - MEMS ultrasound technology will enable segmented large-area body conformal ultrasound transducers that are capable of imaging large parts of the body without the need for a sonographer, to guide surgeons in a multitude of minimally invasive interventions.
  - Combined with other technologies, such as flexible and conformal electronics, low power edge computing, AI and data integration into clinical systems, new optical and acoustic-based technologies will eliminate the use of x-rays during both diagnosis and interventions, enabling in-body guidance without radiation.
  - Augmented reality can be used for image-guided minimally invasive therapies providing intuitive visualisation in the catheterisation laboratory (cath lab).
- As mentioned above, outcomes should cover the full cycle of care for the condition and track the patient's health status once care has been completed. Biomarkers derived from medical images will inform on disease detection, characterisation and treatment response. Quantitative imaging biomarkers will have the potential to provide objective decision-support tools in the management pathway of patients. The ECS industry has the potential to improve the understanding of measurement variability, while systems for data acquisition and analysis need to be harmonised before quantitative imaging measurements can be used to drive clinical decisions.

- Early diagnosis through PoC diagnostic systems represents a continuously expanding emerging domain based on two simple concepts: perform frequent but accurate medical tests; and perform them closer to the patient's home. Both of these approaches lead to improved diagnostic efficiency and a considerable reduction in diagnostic costs.
  - Point-of-care testing (PoCT) methodology encompasses different approaches, from the self-monitoring of glucose or pregnancy, to testing infectious diseases or cardiac problems. However, it should be remembered that disposable PoC devices will need to be environmentally friendly in terms of plastic degradation and the replacement of potentially harmful chemicals.
  - The key enabling components of current PoCT devices must include smart and friendly interfaces, biosensors, controllers and communication systems, as well as data processing and storage.
  - The emerging lab-on-a-chip (LoC) solutions, embedding multiple sensor platforms, microfluidics and simple processing/storage elements, are currently the most promising basis for the realisation and development of accurate, versatile and friendly portable and wearable PoCT devices.
  - LoC solutions, with a simplified operation mode eliminating the constraint of molecular biology expertise to perform a real-time reverse transcription polymerase chain reaction (RT-PCR) test, will enable innovative *in vitro* diagnostic (IVD) platforms, making possible decentralisation from highly specialised clinical laboratories to any hospital lab and near-patient sites, with dedicated sample prep cartridges, a more efficient prevention (referring to the recent Covid-19 pandemic) and prompt personalised diagnosis.
- In addition, digital supply chains, automation, robotics and next-generation interoperability can drive operations management and back-office efficiencies. Using robotics to automate hospital ancillary and back-office services can generate considerable cost and time efficiencies, and also improve reliability. Robotic process automation (RPA) and AI can allow care-givers to spend more time providing care. For instance, robots can deliver medications, transport blood samples, collect diagnostic results, and schedule linen and food deliveries – either as a prescheduled task or a real-time request. Robotic processes also can be used for certain hospital revenue cycle and accounting/finance functions, such as scheduling and claims processing.

3.4.4.3 Major challenge 3: Support the development of the home as the central location of the patient, building a more integrated care delivery system

3.4.4.3.1 Status, vision and expected outcome

- We saw in the previous section the trend towards integrated practice units specialising in specific disease types. This means that certain procedures can move out of the hospital environment and into primary care and home care. Medical equipment that was previously used only in the hospital or clinic is finding its way into the home.
- For example, tremendous progress has been made since the "consumerisation" of the MEMS in developing compact, accurate, low-cost silicon sensors and actuators. This continuous innovation will support diagnostic and treatment in integrated practice units, while supporting recovery and health sustainability at home. This trend will be supported by the integration of solutions and services for specific disease groups with hospital units to optimise patient-generated health data (PGHD: continuous monitoring, clinical trials at home, etc), enhanced by the integration of heterogeneous devices and systems used at home covering parts of the care cycle (smart body patches, monitoring implants, remote sensing, etc). Solutions are needed that can be integrated

into secure health digital platforms, portable end-user devices, remote e-healthcare and AI front-ends.

- In addition, the pharmaceutical market is experiencing strong growth in the field of biologics (genomics and proteomics, as well as microarray, cell culture and monoclonal antibody technologies) that require preparation prior to administration. Smart drug delivery solutions are now based on innovative medical devices for the automated and safe preparation and administration of new fluidic therapies and biologic drugs. These use advanced ultra-low power microcontrollers that control the process reconstitution of the drug based on parameters identified by the practitioner, together with wireless bluetooth communication modules to transmit data and ensure the patient and treatment are monitored. Smart drug delivery will improve drug adherence as patients will be empowered to administer expensive and complex drugs in their own home.
- In this emerging context, care solutions need to be integrated, combining information across all phases of the continuum of care from many sources – preventing, preparing and providing care based on person-specific characteristics.
- This will support the development of applicable biomedical models for specific disease groups, for customer groups and for populations, taking heterogeneous data involving history, context or population information into account.

3.4.4.3.2 Key focus areas

- Supporting prevention, diagnosis and aftercare with sensors and actuators to ensure efficient medical decision, leveraging edge computing and imaging as described in the previous section, will be crucial. The next generation of devices will incorporate increasingly powerful edge computing capabilities. Analysing PGHD from medical devices can be synchronised with a web-based monitoring system. When aggregated, this data can be then sent to the organisation's health data analytics system to process the results and compare them to previous measurements. If the analysis uncovers negative trends in the patient's health status, it will automatically notify the care team about possible health risks. The ECS industry can play an important role here in bringing ambulatory monitoring to the next level. The following enabling technology platforms can contribute to this.
  - Low-power technology for sensors, microprocessors, data storage and wireless (microwave, optical, sound) communication modules, etc.
  - Miniaturisation and integration technologies for sensors, microprocessors, data storage and wireless communication modules, etc.
  - Advanced sensing technologies for multiplex, painless sensing with high sensitivity and reliability.
  - Printed electronics technology for textile integration and the patch-type housing of electronics.
  - Low-power edge AI computing for data analysis and reduction.
  - Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis, and with patient follow-up systems for feedback).
  - Data security technology for interoperability between security hardware and software components (end-to-end information security).
- The development of next-generation drug delivery systems will form part of the IoMT – medical devices and applications that link with healthcare systems using wireless connectivity. Smart drug delivery will improve drug adherence so that patients can administer expensive and complex (biological) drugs in their home environment. Enabling platforms are required to facilitate a

transition from the legacy mechanical components seen in current autoinjectors and wearable drug delivery pumps, to highly integrated, patch-like microsystems. These include:
- high-performance sensors and actuators for drug delivery, monitoring and control.
- on-board microfluidics for in situ preparation and delivery of formulations.
- minimally invasive needles and electrodes for transdermal interfacing, delivery and diagnostics.
- new materials, containers and power sources that will meet stringent environmental and clinical waste disposal standards.
- body-worn communication technologies for IoMT integration and clinical interfacing.
- edge AI for closed-loop control, adherence assessment and clinical trial monitoring.

- The development of low-cost, silicon-based MEMS ultrasound transducer technologies is bringing ultrasound diagnostics within the reach of the ECS industry. The ECS industry has the instruments and production technologies to transform these into high-volume consumer products, something no other industry is capable of. Personal ultrasound assisted by AI data acquisition and interpretation will allow early diagnoses in consumer and semi-professional settings, as well as in rural areas. As such, they present a huge opportunity for the ECS industry, and not only in terms square metres of silicon. It is expected that MEMS ultrasound will enable a completely new industry, with MEMS ultrasound transducers being the enabling platform technology that will drive things on. MEMS ultrasound transducers come in many flavours: capacitive micromachined ultrasound transducers (CMUT) and thin-film piezoelectric micromachined ultrasound transducers (PMUT), processed as standalone or on an application-specific integrated circuit (ASIC), etc. The second enabling platform to allow ultrasound imaging to be executed by laymen is edge AI, which can assist the user in data acquisition and data interpretation.
- Among the emerging applications of advanced medtech, “smart wound care” – i.e. the merger of highly miniaturised electronic, optical and communications technologies with conventional wound dressing materials – will allow the treatment of chronic wounds of patients in their home without the intervention of daily nursing. While much progress has been made in wearable technologies over the past decade, new platforms must be developed and integrated to enable the rapid rollout of intelligent wound care. These include:
  - flexible and low-profile electronics, including circuits, optical components, sensors and transducers, suitable for embedding within conventional dressings.
  - advanced manufacturing techniques for reliable integration of microelectronic technologies with foam- and polymer-based dressing materials.
  - biodegradable materials, substrates and power sources that will meet stringent environmental and clinical waste disposal standards.
  - body-worn communications technologies for low-power transmission of wound status.
  - edge AI to assist the clinical user in data acquisition and data interpretation.

3.4.4.4 Major challenge 4: Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases

3.4.4.4.1 Status, vision and expected outcome

- According to the World Health Organization (WHO) definition, chronic diseases are those of long duration and generally slow progression. Chronic diseases such as heart disease, stroke, cancer, chronic respiratory diseases and diabetes are by far the leading cause of mortality in Europe, representing 77% of the total disease burden and 86% of all deaths.

- These diseases are linked by common risk factors, common underlying determinants and common opportunities for intervention.
- One of the crucial means of coping with the prevalence of the chronic diseases is to achieve a more participative and personalised approach, as such diseases require the long-term monitoring of the patient's state, and therefore need individuals to take greater ownership of their state of health. Most chronic disease patients have special healthcare requirements and must visit their physicians or doctors more often than those with less serious conditions.
- Technological innovation has already been identified as a great medium to engage chronic patients in the active management of their own condition since digital health offers great convenience to such patients. Access to biomedical, environmental and lifestyle data (through cloud computing, big data and IoT, edge AI, etc) are expected to better target the delivery of healthcare and treatments to individuals, and to tailor each decision and intervention, especially for the treatment of those with multiple chronic diseases.
- Patients will be connected seamlessly to their healthcare teams, care-givers and family, as treatment adherence will be more efficient with the innovations mentioned in previous sections.
- Remote sensing and monitoring offer great promise for the prevention and very early detection of pathological symptoms. Remote sensing and monitoring have the potential to become embedded into everyday life objects, such as furniture and TV sets, while bearing in mind the constraints related to security and privacy.
- Remote patient monitoring will support clinical decisions with a reduced potential for false alarms, especially for the long-term monitoring and data analysis of patients with chronic diseases.

3.4.4.4.2 Key focus areas

- The ECS industry will need to take the initiative in the development of the next-generation treatment of chronic diseases.
  - The field of remote sensing holds great promise for the lifelong and chronic monitoring of vital signs. The deployment of remote monitoring system relies on sensors or accelerometers integrated into bed or chair, and optical sensing techniques can be used for remote reflective photoplethysmography, capacitive and radar sensing techniques. This will be multimodal, with fusing techniques to smart analytics to unify the data into usable information. The strength of remote sensing not only relies on the quality of the acquired signals, but also its potential to reveal slowly changing patterns – possibly symptoms from underlying physiological changes. The analysis of such datasets, currently largely unexplored, will provide new insights into normal versus pathological patterns of change over very long periods of time.
  - Treatment of chronic diseases will be enhanced by an upcoming generation of small and smart implantable neuromodulator devices, which are highly miniaturised, autonomous and cost-effective. These will be implanted, wirelessly powered by radio frequency (RF), microwave, ultrasound or energy harvesting with minimal side effects on the selected nerve through a simple and minimally invasive procedure to modulate the functions of organs in the treatment of pain management, brain disorders, epilepsy, heart arrhythmia, autoimmune diseases (immunomodulation), etc.
  - Organ-on-a-chip (OOC) platforms, which lie at the junction of biology and microfabrication and biology for personalised and safer medicines, are another treatment approach, addressing, for instance, pathologies currently without effective treatment (rare diseases). Often rare diseases are chronic and life-threatening, and they affect approximately 30 million people across Europe. In an OOC, the smallest functional unit of an organ is replicated. The

essential capabilities underlying the OOC field are primarily embedded microfluidics and the processing of polymers in a microfabrication environment. Smart sensors can be used as readout devices, while edge AI will be essential in data interpretation and reduction.

- For chronic diseases diagnoses, LoC-based technologies – relying on miniaturisation – show promise for improving test speed, throughput and cost-efficiency for some prominent chronic diseases: chronic respiratory diseases, diabetes, chronic kidney diseases, etc.

3.4.4.5 Major challenge 5: Ensure more healthy life years for an ageing population

3.4.4.5.1 Status, vision and expected outcome

- In the last two decades, effort has been made to enhance two important and specific objectives of smart living environment for ageing well:
  - avoid or postpone hospitalisation by optimising patient follow-up at home.
  - enable a better and faster return to their homes when hospitalisation does occur.
- Related to the first main objective – optimisation of patient follow-up at home – below are some typical examples of assistance capabilities related to major chronic diseases, and whose expansion is associated with the current ageing trend.
  - Vital signs checker: blood pressure meter, oximeter, thermometer, weight scale.
  - Hospital's software interface, the patient's file, the patient's risk alarm centre with automatic call to healthcare practitioners.
  - Video communication support (between the patient and their nurse, doctor and family), and interactive modules for the patient (administrative, activities, menus, medical bot chat, etc).
  - Authentication and geolocation of patients, with patient or patient's family consent.
  - Teleconsultation for nights and weekends at the foot of the bed of patient's hospital or retirement home.
- The second objective – smooth home return – relates to suitable technical assistance in addition to human assistance:
  - Enhance the patient's quality of life and autonomy.
  - Improve the patient's safety and follow-up in their room through a reinforced work organisation.
  - Allow monitoring of the patient's progress to motivate them during their rehabilitation period.
  - Minimally invasive therapies allowing for shorter hospital stays and improved patient wellbeing.
  - First-time-right precision diagnoses to prevent hospital readmissions.
  - Prepare for the return home: patient support in appropriating technical aids by integrating these solutions into rehabilitation.
- Efforts are being made to enhance medical and social care services through different kinds of robots. The purpose here is to provide advanced assisted living services via a general purpose robot as an autonomous interaction device that can access all available knowledge and cooperate with digital appliances in the home. In this sense, autonomous mobile robots offer several advantages compared to the current (stationary) Ambient Assisted Living (AAL) solutions. Due to sensor-augmented user interfaces, human computer interaction is becoming increasingly natural. As a consequence, robots will come to represent a familiar metaphor for most people.
- Neurorehabilitation is sometimes required after hospitalisation. Neurorehabilitation is generally a very complex and challenging undertaking involving "successes" and "failures" (setbacks).

Neurological patients typically report having "good days and bad days", which affect performance, motivation and stamina, and where cognitive stimulation (AI-based speech producing programs, social robots, etc), for example, has the potential to improve the efficiency of neurorehabilitation and relieve some of the pressure on health systems. Robotics is well suited for precise, repetitive labour, and its application in neurorehabilitation has been very successful. This is one of the main reasons why the rehabilitation robotics market has tripled over the last five years and, today, rehabilitation robotics is one of the fastest growing segments of the robotics industry. This industry is dominated by European companies that can deliver highly innovative solutions with a strong scientific basis and exceptional manufacturing quality. Based on market size and need, it is projected that the compound annual growth rate (CAGR) for rehabilitation robotics will soon reach between 20% and 50%.

3.4.4.5.2 Key focus areas

- The ECS industry can significantly upscale the "ageing well" area, as it is enabled by most of the focus topics developed in the previous sections. The industry is playing an important role in bringing ambulatory monitoring to the next level. Important aspects here are reducing costs, improving user friendliness (e.g. easy to wear/use devices, interoperable gateways, reduction of patient follow-up systems) and data security.
- The enabling technology platforms detailed below are expected to significantly contribute to this prevalence of the ECS industry in ageing well, taking into account that ageing well is very much related to "ageing in place":
  - Low-power technology for sensors, microprocessors, data storage and wireless communication modules, etc.
  - Miniaturisation technology for sensors, microprocessors, data storage and wireless communication modules, etc.
  - Printed electronics technology for textile integration and patch-type housing of electronics;
  - Low-power edge AI computing for data analysis and data reduction.
  - Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis and with patient follow-up systems for feedback).
  - Data security technology for interoperability between security hardware and software components.
  - Robotics systems enabling patients to overcome loneliness or mental healthcare issues.
- Interoperability is surely the main challenge faced by the ECS industry in achieving full impact due to the vast heterogeneity of IoT systems and elements at all levels. Interoperability and standardisation need to be elaborated in relation to data and aggregated information. Thus, it is not enough to be able to receive a message, i.e. to understand the syntax of the message, but it is also necessary to understand the semantics. This requirement implies the development of a data model that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons. It must be based on several relatively simple principles: creation of formats and protocols for exchange of data records between healthcare information systems; format standardisation and connected interface unification; improvement of communication efficiency; a guide for dialogue between involved parties at interface specification; minimisation of different interfaces; and minimisation of expenses for interface implementation.

3.4.5
TIMELINE

The following table illustrates the roadmaps for **Health and Wellbeing**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Establish Europe as a global leader in personalised medicine deployment	**Topic 1:** Enable digital health platforms based upon P4 healthcare	• IoMT-enabling patient-generated health data • Expansion of AI on the edge • High level of digital trust – privacy and security by design, hardened embedded AI models
Major challenge 2: Lead the healthcare system paradigm shift from treatment to health promotion and prevention	**Topic 2:** Enable the shift to value-based healthcare	• Disease detection from biomarkers derived from medical images and sensors • Predictable and repeatable outcome of diagnostic imaging • Digital supply chains, automation, robotics, and next-generation interoperability • Early diagnosis through PoC diagnostic systems
Major challenge 3: Home becomes the central location of the "healthcare consumer"	**Topic 3:** Build an integrated care delivery system	• Use heterogeneous data from more sources (patient-generated health data, edge computing and imaging to ensure efficient medical decisions, etc) • Remote decentralised clinical trials development (smart body patches, monitoring implants for continuous monitoring, etc)
Major challenge 4: ECS industry supports EU strategy to tackle chronic diseases	**Topic 4:** Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases	• Accurate long-term monitoring and data analysis of patients with chronic diseases and co-morbidities • Make treatment adherence more efficient (smart drug delivery based on innovative medical devices, etc)
Major challenge5: ECS industry fosters innovation and digital transformation in active and healthy ageing	**Topic 5:** Ensure more healthy life years for an ageing population	• Optimisation of patient follow-up at home to support ageing in place (remote patient monitoring, geolocalisation, etc)

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Development of multimodal data analysis • Improvement of energy efficiency (energy harvesting, etc) • Secure digital health platforms, portable end-user devices, remote e-healthcare and AI front-ends	• New tools for clinical decision-making and precision medicine • Scalable digital health platforms
• Clinical decision-making augmented by a combination of electronic medical records[113], imaging, biomedical models • EHRs supporting precise communication between different care-givers, PoC diagnostic systems or AI-based clinical decisions • Efficient healthcare information infrastructure, lowering costs while improving health outcomes	• Shift from general hospital to specialised integrated practice units • Next generation of smart minimally invasive devices • Disease detection from biomarkers derived from medical images • Outcomes cover the full cycle of care for the condition, and track the patient's health status after care is completed
• Next-generation drug delivery systems (highly integrated, patch-like microsystems) will form part of the IoMT	• Care solutions integrated, combining information across all phases of the continuum of care, preventing, preparing and providing care based on person-specific characteristics • Holistic healthcare involving all imbalanced health situations of the patient
• Development of active or passive implantable medical devices for chronic disorders	• OOC platforms addressing pathologies currently without effective treatment (rare diseases)
• Suitable technical assistance in addition to human assistance (humanoid robots, advanced assisted living, rehabilitation robotics, etc) • Precision diagnosis to prevent hospital readmissions	• Data model diffusion that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons

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113 *Electronic medical record (EMR): A computerised database that typically includes demographic, past medical and surgical, preventive, laboratory and radiographic, and drug information about a patient. It is the repository for active notations about a patient's health. Most EMRs also contain billing and insurance information, and other accounting tools.*

3.4.6
SYNERGY WITH OTHER THEMES

Close collaboration will be useful in all application areas – for example, **Energy, Mobility, Digital Industry, Agrifood and Natural Resources** and **Digital Society** – based on cross-sectional technologies such as **Artificial Intelligence, Edge Computing and Advanced Control, Connectivity** and, of course, **Quality, Reliability, Safety and Cybersecurity.**

More specifically:

- Related to digital industry, "bio-production", which has the objective of developing an innovative field to produce the biologic products of the future through the implementation of disruptive technologies, should be an important topic to address in future years.
- The relationship between food systems and health is obvious and well-identified, especially in preventative health. This is an aspect that needs to followed up to reinforce health prevention in the long term.
- In terms of energy and connectivity, it is important to consider the impact of innovative wearables and implantables, sensors and actuators in general, as they represent a crucial sector with a direct impact on the further development of digital health.
- Embedded systems are an essential enabler of healthcare digital transformation. The challenges are defined in the transversal section **Quality, Reliability, Safety and Cybersecurity**, with the aim of ensuring hardware quality and reliability, dependability in connected software, human/ systems interaction and, again, the required privacy and cybersecurity to share the necessary requirements to support the expansion of digital health.

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3.5

ECS Key Application Areas

AGRIFOOD AND NATURAL RESOURCES

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114 *FAO UN: The Future of Food and Agriculture, 2017.*

3.5.1
SCOPE

Smart Internet of Things (IoT) systems are vital for the sustainable production and consumption of safe and healthy food, as well as for sustainable practices in agriculture, livestock, aquaculture, fisheries and forestry. They can also foster access to clean water, fertile soil and healthy air for all, in addition to helping preserve biodiversity and restore the planet's ecosystems.

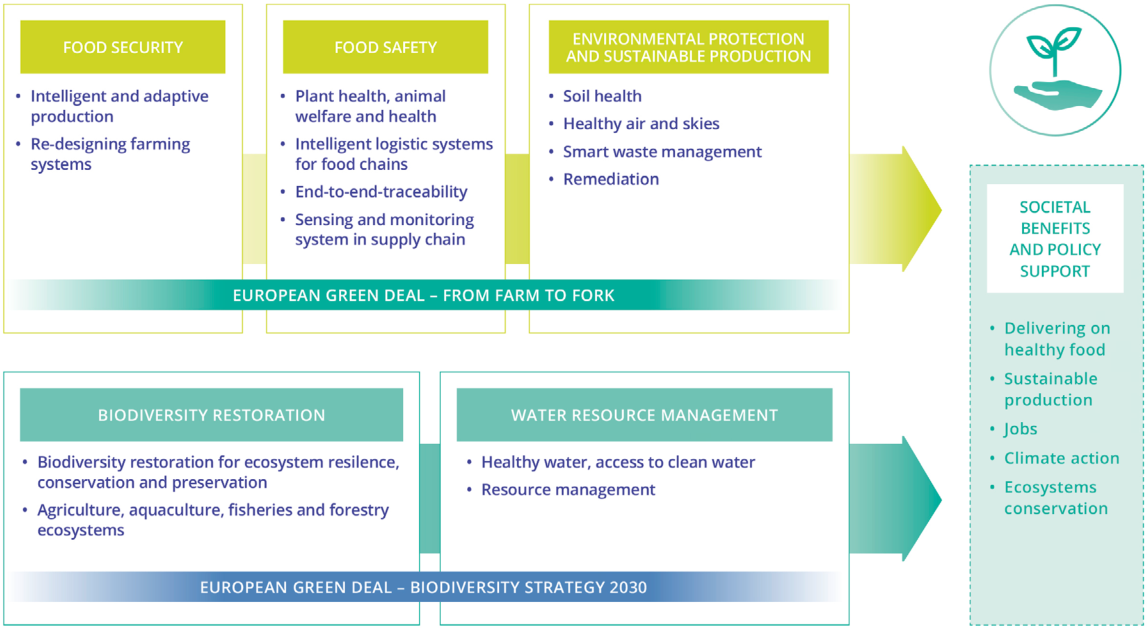
The first two **Major challenges** relate to livestock and crop health, and also to farming systems and food supply chain assurance and management. For instance, IoT system technologies can be used in pest management or towards minimising the use of antibiotics. Farming systems and food supply chain management will benefit from smart IoT systems, including the use of traceability frameworks, and from robots and drones, to revolutionise modern agriculture and food production. The third **Major challenge** addresses issues such as soil health, air quality and the environment in general, all in terms of smart integrated monitoring technologies, and the use of smart waste management systems and remediation methodologies. The objective is to protect the environment to reduce the destruction of ecosystems caused by a myriad of anthropogenic activities. The fourth **Major challenge** refers to the key role that IoT systems can play in water quality monitoring and access to clean water. An important aspect here is the overall management of water usage, as well as smart treatments to foster the circular use of wastewater, rainwater and storms/floods. In the last **Major challenge,** biodiversity restoration for ecosystem resilience, conservation and preservation address how electronic components and systems (ECS) can contribute to the restoration/preservation of a greater variety of crops, and greater fauna and flora species diversity, to ensure the natural sustainability of healthy ecosystems (agriculture, aquaculture, fisheries and forestry) by enabling them to better withstand and recover from disasters.

All five **Major challenges** in this section align with key Horizon Europe missions, as well as the European Green Deal and future digitalisation technologies. To master these challenges significant advances are crucial in the new fields of materials, manufacturing technologies, information and communications technology (ICT), Artificial Intelligence (AI), robotics, electronics and photonics, and other technologies, as well as in circular industries.

3.5.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

External requirements

According to the UN, if the global population reaches an expected 9.6 billion by 2050, the equivalent of almost three Earth planets could be required to provide the natural resources needed to sustain current lifestyles. Increasing food production is driven not only by population growth, but also by more demanding diets as populations become wealthier. On the other hand, productivity is being hit hard by climate change in regions where food scarcity and inefficient resource management is most prevalent. The necessary acceleration in productivity growth is being hampered by the degradation of natural resources, a reduction in biodiversity, and the spread of transboundary pests and diseases of plants and animals, some of which are becoming resistant to antimicrobials[114]. Investment in changing agricultural practices, incorporating technological innovations, has boosted productivity, but the yield growth is far from sufficient. A more



F.64 *Main agrifood and natural resources goals and associated challenges*

holistic and innovative approach is needed to reduce the strain on natural resources and enhance their quality, while also increasing food productivity. At the same time, food losses and waste claim a significant proportion of agricultural output, whereas poor bio-waste management and packaging is increasing environmental pollution.

Addressing the key issues on food security and sustainable production would lessen the need for production increases while improving the natural resource base. For example, mitigating the effect of natural and human pressures on water bodies is a priority, namely by reducing as much as possible general pollution and plastics, eutrophication, acidification and warming up. Less than 2.5% of the world's water is fresh[115], and water pollution in rivers and lakes is occurring faster than nature can recycle and purify. Currently, more than 2 billion people live with the risk of reduced access to freshwater resources[116], and by 2050 at least one in four people is likely to live in a country affected by chronic or recurring shortages of freshwater. At the moment, 2.6 billion people are economically dependent on agriculture[117] despite 52% of arable land being moderately or severely affected by soil degradation. Air quality has also been deteriorating in both rural and urban areas as a result of the spread of particulate matter in addition to the release of greenhouse gases (GHGs) and their effect on climate.

Today, farmers still spread much more fertiliser on their fields than is required. Consequently, nutrients such as nitrates and phosphates, which cannot be absorbed by the plants, accumulate in the soil and

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115 *All about water, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull53-1/53105911720.pdf*

116 *UN 2019 The Sustainable Development Goals Report 2019: Goal 6: Clean water and sanitation/https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf*

117 *ibid: Goal 15.*

filter into groundwater with a dramatic impact on the environment and public health. Therefore, there is increasing pressure on the agricultural industry to find sustainable solutions for reducing environmental pollution caused by fertilisation. On the other hand, smart production processes and intelligent logistic systems across the whole supply chain can yield further optimisations in an effort to keep emissions constant with increased productivity, while ensuring safe food. Every year, almost one in 10 people will fall ill due to foodborne diseases[118].

Societal benefits

Due to the challenges that the world is facing, the UN has defined several Sustainable Development Goals (SDGs) that are a blueprint to achieving a better and more sustainable future for all. The SDG implementation plans address the global challenges we face in protecting biodiversity, our natural resources and acting on climate change. Furthermore, it includes actions relating to socioeconomic drivers aiming at eliminating poverty, hunger, inequality, and achieving responsible consumption and production, sustainable prosperity, peace and justice. In Europe, national and EU policies such as "From Farm to Fork" [119] and "Biodiversity Strategy 2030" [120] reflect and amplify the underlying objectives with a set of measures – from regulatory frameworks to incentives and investments for development, and the deployment of holistic innovative approaches in a circular economy, agroecology, agroforestry, climate-smart and sustainable agriculture, bioeconomy and the Blue Economy.

3.5.3
STRATEGIC ADVANTAGE FOR THE EU

Within the next framework programme on research and innovation by Horizon Europe, it is envisioned that Europe will achieve high-impact missions on: "adaptation to climate change including societal transformation", "cancer", "healthy oceans, seas, coastal and inland waters", "climate-neutral and smart cities" and "soil health and food".

Innovative solutions based on IoT systems have a significant socioeconomic impact for the EU in rural, coastal and urban areas. For instance, agriculture is being transformed by the IoT revolution, with the use of smart devices allowing farmers to better control the process of raising livestock and growing crops. As a result, quality and safety in food production are rapidly evolving, becoming more predictable and efficient than ever. According to the European Innovation Partnership "Agricultural Productivity and Sustainability" (EIP-AGRI)[121], the digitalisation of rural areas can help to improve the

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118 *Food safety - World Health Organisation at https://www.who.int/news-room/fact-sheets/detail/food-safety*

119 *https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf*

120 *https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN*

121 *https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-seminar-multi-level-strategies-digitising-0*

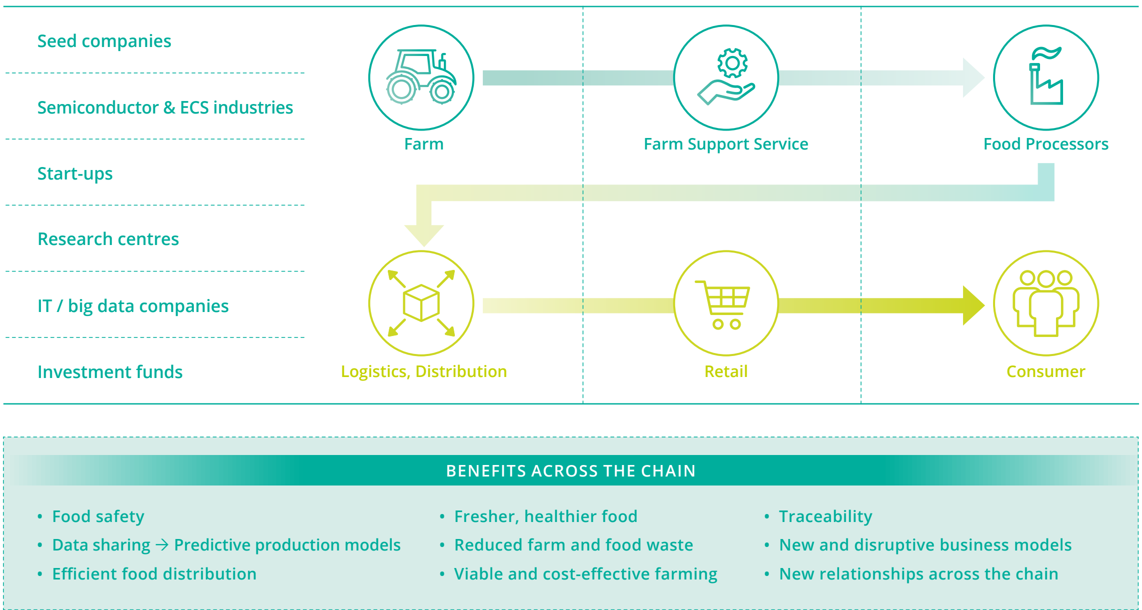
economic and environmental sustainability of the agricultural sector. Moreover, it can make farming more attractive for young people, improve the quality of life of farmers and multiply the number of rural businesses. Consequently, rural depopulation could be greatly reduced.

For instance, the Smart Water Management (SWM) project [122] points to an acceleration in the deployment of smart water networks with the aim of upgrading the reliability, efficiency, quality control, sustainability and resilience of drinking water supply services while also educating end-users on the benefits of water conservation. Strategies of this nature could represent the solution for urbanisation-related issues (scarcity, pollution, etc.) by providing a better use of our water resources while protecting the most vulnerable places, and by creating innovative types of economy and management.

Developments in smart IoT systems for agriculture and food production based on innovative and advanced ECS will strongly contribute to reach of the objectives set by the European Green Deal and the EU's Biodiversity Strategy for 2030. These will be enabled the following three sets of main actions and respective targets.

01. **From Farm to Fork:**
    Moving towards a fair healthy and environmentally friendly EU food system by 2030 through the targets listed in *Figure F.66/Topic 1* [123].
02. **Natural resources**
    Figure F.66/Topic 2: Targets set for natural resources
03. **EU Biodiversity Strategy for 2030**
    Figure F.66/Topic 3: Targets set in Biodiversity Strategy for 2030 [124]

Figure F.65 depicts the agrifood value chain and the main actors involved, along with a list of the benefits obtained for farmers and consumers by using smart IoT systems. Moreover, the advanced technology applied throughout the whole chain will bring new market opportunities for the European semiconductor and ECS industries.



F.65 *Agrifood value chain (Source: STMicroelectronics adoption of AIOTI graphics)*

TOPIC	TARGET ACTIONS	MAIN GOALS
Topic 1: From Farm to Fork	**Target actions 1.1:** Reduce the use of pesticides in agriculture that contribute to the pollution of soil, water and air	• Reduce by 50% the use and risk of chemical pesticides by 2030 • Reduce by 50% the use of more hazardous pesticides by 2030
	Target actions 1.2: The excess of nutrients in the environment as a major source of air, soil and water pollution, negatively impacting biodiversity and climate	• Reduce nutrient losses by at least 50%, while ensuring no deterioration in soil fertility • Reduce fertiliser use by at least 20% by 2030
	Target actions 1.3: Antimicrobial resistance linked to the use of antimicrobials in animal and human health leads to an estimated 33,000 human deaths in the EU each year	• Reduce by 50% the sale of antimicrobials for farmed animals and in aquaculture by 2030
	Target actions 1.4: Organic farming as an environmentally friendly practice that needs to be further developed in the EU each year	• Boost the development of EU organic farming areas to achieve 25% of total farmland under organic farming by 2030
Topic 2: Natural resources	**Target actions 2.1:** Optimisation and remediation towards climate-neutrality – first step for 2030 and then 2050, through:	• Reduction of water pollution and GHG emissions, including methane and nitrous oxide • Reduction of European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agricultural and halting biodiversity erosion
Topic 3: EU Biodiversity Strategy for 2030	**Target actions 3.1:** Establish protected areas	• For at least 30% of land in Europe • For at least 30% of sea area in Europe
	Target actions 3.2: Restore degraded ecosystems at land and sea across the whole of Europe	• Increasing organic farming and biodiversity-rich landscape features on agricultural land • Halting and reversing the decline of pollinators • Restoring at least 25,000 km of EU rivers to a free-flowing state • Reducing the use and risk of pesticides by 50% by 2030 • Planting three billion trees by 2030

F.66

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[122] *https://www.iwra.org/swmreport/*

[123] *https://ec.europa.eu/commission/presscorner/detail/en/fs_20_908*

[124] *Facsheet EU-Biodiversity-strategy-en.pdf,*
https://ec.europa.eu/commission/presscorner/detail/en/fs_20_906

3.5.4
MAJOR CHALLENGES

This section discusses five **Major challenges** that need to be addressed in the domain of agriculture (food security, food safety, environmental protection and sustainable production), natural resources and biodiversity, and how smart IoT systems and associated key enabling technologies can help achieve them.

3.5.4.1 Major challenge 1: Food security

To define the difference between food security[125] and food safety[126], *Figure F.67* presents the interrelation between both concepts, as well as their main constituent elements. This section and the next will address the challenges related to food security and food safety from an ECS perspective.

F.67 *Food security versus food safety*

3.5.4.1.1 Status, vision and expected outcome

Consolidated advances in Industrial Internet of Things (IIoT) have already started to shape smart manufacturing in the food and beverage[127] industry. The access to relevant and role-based information, in real time or near-real time, is key to ensuring not only the efficient storage and processing of data, but also their appropriate use for optimised decision-making at every level of next-generation automation systems and robotics (e.g. cyber-physical systems, CPS). Therefore, sustainable production, safety and quality do not only depend on the product itself, but on the respective processes and their control as offered by key data gathering and monitoring, smart sensing, data analysis and diagnostics systems. Ultimately, intelligent food production can take into account the consumer needs of each market, and such systems can provide intelligent recommendations for adjusting the amount and quality of food accordingly, assuring food security (i.e. enough food for each market) and food safety (i.e. healthy food), and also taking into account environmental concerns and societal impact.

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125 *Food security has been defined by the FAO as "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life".*

126 *Food safety is an umbrella term that encompasses many facets of handling, preparation, and storage of food to prevent illness and injury. Included under the umbrella are chemical, microphysical and microbiological aspects of food safety.*

127 *Beverage will be considered as food for the rest of this section.*

3.5.4.1.2 Intelligent and adaptive food production

To develop intelligent food production systems, solutions are required in (but not limited to) the following fields.

- In-line inspection, networked packaging systems and robot technology in the warehouse to allow for a smart workflow to manage, monitor, optimise and automate all processes accordingly.
- Intelligent control room systems to enable correlations between machine malfunctions and load parameters to be detected immediately, thereby enabling maintenance work to be carried out early and on schedule, with a reduction in costly downtimes.
- Food industry imposes specific requirements (e.g. in food processing) that may take advantage of smart (bio-)sensing for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
- AI/machine learning (ML) and big data models must be devised and used to offer further intelligent decision-making and, whenever possible, should be employed directly at-the-edge for greater energy efficiency.
- IIoT systems can provide the flexibility to tailor-make new products to help cope with ever-demanding diets.

3.5.4.1.3 Re-designing farming systems

Precision farming systems

Advanced farming machines and robotic collaborative systems are needed for cost-effective land and livestock management, as well as for large-scale arable and fruit crops, as tasks can thereby be performed in parallel, enabling economies of scale. Advanced machines include the following.

- Harvesting robotic systems: Autonomous robots or swarms of robots can replace intensive and strenuous labour practices as the worldwide population transitions from rural to urban areas and manual labour declines. Agricultural robots need to be equipped with improved capabilities for sensing and perception. Special attention must be paid to safety aspects for those robots expected to work collaboratively with humans or close to livestock.
- Drones: Remotely piloted autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, can mainly improve efficiency in two application areas: (i) monitoring large areas with intelligent computer vision devices to provide a higher level of detail and on-demand images, especially as drones can overcome limitations of satellite imagery (e.g. images below forest cover); and (ii) in the use of phytosanitary products to increase efficiency and reduce environmental impact by avoiding indiscriminate chemical dispersion, and following predetermined prescription maps.
- Satellites: These allow for improved information regarding fields, although a combination of data from further sensors with increased update frequency, improved performance and spatial resolution would also be needed.

All the proposed solutions should meet important requirements such as cost-efficiency, compactness, reliability, low power, interoperability with existing machinery, and human factors. Furthermore, training systems based on augmented reality, virtual reality and simulators are needed for training people (e.g. operators) independent of seasonality or safety issues.

Horticulture/greenhouses, urban and vertical indoor agriculture

Urban agriculture is being promoted as a promising option for sustainable food, a better quality of life, and community engagement. The goal of this modern version of agriculture is to grow and deliver high-quality food with a minimal waste of resources.

Many crops in vertical indoor farms are often cultivated using hydroponics, a technique where there is no need of soil and fertiliser as the growing plants are supplied with irrigation water. In fact, recent environmental challenges have promoted the intensification of "soil-less agriculture" in an urban context to decrease the negative impact on nature. Even if hydroponics produces quality crops with high efficiency, there is an area of opportunity here to better monitor and control the fertiliser components in the irrigation water, such as through the development of:

- novel and low-cost online sensors for optimised control, such as nutrient sensors to enable smaller discharge of fertiliser into natural waters.
- robots with a high precision level to perform automatic harvesting to reduce the overall production costs, which are currently high, to be competitive with traditional agriculture.
- autonomous indoor farming systems in which cultivation is controlled remotely via AI, based on measurements of crop properties with the help of intelligent sensors and AI-based digital twin models of such plants.

3.5.4.2 Major challenge 2: Food safety

3.5.4.2.1 Status, vision and expected outcome

Key for the next generation of novel ecology-based agricultural systems is the use of high-tech sensors and AI to monitor, quantify and understand individual plants and animals, as well as their variability, to ensure food safety. This requires smart sensors and monitoring technology that can adapt to the unpredictability and variation of living systems. It will require integrated digital technology solutions such as ecology-based robotic systems that can control the bio-physical processes (including growing conditions) and understand the biological environment (for plants and animals). However, innovative ecology-based robotic systems' manipulation of operations is a huge challenge in environments that are only modestly defined and structured.

Furthermore, detection in the supply chain and "at the fork" should be also considered. This implies low-cost compact sensors, connected to information processing systems used in the food supply chain and by consumers, that allow, for instance, freshness and food safety detection for meat and vegetables (such as integrated into a smartphone).

3.5.4.2.2 Crops quality and health

Integrated pest management (IPM)

Novel IPM strategies are needed to detect diseases and prevent their spread in crop production for European organic and conventional agriculture, and to increase organic farming and horticultural systems. Improved IPM will require developments in the following fields.

- Smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced) – e.g. weather/climate information for predictive models providing risk assessments and decision support for IPM.
- IoT devices specialising in pests and disease measurements, such as insect traps and other systems based on image recognition or AI models.

Agro-ecology based: Move from conventional to organic, regenerative agriculture

To support the EU's "From Farm to Fork" implementation, smart ECS can help farmers to drastically decrease the use of pesticides and their impact on human health and the environment. This will require:

- development of cost-effective and intelligent intra-row, herbicide-free weeding techniques using advanced robots and robot fleets for individual plant recognition with high precision based on advanced (vision) sensor technologies and AI algorithms working under in-field conditions.
- development of smart sensors to monitor the quality of spraying, as this is essential for biocontrol products and contact pesticides.
- integration into the same framework of decision-support tools and precision agriculture tools to simplify farm management, improve crop quality and reduce costs.

Plant precision breeding and plant phenotyping

The development of smart technologies can support precision plant breeding and phenotyping. These could be nanotechnology solutions or smart sensor solutions to support the following.

- Genomics and transcriptomics: DNA-informed breeding, gene editing, genome prediction, breeding optimisation, phenotyping and seed sowing optimisation.
- Large-scale and high-precision measurements of plant growth, architecture and composition: These are required to optimise plant breeding by increasing our understanding of the genetic control and response of plants to their environment. These sensor systems should allow the study of plants in relation to biotic and abiotic factors, including plant–microbiome interactions, plant–plant competition, plant diseases and exposure to a multitude of variable abiotic environmental conditions – such as light quality, irradiance levels, nutrient supply, temperature, humidity, soil pH and atmospheric CO_2 levels.

3.5.4.2.3 Livestock welfare and health

Livestock health is crucial for food safety. Healthy animals should not need antibiotics, and their reduced use would decrease the risk of transmission of diseases to humans by healthy animals. Animal welfare is also an important concern for a growing number of consumers.

These two aspects are drivers for investing in better sensing systems for animal monitoring. Combined with data intelligence solutions, this will improve animal health and welfare, resulting in more animal-friendly production, higher efficiency, better quality and improved food control safety.
They should include, for instance:

- wearable sensors at the farm/barn level, and ambience sensors during cattle transport.
- smart sensor systems to monitor animal activity, such as individual or group behaviour, to provide useful information for the early detection of diseases and to increase animal wellbeing.
- smart sensor systems for the rapid verification of bacterial infection and behavioural observations to control disease spread and support clinical and veterinary stakeholders to effect suitable therapeutic interventions when required; body temperature can also be monitored for early disease detection to reduce antibiotics use.

3.5.4.2.4 Food chain

Intelligent logistic systems, including sensing and monitoring for food chains

Logistics are a critical component of the food chain. It does not only determine the reach of distribution, but logistics delays and conditions profoundly affect the quality and safety of the products received by consumers, and can result in food loss and waste in the supply chain.

Smart real-time sensing, monitoring and control systems in the food supply chain will safeguard food quality and food safety, while eventually reducing food losses in the supply chain. Therefore, technological solutions are required, but not limited to:

- systems for monitoring and controlling food quality during transport and storage (e.g. temperature in cold chain monitoring, moisture, controlled atmosphere, ethanol, ethylene), which should be efficient and interoperable along the logistics chain.
- predictive systems of the quality of (perishable) food products in the supply chain, providing real-time decision-support based on actual sensor measurements, supply chain data and AI models.
- transport route optimisation, considering not only time and cost, but also external conditions and the intrinsic properties of the products being transported.

These needs are strongly related with traceability, as shown below.

End-to-end food traceability

Food and beverage manufacturers and producers are faced with increasingly complex and fragmented supply chains, stricter regulation and more demanding consumers. Regulatory compliance, competitive advantage, brand reputation and costs have made product traceability a priority and end-to-end traceability a major challenge. In today's globalised world where people of any origin live across every country, the source of food products and ingredients, as well as their certification, are a major concern/priority for consumers. Therefore, traceability should also encompass certifying food origin and not be restricted to tracking across the supply chain. End-to-end traceability solutions are required, but should not be limited to:

- integrating blockchain into current technology to prevent fraud and counterfeiting.
- traceability to increase alignment between production and individual consumer demands, leading to more personalised nutrition support.
- traceability to optimise distance between farm and fork – although many products are produced preferentially in specific parts of the world, there are also many examples of food that could be produced economically closer to consumers.

To this end, as IoT solutions are increasingly being deployed, integrated hardware systems need to deliver mobility, connectivity, long lifetime autonomous sensing and AI-based intelligence at-the-edge, edge and/or cloud analytics and cybersecurity, complying with privacy regulations when applicable, on a plug-and-play, open, interoperable architecture and platform.

3.5.4.3 Major challenge 3: Environmental protection and sustainable production

3.5.4.3.1 Status, vision and expected outcome

EU regulations, together with consumers' increased interest in organic food, is compelling farmers to drastically decrease the use of pesticides to reduce the risks and impact on human health and the environment, as well as to undercut the maximum residue levels of pesticides. Pesticides are found not only in drinking water[128] but also in food and beverage. Lively debates have shown that our society demands alternatives to pesticides to help preserve the environment and improve food quality.

Drastic reduction in the use of pesticides is one of the major goals of the EU's agricultural policy, with some countries planning to halve their pesticide use by 2025 (e.g. ecophyto plans[129] in France, and the Aktionsplan Pflanzenschutzmittel[130] in Switzerland). The EU Farm to Fork strategy also aims to implement a plan that significantly reduces the risks from chemical pesticides, as well as the use of fertilisers and antibiotics, and to increase the amount of organic farming carried out in Europe.

3.5.4.3.2 Soil health

The in situ real-time monitoring of soil nutrients and herbicides

The optimal use of chemical fertilisers and organic manures to deliver the required increase in food production requires a complete understanding of applied nitrogen- and phosphorous-based nutrients with a much greater spatial and temporal resolution than is available today. Current methods of soil analysis do not provide real-time in situ nutrient analysis in fine detail, and delays in receiving soil results are common because of backlogs in commercial labs due to high sample volumes, thus reducing the value of the soil test results for the farmer. Moreover, herbicides are another huge problem due to their environmental and health impact. To solve these issues, the following approaches could be explored.

- Intelligent sensors (with miniaturised and ultra-low power consumption components) must be developed to deliver measurements in situ and in real time of soil nutrients at parts per million (ppm) concentrations. Such devices must have the appropriate packaging to extract water from the soil and to able to be buried in the soil for long periods of time. To optimise effectiveness, low proximity sensors should be combined with optical sensors and high proximity sensors to retrieve the maximum amount of information on soil health.
- IoT systems with edge and/or cloud-based data analytics are also necessary to provide farmers with decision-support regarding fertilisation strategies, by translating measurements into meaningful agronomic indicators and respective measures. These strategies should prioritise the use of organic fertilisers and the gradual reduction of chemical fertilisers until completely eliminated to restore the biodiversity contribution in the preservation of soil health. Furthermore, this type of system should detect weeds, preserve the "good ones" and eradicate those that are competing with the crop in question. This requires low-cost vision technologies (not only red/green/blue (RGB), but also 3D, hyperspectral imaging, etc) and edge AI for in situ real-time recognition.

3.5.4.3.3 Healthy air and skies

Sensors and diagnostics for air quality monitoring (indoor, urban and rural)

According to the World Health Organization, the air we breathe is growing dangerously polluted: nine out of ten people now breathe polluted air, which kills seven million people every year. In fact, there has been much progress on identifying and reducing the sources of air pollution at lower concentrations and with higher spatial coverage. This is necessary to provide adequate data on what people are breathing, and to provide localised as well as holistic solutions. Microsensors and/

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[128] *https://ree.developpement-durable.gouv.fr/donnees-et-ressources/ressources/cartes/article/nombre-des-pesticides-trouves-par-masse-d-eau-et-leur-classement-selon-le-taux*

[129] *Ministère de l'Agriculture, Le Plan Ecophyto, qu'est-ce que c'est? https://agriculture.gouv.fr/le-plan-ecophyto-quest-ce-que-cest*

[130] *Aktionsplan Pflanzenschutzmittel, https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/pflanzenschutz/aktionsplan.html*

or mini-stations can be used during fieldwork campaigns in cities, but there are technical problems relating to power source, data transmission, data storage, and data handling and assessment. Besides, local measures are not always effective since local concentrations of particulate matter may be influenced by long-range transported pollutants from agricultural activities occurring outside city boundaries.

Similarly, while indoor air quality has been shown to unambiguously impact the wellness and performance of people, there is also a lack of spatial granularity and a significant lag between exposures and sensing, actuation and management interventions for risk mitigation. In addition to indoors, air quality is made more complex by the interaction between indoor and outdoor air, emissions from buildings and their contents (paints, furniture, heating and cooling systems, etc), human activities (breathing, cooking, cleaning, etc) and the effects of long-term exposure to low concentrations of volatile organic compounds. These issues necessitate the development and deployment of real-time intelligent multi-sensor technologies with high selectivity and embedded (re-)calibration techniques. These should be combined with a monitoring network (edge-based) as part of the indoor infrastructure to provide the spatial and temporal information needed for specific, targeted and appropriate actions. Such actions should also include public awareness and the promotion of behavioural changes.

Smart systems for controlling and preventing GHG emissions

Strong evidence has been accumulated on the climate emergency resulting from human activities that add GHGs to the Earth's atmosphere. The EU is the world's third biggest GHG emitter after China and the US. Although several measures have been taken since the Paris Agreement, breakthrough technologies and state-of-the-art deployment is still needed across the transport sector and several industries with a high emission footprint to achieve a further reduction in emissions. These would be facilitated by the following.

- Smart systems and digitalisation to improve industrial processes performance and energy/ resource efficiency towards a low-carbon economy, while reducing the impact of mobility and agricultural processes on the environment and human health, thereby controlling and preventing GHGs.
- A focus on the GHG emissions from animals by investigating microbiological sensing technologies on or in animals (in their rumens, for instance) to increase efficiency while reducing environmental impact, as well as performing analysis of the gathered data to support decision-making for mitigation measures (for instance, leading to change in feed).

3.5.4.3.4 Smart waste management

Integrated bio-waste systems

Despite proactive European policies and regulations [131], effective bio-waste management remains a challenge. For instance, 14 member states have been identified as at risk of missing the 2020 target of 50% preparation for the re-use/recycling of municipal waste. Reducing, recycling and reusing food/kitchen waste requires significant progress in technological solutions along with strong policy-making and shifting community behaviour. These solutions could be based on the following.

- Smart monitoring, controlling waste treatment units in real time as well as gas emissions in landfills and anaerobic digestion monitoring. Data analytics should include gamification for behavioural triggers.
- Smart waste collection bins (radio-frequency identification (RFID) tags, self-compacting bins, fullness level sensors, automated waste segregation), including automated robotic systems and optimised separation systems, which can be complemented by the upcycling of waste streams into usable resources and optimal routing systems, as well as vehicle tracking. These solutions should be integrated and interconnected into the product cycle "from cradle to grave" to enable circular and resource-efficient methodologies.

Intelligent sustainable/biodegradable packaging

Intelligent and biodegradable packaging concepts have been gaining traction in the food industry to improve product safety and reduce environmental impact. Smart sensors of an IoT system can monitor environmental conditions and product quality, while communication devices can store and convey data throughout the product lifecycle. While these concepts need to be further advanced for efficient, safe food production and waste management, intelligent packaging itself needs to become more sustainable. Novel ideas are required to solve the problem of the amount of plastic packaging produced by food manufacturers. The definition of biodegradable packaging should lead to a new generation of food packaging. Such novel ideas include:

- a synergetic interdisciplinary approach to cross the boundaries of novel materials for food packaging and smart sensors associated with analytical methods for the detection of harmful substances that can infiltrate into food, cause water contamination, etc.
- fabrication and hybrid integration of eco-friendly nanostructured electrodes, sensors, energy harvesting and storage devices on rigid and flexible biodegradable substrates to reduce the waste from embedded electronics in smart packaging.

3.5.4.3.5 Remediation

Efficient smart networks for remediation

Remediation processes aimed at converting harmful molecules into benign ones can be undertaken in different ecosystems, such as water bodies (e.g. biotic and abiotic farming by-products), air (e.g. GHGs) and soil (e.g. pesticides). Remediation processes are mainly carried out in wastewater treatment plants. Although some pollution sources are static and sufficiently well known that treatment can be undertaken effectively, other pollution sources are more mobile in both time and/or space, making treatment at single points unsatisfactory. Another limiting issue is that remediation technologies are often power-intensive, and can therefore not be deployed for long in remote locations. Alternative high-efficiency remediation methods are needed, such as to transform/reduce the levels of CO_2 in chemical products. Current devices are also prone to fouling. This means remediation processes cannot be run constantly in remote locations, and there is thus a necessity to undertake them only when and where they are most required. In this regard:

- a network of smart sensors (an IoT system) that can monitor relevant status in real time, and inform on the necessity of remediation, would provide unique decision support that would be invaluable for efficient water, air and soil management.
- techniques used in the measurement and analysis of carbon sequestration by soils could also investigate the current potential of soils as a remediation mechanism to improve

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[131] *https://www.consilium.europa.eu/en/press/press-releases/2018/05/22/waste-management-and-recycling-council-adopts-new-rules/*

the sequestration capacity – such investigation should include the initiative of "four per 1,000"[132] presented at COP21 in Paris.

3.5.4.4 Major challenge 4: Water resource management

3.5.4.4.1 Status, vision and expected outcome

The quality of groundwater, surface water bodies (oceans, seas, lakes), waterways (rivers, canals, estuaries) and coastal areas has a great impact on both biodiversity and the water quality in daily use by people. While natural droughts may lead to increased salinity and, along with floods, impact or endanger the quality of water bodies, human activities in energy production, manufacturing and farming industries have a major detrimental effect through thermal pollution, chemical, microbiological and micro-plastic contaminants, and biotic and abiotic farming by-products. Moreover, the outdated and deteriorating water infrastructure is having a detrimental impact on water quality.

3.5.4.4.2 Access to clean water (urban and rural)

Healthy water

With the aim of reducing pollution-related problems, water utilities, water associations, academia and private industry have focused on developing new methods, policies and procedures to secure drinking water distribution by detecting in real time compounds and contaminants in order to take the required measures to mitigate these issues. This necessitates online information on the status of water sources at a larger scale than ever before. To mitigate both accidental and intentional contamination of freshwater resources, the deployment of sensors and diagnostic systems with rapid communication technologies and data analysis capabilities are needed to secure water quality and its distribution over the network. Such actions would provide:

- connected and highly integrated multiparameter diagnostic sensors for real-time chemical analysis (temperature, ionic electrical conductivity, pH, etc).
- online monitoring systems, including sensors to monitor biofilm growth in water pipes and AI/ML techniques for data analysis.

Integrated systems for demand reduction and conservation of water

According to the UN Development Programme, dwindling drinking water supplies are affecting every continent. On the one hand, increased urbanisation and farming have amplified the demand for drinking water, and for domestic and agricultural use. On the other hand, an increasing number of countries are experiencing water stress due to longer drought periods and the spread of desertification. In

132 Researchers from the French National Institute for Agronomic Research, mentors of the project, have observed that by increasing the organic matter in the soil by four grams per 1,000 – hence its name – it would be possible to limit the current growth of CO_2 emissions to the atmosphere. Promoting good agricultural practice would combat climate change and, at the same time, guarantee the food security of the population.

133 Leakage Reduction in European Water Mains; Layman Report https://ec.europa.eu/environment/eco-innovation/projects/sites/eco-innovation-projects/files/projects/documents/curapipe_layman_report.pdf http://www.fao.org/nr/water/aquastat/water_use/

addition, approximately 25% of all urban drinking water is being lost forever[133] in global water systems before it even reaches the end-user. There is an urgent need to prevent losses from water abstraction as climate effects intensify. Leak localisation is currently very time-consuming, labour-intensive and costly. Operators have to manually place equipment that "listens" to the water flow during the night. Smart integrated systems can significantly contribute to key measures aiming at affecting consumer practices in water usage, delivering greater efficiency and reducing water wastage. Developments are needed in the fields of:

- smart metering, time-of-use pricing and gamification to control consumption and appliances, along with interoperable solutions for a truly connected smart household (taps, lavatories, showers, appliances).
- low-cost sensors for flow control, leak detection and auto shut-off, along with inexpensive actuators to remotely control valves for limiting water usage by volume/time – IoT systems can optimise the control of household, agricultural and industrial infrastructure/equipment in water-intensive processes.
- smart systems able to automate leak localisation, and to respond promptly and cost-effectively – this can be a combination of in-pipe inspection (to locate the leak) and a network of low-cost, fine-grained sensors to allow predictive maintenance of distribution systems.

Efficient and intelligent water distribution

The main challenge for improving the use of water is to guide its distribution depending on its final application (drinking water, water for industry, etc). However, the existing sanitary regulations always look to optimise water safety regardless of its final use. To apply the most effective measures to make water distribution more efficient, it is necessary to thoroughly review the different supply protocols and quality criteria for each sector. Moreover, by continuously monitoring the quality and availability of water, it would be possible to better regulate its distribution depending on the final use and to adjust the price accordingly. Intelligent systems connected to smart grids will allow water inputs to be made in the network at the right times, optimising the energy cost as a result.

To address these challenges, there is a need for the following.

- novel smart metering solutions based on various technologies, including electrochemical multiparameter sensors (pH, chlorine, conductivity, etc) with high stability, anti-fouling, high accuracy capabilities and cost-effectiveness, as well as optical sensors based on different principles (fluorescence, absorbance, etc) integrated into miniaturised systems at a low cost.
- IoT systems with the adequate data analysis processing power and AI capabilities to process the large volume of data generated by the different water management processes to satisfy quality, usage type and associated pricing.
- efficient year-round water management in terms of storage to deal with some of the most urgent shortages, with better forecasting and warning systems based on extensive measurements – e.g. intentionally flooded areas could be used to store water in times of expected scarcity.

3.5.4.4.3 Resources management

Smart systems for irrigation management

At a global level, agriculture consumes 69% of the world's freshwater[134]. Because of this, precise control of irrigation is essential to guarantee water and food security for all. Irrigation water management is the practice of monitoring and managing the rate, volume and timing of water applications according to seasonal crop needs, considering the soil intake and water holding capacities with the objective of using water in the most profitable way at sustainable production levels. To this end:

- smart sensors are increasingly required as tools to implement irrigation management and monitor water levels. Sensors should be more intelligent to support real-time applications and/or reduce latency, optimise power consumption of the overall system, and facilitate local (at the edge) cost-effective solutions for both outdoor and indoor use.
- integration of systems monitoring water deficiency or surplus is also required. These could be based on narrow-band spectral reflectance of water and land surfaces for vegetation/habitat mapping, along with UAV utilisation in remote areas.

Smart systems for flood management

Flood management has been gradually integrating smart sensors. IoT systems with water-level sensors can also play a significant role, not only in real-time monitoring but also in predictive/forecasting capacity models in occurring natural hazards. This requires:

- the monitoring of water levels and devising prediction models to identify areas at a high risk of flooding. This is possible through the development and deployment of more intelligent sensors in combination with smart predictive algorithms to integrate information from other sources, such as weather forecasts and regional georeferenced data.
- Key are IoT interoperable systems to provide real-time information to first responders, civilians and companies to proactively take countermeasures.

Smart water treatments fostering circular use (wastewater, rainwater, stormwater)

Around 80% of all wastewater is currently being discharged into the world's waterways, where it creates health, environmental and climate-related problems. Water from industrial, agriculture and domestic use contains organics, phosphates, nitrogen, cellulose, rare earth elements and other substances. In addition to its domestic use, purifying, distilling or deionising water is essential for many agricultural and industrial uses – both to ensure the consistency of products and to meet strict safety regulations. The global market for water and wastewater technologies reached US $64.4 billion in 2018, and is expected to rise to US $83 billion by 2023[135]. Technologies that allow resource recovery from wastewater to be commercially feasible are increasingly being developed, making transitioning to a circular economy an opportunity to accelerate and scale-up the most recent scientific and technological advances that support greater efficiency in the water sector. There is an increasing requirement for:

- a range of sensors in water systems to monitor water levels, the flow of water through different channels, temperature changes, chemical leakage, pressure level, chemical residues, etc.
- IoT-enabled water purifiers that can predict potential system failures to reduce downtime in public water systems, and to enable remote sensing for mapping groundwater resources and monitoring sustainable extraction levels.

3.5.4.5 Major challenge 5: Biodiversity restoration for ecosystems resilience, conservation and preservation

3.5.4.5.1 Status, vision and expected outcome

It has been stated that: "Biodiversity boosts ecosystem productivity where each species, no matter how small, all have an important role to play"[136]. For example, increasing the number of plant species means a greater variety of crops, as greater species diversity ensures natural sustainability for all life forms. Healthy ecosystems can better withstand and recover from a variety of disasters, anthropogenic or not. A healthy biodiversity offers many natural services for everyone.

It should be noted that there are many such services that we already get for free! However, the cost of replacing these, even if possible, would be extremely expensive. It therefore makes economic and development sense to move towards sustainability. From this perspective, ECS will contribute to addressing some of the key challenges relating to biodiversity and sustainability for the four ecosystems described below.

3.5.4.5.2 Biodiversity restoration for the agriculture ecosystem

Agriculture is one of the economic activities that has the highest dependence on nature and biodiversity[137]. On average, global mean crop yields of rice, maize and wheat are projected to decrease between 3% and 10% per Celsius degree of warming above historical levels. All crops depend directly on soil health and fertility, and more than 75% of global food crop types rely on animal pollination. However, the impact of agriculture activity on the environment must be as low as possible to preserve biodiversity.

In this regard, the EU Biodiversity Strategy 2030 establishes several objectives[138], as summarised in *Sub-section 3.5.5* Timeline. To address these objectives, there is a need to develop

- precision farming systems for optimal use of fertilisers and pesticides
- sensing and monitoring systems for soil nutrients measurement, connected insect traps and landscape monitoring.

3.5.4.5.3 Biodiversity restoration for the aquaculture ecosystem

Aquaculture impacts biodiversity negatively in several ways[139]: (i) antibiotics and hormones are used to reduce farm stock mortality and improve growth rates, but their use has side effects for the flora and fauna of water bodies receiving farm effluents; (ii) through eutrophication and changes in flora and fauna in waters receiving effluents from aquaculture facilities; (iii) risk of excessive exploitation of wild fish stocks for use in farm fish feeds; and (iv) transfer of disease and parasites from farm animals to wild animals.

To address these side effects, there is a need to develop:

- precision aquaculture systems for optimal feeding (minimising waste and feed residuals), optimal use of antibiotics/hormones and the optimal use of freshwater.
- smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents.
- smart systems combining data collected from different sources (IoT, satellite and drones) and data analysis based on AI/ML techniques to create predictive models leading to more confident decision-making, timely alerts and automated systems in general.

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134 *https://www.bccresearch.com/market-research/environment/water-and-wastewater-treatment-technologies-global-markets.html*

135 *Anup Shah, "Why is biodiversity important? Who cares?" https://www.globalissues.org/article/170/why-is-biodiversity-important-who-cares*

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136 *European Commission. The business case for biodiversity. May 2020. https://ec.europa.eu/commission/presscorner/detail/en/fs_20_907*

137 *European Commission. EU Biodiversity Strategy for 2030: bringing nature back into our lives. May 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX%3A52020DC0380*

138 *Claude E. Boyd, What is biodiversity and its relevance to aquaculture certification? https://www.aquaculturealliance.org/advocate/biodiversity-relevance-aquaculture-certification/*

3.5.4.5.4 Biodiversity restoration for the fisheries ecosystem

The EU's Biodiversity Strategy has set an objective of protecting a minimum of 30% of its sea area. Similar to agriculture, fishing is an economic activity with a strong dependence on biodiversity. Keeping fish stocks healthy is critical to guaranteeing ocean biodiversity and thus the economic sustainability of fisheries. According to recent studies, the preservation of marine stocks could increase the annual profits of the European seafood industry by more than €49 billion.

Fishing activities impact biodiversity negatively in several ways, particularly by: (i) increasing fish mortality, so measures must be taken to keep this under maximum sustainable yield levels; and (ii) damaging the ocean ecosystem due to the use of certain fishing techniques, currently the most damaging activity to the seabed. In addition, the effect of by-catching from non-selective industrial fishing methods endangers many species of marine animals not being fished for. It is therefore necessary to evolve towards more selective and less damaging fishing techniques, as well as the more effective control of illegal fishing practices.

To reduce these negative impacts, there is a need to develop:

- oceanographic sensing and monitoring solutions (including unmanned vehicles, UXVs) for fisheries ecosystem to estimate biodiversity indices, fish stocks and species distribution, and to build fishery management systems consistent with conservation objectives and rules.
- technologies to make fishing gear more selective and environmentally respectful.
- technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc).

3.5.4.5.5 Biodiversity restoration for forestry ecosystem

The EU Biodiversity Strategy has set the objective of protecting a minimum of 30% of the EU's land area. At least one-third of protected areas – representing 10% of EU land – should be strictly protected. In particular, the strategy identifies the crucial need to strictly protect all the EU's primary and old-growth forests (see *Figure F.66*), which are the richest forest ecosystems removing carbon from the atmosphere, while storing significant carbon stocks[139]. The strategy also calls for preserving the good health and increasing the resilience of all EU forests, especially against wildfires, droughts, pests and diseases. It is envisaged that the European Commission will develop a forest information system for Europe that integrates data from multiple sources and providers. To prevent more wildfires, grow rural economies in a sustainable way and manage climate change, a much better understanding and continuous assessment of EU forests is necessary. To this end, there is a need to develop:

- a precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests, as well as for early detection and prevention of threats to forests (wildfires, pests, diseases, etc).
- smart systems for the environmental monitoring of forests and fields, as well as CO_2 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and to provide timely warning concerning illegal poaching activity.

3.5.5
TIMELINE

The following table illustrates the roadmaps for **Agrifood and Natural Resources**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Food security	**Topic 1.1:** Intelligent and adaptative food production	• Advanced analytical processing based on several data sources • IoT devices with integrated firmware for implementing big data solutions
	Topic 1.2: Redesigning farming systems	• A farm management information system (FMIS) thoroughly integrated with IoT and automated systems; all the data should be gathered automatically and digitalised
Major challenge 2: Food safety	**Topic 2.1:** Crop quality and health	• IoT for monitoring the key parameters related to plant health • DSS for recommendation/decisions related to agri-chemical application; health and environmental care
	Topic 2.2: Livestock welfare and health	• Advanced indicators of welfare, health and performance monitoring (integration of milking robot, wearable sensors data, etc) at the individual and herd scale
	Topic 2.3: Food chain	• IoT devices monitoring food transport from production to the retailer; end-consumers to have full access to this information; AI (ML/deep learning) models based on the recommendations and decisions that the IoT devices could take to monitor the whole supply chain • Global accessibility for end-consumers to the traceability of the whole value chain – i.e. total transparency
Major challenge 3: Environmental protection and sustainable production	**Topic 3.1:** Soil health	• Autonomous recommendations done by the IoT devices directly related to fertilisation and phytosanitary application.
	Topic 3.2: Healthy air and skies	• CO_2 capture materials in use
	Topic 3.3: Smart waste management	• Forecasting models of potential waste that will be produced by the farm management system
	Topic 3.4: Remediation	• Network of sensors for target pollutant with antifouling properties for use in real environments • Development of capture materials for targeted pollutants, including CO_2 capture materials

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• AI applied to food production to define advanced analytical processing related to prescriptive and predictive analysis	• AI applied to food production, not only in pre-harvest areas but also post-harvest – i.e. applied to the whole value chain integrally
• Telecontrol of agronomic systems (irrigation systems, climate control systems, etc) based on expertise and farmers' decision-support systems (DSS)	• Automatisation of labour; resource optimisation (environmental care and social impact)
• AI for automatic decisions and action; ML and deep learning related to agronomic models and algorithms	• Robots with AI for managing plant health automatically
• Reduce by 50% the sale of antimicrobials for farmed animals by 2030	• Fully automated herd performance control (growth and milk production, forage efficiency, early disease detection for antibiotics use reduction), and applications for genetic selection to optimise breeding performance and resilience
• Interoperability among all the systems that manage the whole value chain • Normalisation and homogenisation of communication protocols • IoT devices integrated in the food chain where the end-consumers will be able to read them by mobile phone and directly access for complete traceability	• IoT devices making recommendations automatically and take autonomous decisions related to food safety, acting directly with the transport mechanism (cooling mechanism and others that impact food safety) • Systems automatically and autonomously act in all the machinery located at each step of the supply chain
• Combination of several data sources to define key performance indicators (KPIs) related to environmental protection and sustainable production	• Autonomous actions performed by IoT devices directly in the telecontrol systems related to fertilisation and phytosanitary applications
• CO_2 capture and conversion on-site	• Low or no carbon fuel sources
• Registration of the traceability related to residues management, including the residue management in food traceability and the environmental footprint	• AI models providing recommendations for decision-making related to minimising farm waste
• Coupled sensor and CO_2 capture/conversion system for CO_2 remediation • Solar/thermoelectric in situ driven pollutant removal	• Real-time multiparameter sensing with AI decision-support for management • Efficient and low-cost general pollutant removal and conversion systems using energy harvesting towards in situ remediation

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 4: Water resource management	**Topic 4.1:** Access to clean water (urban and rural)	• ICT solutions allowing greater societal involvement in water management through online knowledge of its consumption data (remote meter reading), and quality parameter monitoring for greater awareness about the optimisation of the freshwater as a limited resource • Water quality monitoring systems based on hybrid technology (mono-parameter bulky probes and some miniature chips) • Sensors for basic parameters such as chlorine, conductivity and pH are available for real-time monitoring; more complex parameters require lab analysis • Cost and integration are still challenging for massive deployment in water distribution networks based on current IoT system applications • Limited amount of data (systems are installed only at critical locations) • Centralised control and data analysis based on AI on the cloud
	Topic 4.2: Resource management	• Requirements identification and classification for biodiversity protection in the exploitation of aquifers for human supply • Monitoring systems for the water lifecycle, including supply and sanitation through the development of digital tools allowing the intensification circular economy • Progressive transformation of wastewater into raw materials for the generation of products and services
Major challenge 5: Biodiversity restoration for ecosystems' resilience, conservation and preservation	**Topic 5.1:** Biodiversity restoration for agriculture ecosystem	• Sensing and monitoring systems for soil nutrients measurement, connected insect traps and landscape monitoring
	Topic 5.2: Biodiversity restoration for aquaculture ecosystem	• Smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents
	Topic 5.3: Biodiversity restoration for fisheries ecosystem	• Technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc)
	Topic 4.4: Biodiversity restoration for forestry ecosystem	• Precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests, as well as early detection and prevention of threats to forests (wildfires, pests, diseases, etc)

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Smart monitoring systems at home to optimise household water spending and tools to improve performances through KPIs that allow for measuring progress at the microscale; water users must move from passive consumers to active management • New generation of more integrated and miniaturised multiparameter autonomous sensors (e.g. pH, chlorine, and conductivity parameters) • More complex sensors are available for the real-time detection of pollutants in water, such as heavy metals and nitrates • Edge computing and multiparameter devices allowing decentralised data analysis and control • Massive deployment starts being cost-effective with more accurate solutions due to the availability of an increased amount of data	• Use of different water qualities for different usages (at home, industry, etc) through secure monitoring systems, always guaranteeing the water quality (especially freshwater) • Advanced multiparameter sensors supporting new capabilities, such as stability, antifouling, accuracy, etc • Real-time bacteria detection is feasible • Large-scale deployment of multiparameter devices allowing advanced data analysis in water distribution networks for more intelligent water management • Freshwater quality prediction based on digital twin technology capabilities considering real-time environmental conditions
• Improvement of knowledge through the accumulation of consolidated and valid data series, on the natural environment through the implementation of monitoring systems, for both the water and natural environment (fauna, ecology, sociological aspects, uses, etc), as a basis for sustainable management through AI/ML tools, allowing for identificaiton of the correlation between the evolution of the environment quality and water use • Design of environmental evolution models in different use scenarios • Industrial transformation of wastewater treatment plants in bio-factories	• High-performance monitoring systems to identify and quantify the presence of emerging pollutants and high-risk chemical species derived from human action • Integrated vision for all aspects related to water in systemic and non-cyclical areas; process reengineering and redesign of monitoring, control and exploitation systems based on advanced tools for decision-making through the generation of models • Paradigm shift in the vision of water as a cycle to a system that must be optimised

• Precision farming systems for optimal use of fertilisers and pesticides • Reduction by 50% of the use and risk of chemical and more hazardous pesticides by 2030 • Reduction of nutrient losses by at least 50% while ensuring no deterioration to soil fertility • Reduction in fertiliser use by at least 20% by 2030 • Reduction by 50% in the sales of antimicrobials for farmed animals and in aquaculture by 2030 • Boosting the development of EU organic farming areas with the aim of achieving a 25% increase in total farmland under organic farming by 2030	• Reduction of European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agricultural and stopping biodiversity erosion
• Smart systems combining data collected from different sources (IoT, satellite and drones) and data analysis based on AI/ML techniques to create predictive models leading to more confident decision-making, timely alerts and automated systems in general	• Precision aquaculture systems for optimal feeding (minimising waste and feed residuals), optimal use of antibiotics/hormones and optimal use of freshwater
• Oceanographic sensing and monitoring solutions (including UXVs) for fisheries ecosystem to estimate biodiversity indices, fish stocks and species distribution	• Technologies to make fishing gear more selective and environmentally respectful
• Smart systems for environmental monitoring of forests and fields, as well as CO_2 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and provision of timely warnings about illegal poaching activity	• Preserve the protected and restored forestry areas, as well as continuing to restore the remaining degraded forests

3.5.6
SYNERGY WITH OTHER THEMES

The IoT system technologies and related activities prioritised in this section are key to addressing the specific challenges of food, agriculture and natural resources. The **Major challenges** of food safety and security, environmental protection and sustainable production, water resource management and biodiversity restoration are in alignment with the European missions on "adaptation to climate change including societal transformation", "healthy oceans, seas, coastal and inland waters", "climate-neutral and smart cities" and "soil health and food". The application needs under those missions can be addressed through the integration of IoT systems into innovative technological solutions, as well as holistic approaches in processes covering the whole supply chain, from resource utilisation and production to food packaging, waste management and remediation. As such, there are potential synergies with the **Health, Mobility** and **Digital Industry** sections.

On the technology side, the envisaged IoT system solutions will require significant advances in terms of functionality. Synergetic topics include advanced sensing capabilities, energy autonomy (harvesting, storage and power management), connectivity, lifecycle properties, reliability, privacy and security. There are also great challenges to make these heterogeneous systems manufacturable at the right cost for market entry while simultaneously achieving miniaturisation, low-power consumption, packaging and other constraints. To this end, significant collaborative effort will be required in materials integration and process technologies for individual components, modules and systems. New design paradigms and tools are also needed. This is required to cross boundaries between domains, e.g. for verification and automated design space exploration, AI and ML capabilities. Overall, an orchestrated synergetic approach in the areas of advanced materials, circular industries, manufacturing technologies, ICT, AI, edge and cloud computing, robotics, electronics and photonics, as well as other key technologies, will facilitate technology-push/demand-pull advances in the activity fields of IoT systems for agriculture and natural resources.

3.6

ECS Key Application Areas

DIGITAL SOCIETY

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140 *GAIA-X: A project initiated by Europe for Europe with the aim of developing common requirements for a European data infrastructure.*

3.6.1
SCOPE

Supporting the digital transformation throughout society

This section describes the type of digital innovations that are essential to stimulate an inclusive and healthy society, and which will in turn contribute to solutions for European challenges in the fields of health, mobility, security, energy and the climate, and consequently to European economic prosperity.

Europe needs digital solutions that support the individual, and at the collective level to empower society as a whole. These (smart) digital solutions will be driven by new technologies such as 5G, Artificial Intelligence (AI) with deep learning (DL), virtual reality (VR) and augmented reality (AR), brain–computer interfaces (BCIs) and robotics. They will shape new ways of how people use and interact with these technological solutions, with each other, and with society and the environment. Digital innovations should facilitate individual self-fulfilment, empowerment and resilience, collective "inclusion" and safety, as well as supportive infrastructure and environment.

However, such a transformation will also introduce a wide range of ethical considerations. Future digital innovations will therefore need to address societal concerns in a sustainable way, guaranteeing participation and reducing inequality. A human-centred approach is therefore a key aspect of the EU's approach to technology development. It is part of European social and ethical values, (social) inclusiveness, and the creation of sustainable, high-quality jobs through social innovation.

3.6.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

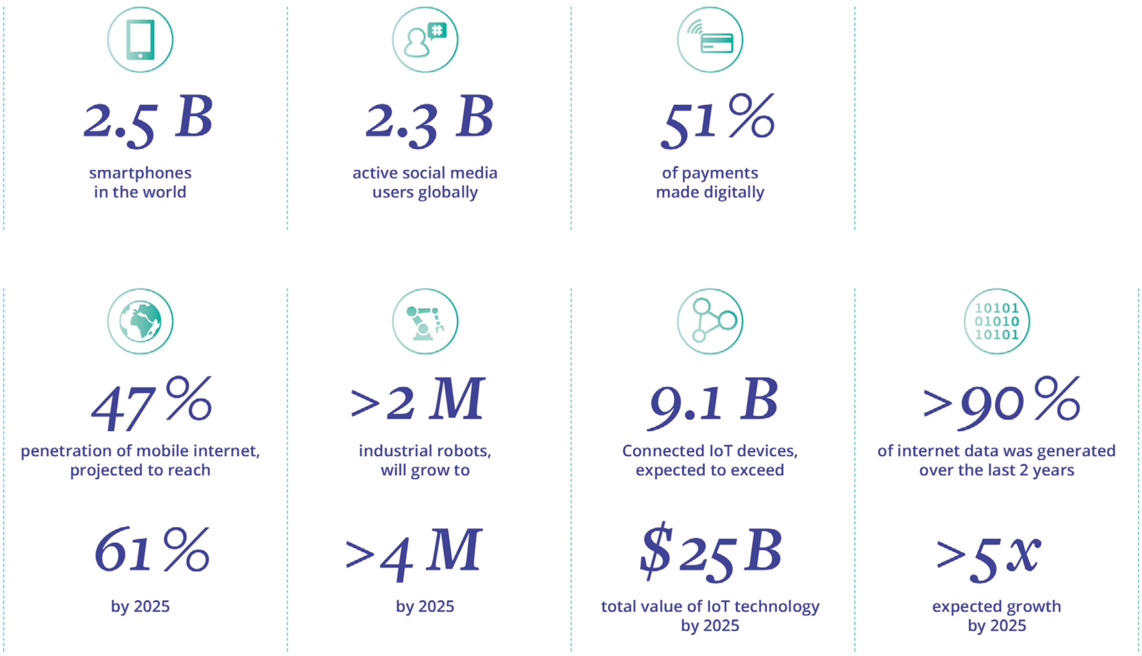
External requirements

To guarantee economic and societal growth in Europe, digital inclusion requires tools and infrastructures in application domain roadmaps as described in the other sections. Technology permeates every aspect of society, and is an important instrument of change (as can be seen in *Figure F.68*, where two distinct rows are shown: current status and future expansion).

People's expectations of the future impact of technology are broadly positive, but also involve specific concerns around employment, income, safety, equality and trust. By 2035 the impact of science and technological innovation will be enormous on prosperity, individual wellbeing, sustainability, fairness and trust (see *Figure F.69*). This underlines the importance of investing in our digital strategy today.

In striving to guarantee European sovereignty to support European digital societal goals (for instance, through the GAIA-X[140] project), safety, equality and trust are key requirements. What does this mean for electronic components and systems (ECS) for our society? Ubiquitous connectivity ("everywhere and always on"), online services and social media ("always online") drive people to rely on intelligent applications and the services they offer. Public and private infrastructures will increasingly be connected, monitored and controlled via digital infrastructures ("always measuring").

TECHNOLOGY PERMEATES EVERY ASPECT OF SOCIETY AND IS AN IMPORTANT INSTRUMENT OF CHANGE.



F.68 *Technology permeates every aspect of society (Source: Why digital strategies fail, McKinsey & Company, March 2018; GSMA 2019; Domo; IDC; McKinsey Global Institute analysis)*

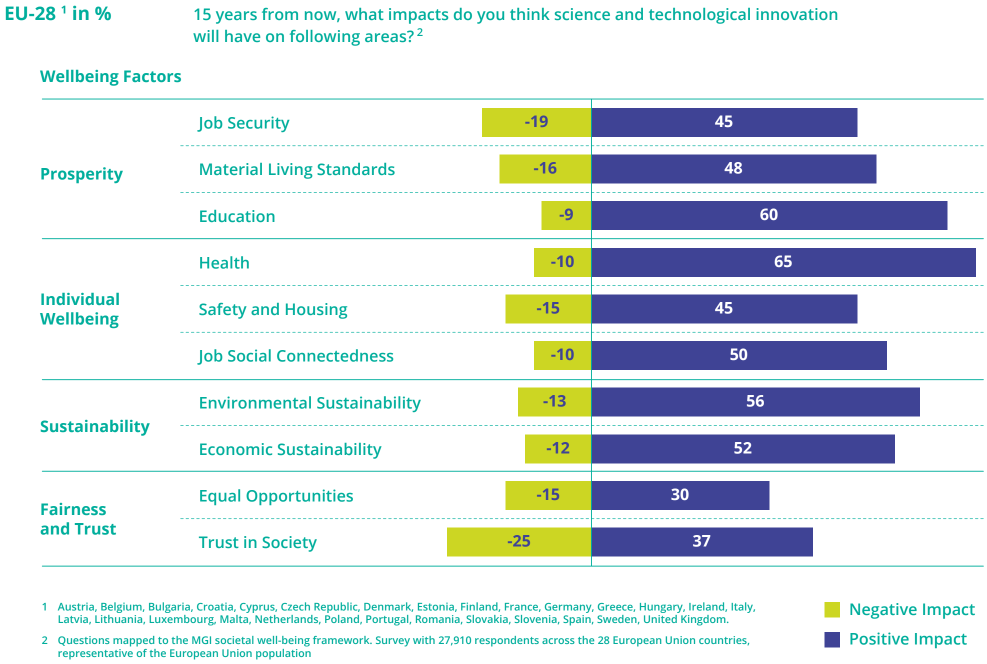
Two important further drivers for European society and economy – from a human-centred approach on AI perspective – are lifelong learning and training, as well as being able to work anywhere, anyplace. The trend to work from home whenever possible, which has been triggered by the Covid-19 pandemic, will continue, and people will endeavour to combine work and private life in a better way. In rural areas, as well as in cities, it should be easy to work either from home or remotely in distributed groups/workforces. This can be achieved through living labs and learning factories at both a personal and collective level.

Societal benefits

All of European society will benefit from a major (AI-based) evolution in intelligent systems, on both the individual and collective levels.

- The benefit of digital inclusion for all individuals will involve employability through lifelong learning and training, and the personal wellbeing of individuals. To achieve these, the key ambition is to maximise the individual development of citizens.
  - How? By ensuring personal resilience, enabling lifelong learning and development, and stimulating employability. Human-centred solutions will optimise services to each individual's needs and level of understanding, for applications in areas such as healthcare, lifestyle, coaching, training, and working from home or remotely collaborating in a "distributed" workforce. This will boost employee productivity, improve their work/life balance and foster better mental health, and reduce pollution from commuters.
- The overall individual benefit is "wellbeing". A factor such as "prosperity" means job security, material living standards and the right to have the optimum education, any time, any place. On an individual level, wellbeing means health for everyone of every age, and also adequate housing, ensured safety, protected privacy, reliable and ubiquitous digital infrastructures, in addition to

PEOPLE'S EXPECTATIONS OF THE FUTURE IMPACT OF TECHNOLOGY ARE BROADLY POSITIVE, BUT WITH PARTICULAR CONCERNS AROUND JOBS, WAGES, SAFETY, EQUALITY AND TRUST.



People's expectation of the future impact of technology (Source: Special Eurobarometer 419, Public perceptions of science, research and innovation, 2014; McKinsey Global Institute analysis) **F.69**

social connectedness and more intense social cohesion. Our key objective is to empower and protect the individual.

- How? By ensuring acceptable and trustable AI technologies to increase inclusion and prevent exclusion, protecting citizens against identity theft, and providing a protective environment against new virus infections; in addition, through lifestyle monitoring and coaching, to enable and support healthier lifestyles.

▸ The benefits of digital inclusion, a society resilient against setbacks, and the societal acceptance of novel technologies will achieve the key ambition of safeguarding collective society and wellbeing for all.

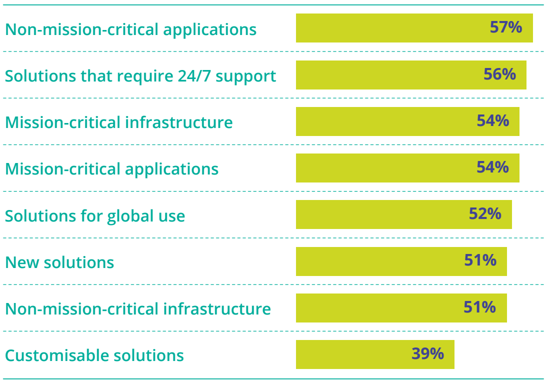
- How? By societal and digital inclusion, providing societal access for all, and ensuring collective resilience against setbacks. Also, the elderly will be supported to continue their social participation, which will reduce feelings of loneliness, improve their wellbeing and health, but provide reassurance that their precious experience can still be used.

▸ On an environmental level, the benefits are a physical and digital sustainable environment, intelligent Infrastructure management, stability and resilience against threats, and agreement on fall-back solutions in times of crises. The main aim is to contribute to a supportive infrastructure and environment.

- How? By providing reliable and resilient infrastructures, protecting society against destabilising forces, establishing a sustainable environment, and securing controlled climate change. Monitoring and intelligent control of infrastructures will also contribute to a sustainable environment by solutions that address, for example, optimal use of natural resources, reduction of pollution and crisis management.

EXPECTED USES OF CLOUD COMPUTING IN THREE YEARS

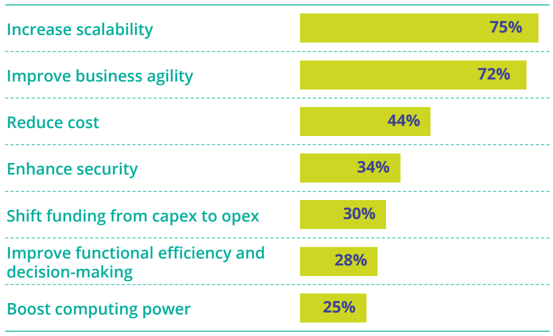
Which of the following areas do you foresee shifting to a cloud-based flexible consumption model in the next three years?



(FIGURE A)

PRIMARY CLOUD DRIVERS

What are the primary reasons for using cloud technology? (select all that apply)



(FIGURE B)

F.70 *Expected uses of cloud computing and their primary drivers (Source: Deloitte 2018 Global CIO Survey)*[141]

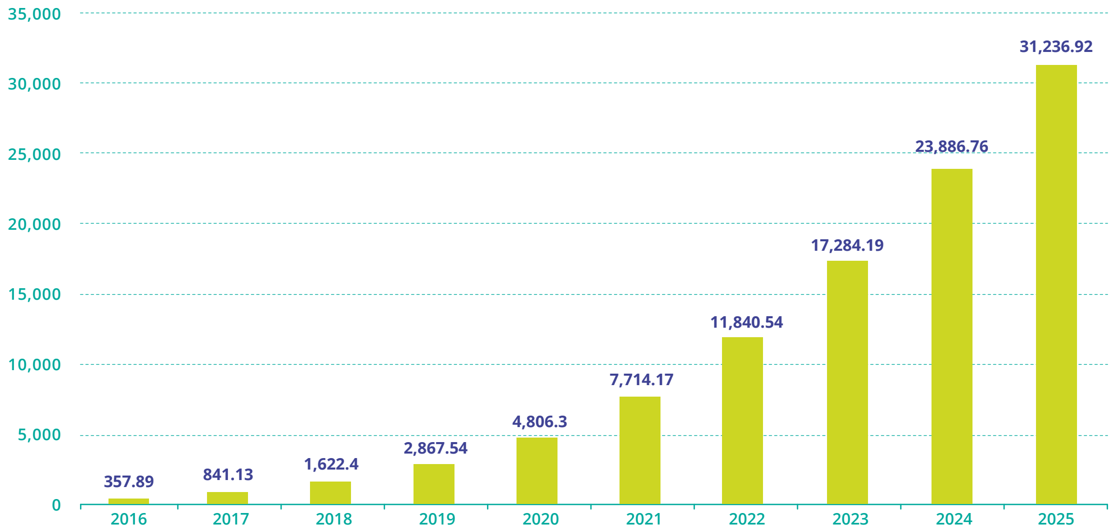
”Sustainability“ means environmental as well as economic sustainability, and equal opportunities for all people. It is related to fairness and trust in our societies. It must be ensured that AI-based systems will take European-style human values into account by design. A human-centred approach will therefore be a key requirement. As such, “FAIRness” (findability, accessibility, interoperability and re-use) will help shape future applications.

3.6.3 STRATEGIC ADVANTAGE FOR THE EU

Overall, a strategic advantage for the EU lies in digital solutions and people with high-developed digital skills that can contribute more efficient solutions for European challenges in the fields of health, mobility, security, energy and the climate. A digital “healthy” society will contribute to European economic prosperity. Digital tools, infrastructures, applications and digital skills will offer the following.

- Ensure companies that their labour force will work efficiently, whether they work at the head office or from their homes (i.e. to prevent virus spread, or for other reasons). An advantage here is the widespread empowerment of citizens to work from different locations, taking into account that some jobs will need to be undertaken in the office or factory, but that knowledge workers with computer-based jobs can work remotely.
- Provide people with greater employability and better protection against social or economic exclusion (the possibility of ubiquitous connectivity).

REVENUES FROM THE ARTIFICIAL INTELLIGENCE FPR ENTERPRISE APPLICATIONS MARKET WORLDWIDE, FROM 2016 TO 2025 (IN MILLION U.S. DOLLARS)



Enterprise AI market revenue growth worldwide (2016–25)[142]

F.71

- Support citizens instead of replacing them with robots, as EU technical solutions will be based on human-centred AI systems that have a focus on human values. AI solutions applied should be trustworthy (responsible, transparent and explainable).
- Help European governments, companies and citizens to cooperate more easily, and develop reliable societal emergency infrastructures. This will make European societies better prepared to deal with emergency and crisis situations.

Widespread empowerment to work from different locations will require optimal use of (but also drive) the growth of interconnection bandwidth (*Figure F.70 A*). Remote working will also require further use of cloud applications (see *Figure F.70 B*), using AI software as a service (SaaS) to automate processes and support employees in decision-making, resulting in the growth of AI (as shown in *Figure F.71*).

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141 *https://deloitte.wsj.com/cio/2018/11/11/the-state-of-cloud-adoption/*

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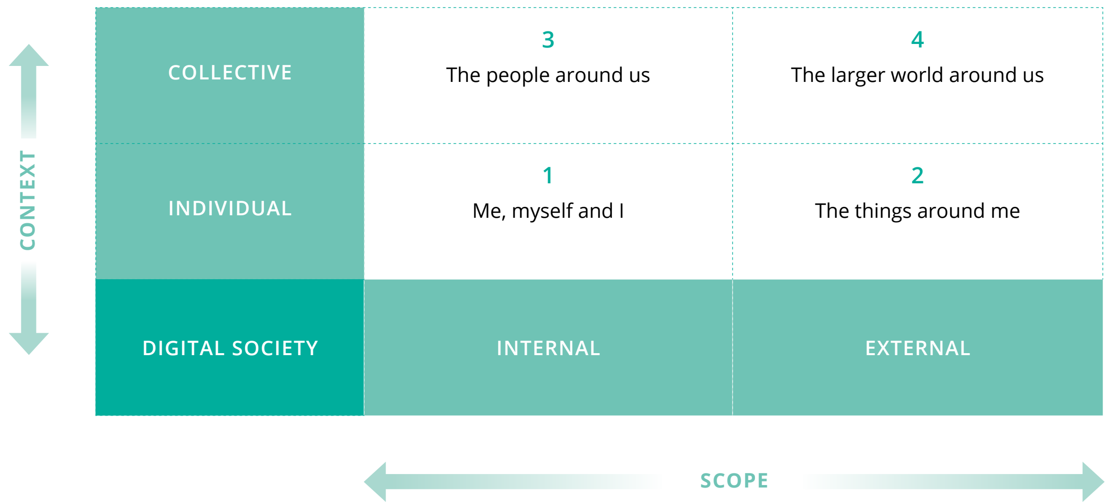
142 *https://www.forbes.com/sites/louiscolumbus/2018/01/12/10-charts-that-will-change-your-perspective-on-artificial-intelligences-growth/#31791eef4758*

3.6.4
MAJOR CHALLENGES

Enabling and ensuring a digital society implies various aspects will be facilitated by ECS products and services. To structure these aspects, we distinguish between the individual or collective context and the internal or external scope. This leads to the matrix shown in *Figure F.72.*

Each of these four areas relates to one of the following Major challenges.

- **Major challenge 1:** Facilitate individual self-fulfilment.
- **Major challenge 2:** Facilitate empowerment and resilience.
- **Major challenge 3:** Facilitate inclusion and collective safety.
- **Major challenge 4:** Facilitate supportive infrastructures and sustainable environments.



F.72 *Structuring the Major challenges in scope and context*

3.6.4.1 Major challenge 1: Facilitate individual self-fulfilment

3.6.4.1.1 Status, vision and expected outcome

Ambition: to maximise the individual development of citizens

- Provide empowerment to citizens.
- Ensure personal resilience.
- Enable lifelong learning for both children and adults (serious gaming, including AR/VR).
- Give citizen more freedom to do their work wherever they want/need.
- Stimulate employability.
- Wellbeing (e.g. by gamification[143], connection to others, leisure).
- Improved human–machine interaction solutions for perception, reasoning and autonomy, with interaction being adaptive to the user's abilities.

To maximise the empowerment and self-fulfilment of citizens, Europe has to strive for lifelong learning, employability and the freedom to work wherever one resides, as well as optimal wellbeing in the context of an independent and pluralistic media. These enable lifelong empowerment by keeping citizens informed and facilitate the flow of educational content. Educating through the media is an important means to develop valuable skills that will help to end violence and eradicate forms of discrimination (such as sexism and racism). More fundamentally, the media encourages the acquisition of civic knowledge and facilitates discussion concerning current issues[144], while at the same time entering new frontiers of engagement using on-demand and interactive paradigms, and in employing AR/VR technologies backed by 5G/6G connectivity.

The 30-year career has become a thing of the past. Education does not end after school; individuals need to keep on learning throughout their careers to stay up to date and adapt their skills as the world changes at an unprecedented rate. To better support lifelong learning, technologies are needed that encourage collaboration, foster autonomy and responsibility, and implement learning initiatives. Technological advancements such as cloud computing, mobile devices and web 2.0 technologies are still relatively new additions to the workplace that must be further explored[145].

To provide the citizen with more freedom to do their work wherever they want or need, Europe must ensure the availability of high bandwidth secure connections (wired and wireless) at all possible locations one could use to work from. This should be reinforced by easy and secure access to cloud applications, and novel AI-based solutions to automate processes, analyse data, guide the user in decision-making, and to minimise repetitive work.

Advanced technologies, including smart automation and AI, have the potential to not only raise productivity and GDP growth, but also to improve wellbeing more broadly, as well as offer a healthier life and longevity, and greater leisure time. Studies have shown that, besides income, the following factors contribute to individuals’ wellbeing and self-reported life satisfaction: social life, use of leisure, health, spouse/partner, job, flat/house and the amount of leisure[146]. New technologies in the digital society can, and will, influence all these factors.

An example of the relevant tools is shown in *Figure F.73* for Coursera, which utilises of gamification to offer the lifelong free and open learning of languages and brings massive open online course (MOOC) platforms to the public.

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143 *Gamification: The application of game design elements and principles in a non-game context.*

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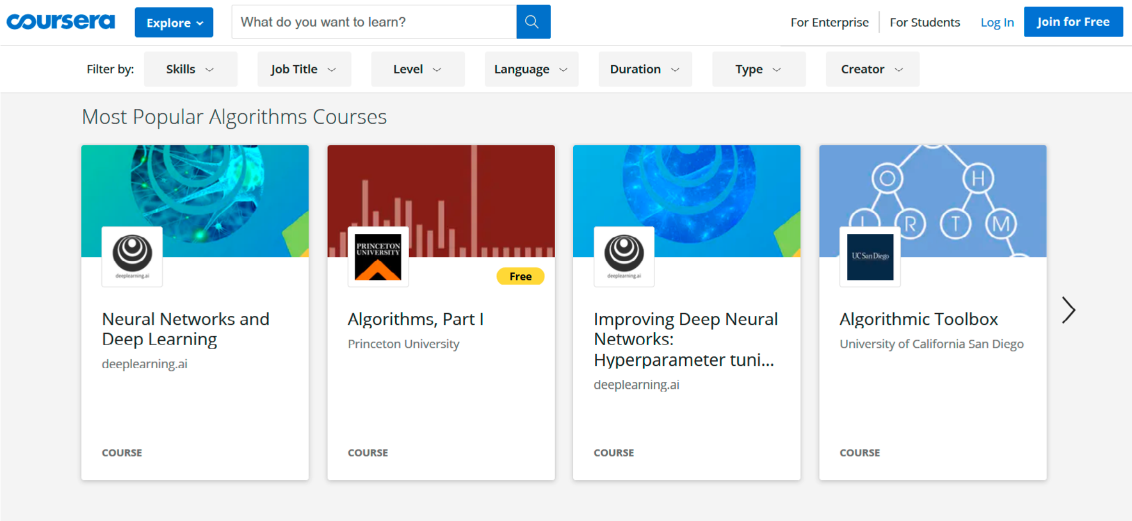
144 *http://www.unesco.org/new/en/unesco/events/prizes-and-celebrations/celebrations/international-days/world-press-freedom-day/previous-celebrations/worldpressfreedomday200900/themes/empowering-citizenship-media-dialogue-and-education/*

145 *https://www.trainingjournal.com/articles/opinion/how-promote-lifelong-learning-using-technology*

146 *https://www.mckinsey.com/featured-insights/future-of-work/tech-for-good-using-technology-to-smooth-disruption-and-improve-well-being*



F.73 *Coursera (Source: Coursera, Inc)*

3.6.4.1.2 Key focus areas

High-priority research and development and innovation (R&D&I) areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Online education and examination: VR/AR training and support.
- Improved human–machine interaction (HCI) solutions.
- Support devices: wearables, robots, cobots , chatbots, etc.
- Nudging and serious gaming: for personal development and healthier lifestyles.

To improve the awareness of our body's condition to external or internal stimuli, smart systems can provide support for disabilities, or a personal coach and trainer to identify behaviour to be avoided (wrong body position, bad habits), as well as possible future injuries or disorders. Smart systems can also offer an immersive experience through vision, gaming and sensory interaction by way of VR or AR. Consumers can be offered the immediacy, individualisation, interactivity and immersion they expect from media content consumption ("even better than being there").

A healthier and more comfortable environment can be offered based on personal preferences (control of temperature, humidity, air flux, etc), in the context of running activities and clothing, and by adapting lighting and acoustic quality to one's own sense of wellbeing. It also provides the capability to comfortably communicate and interact remotely with people, institutions and sellers, possibly without leaving home, saving time for self-development and leisure.

Selective automation, AR at work and a range of feedback tools can help boost satisfaction and give more meaning to work. This is a particularly important element for the millennial generation, which according to surveys tends to place more emphasis on work satisfaction than on income (above a certain income level). Due to the Covid-19 pandemic, large events are becoming more difficult to organise, and many people may prefer to take part in events while not physically being present. Technological advances will make it possible to place audiences in the middle of the action and to offer them immediacy, individualisation, interaction and immersion without it being necessary for them to actually be there in person. This will further change consumption patterns and open up new business opportunities.

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major challenge 1: Facilitate individual self-fulfilment	1.1 PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING	1.2 COMPONENTS, MODULES AND SYSTEMS INTEGRATION	1.3 EMBEDDED SOFTWARE AND BEYOND	1.4 SYSTEM OF SYSTEMS	2.1 ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL	2.2 CONNECTIVITY	2.3 ARCHITECTURE AND DESIGN: METHODS AND TOOLS	2.4 QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
Reliable, dependable and secure SW and HW	X		X					X
Mature human–systems interaction methods				X			X	X
Trustable AI/ML algorithms					X			X
Energy-efficient HW and SW solutions (e.g. for IoT devices, wearables)	X		X		X			
Seamlessly operating SW (e.g. for IoT devices, wearables)		X	X	X		X		
Ubiquitous, reliable and energy-efficient connectivity	X	X	X			X	X	X

Required R&D&I developments within ECS – Major challenge 1 **F.74**

Required R&D&I developments within ECS

Taking the above into account, specific R&D developments are necessary within ECS technology, as shown in *Figure F.74*.

3.6.4.2 Major challenge 2: Facilitate empowerment and resilience

3.6.4.2.1 Status, vision and expected outcome

Ambition: empower and protect the individual citizen

- Increase inclusion and prevent exclusion.
- Protect citizens against cyber-fraud (scams) and identity thefts; provide privacy.
- Enable smart homes with ubiquitous connectivity.
- Ensure acceptable AI technologies.

Diversity and inclusion within societies are increasingly recognised as crucial for equality at work and economic development. Research has established a strong link between gender equality in society, attitudes and beliefs about the role of women, and gender equality in work[147]. Technology can improve equality at work – for instance, by revealing pay gaps and biases, and helping de-bias recruitment. It can also improve equal access to essential services – for example, biometrics and cloud technology can contribute to increasing the diffusion of microfinance to women and underserved populations. Technology can also help enforce inclusive legal rights, policies and social norms. While e-voting still poses a number of cybersecurity challenges, it can support diversity by facilitating the vote for vulnerable and marginalised parts of society. Finally, technology can help with physical security and autonomy for minority groups through objects and digital communications tools that reduce or mitigate exposure to risk – for example, connected devices such as smart bracelets can enable women to signal an assault and call for help.

Reliance on technology comes with many benefits, but also brings new risks[148]. The radical nature of the ongoing technology transition could results in risks that are not just an extension of the previous challenges, but require fundamental changes to core aspects of our society, including how we think about our identity, security and rights. Concerns about technology are justified by recent events, such as security breaches in prominent companies, data theft and information misuse. In addition, AI provides more powerful examples of potential risks. Its full potential can be utilised only if we fully rely on it for decision-making, allowing it to process data beyond the human ability to cross-check and verify. This depends a high level of trust, raising questions about and requiring new technical solutions that take into account explainability, accountability, trustworthiness and ethics.

In 2020, we have experienced the necessity of a connected smart home and an adequate home office during the pandemic. However, the availability of high bandwidth connectivity is not yet evenly distributed geographically across Europe.

Machine learning is essential for a resilient future. AI will have a far greater chance of successful implementation if there is a focus on four key areas: augmented intelligence; intelligent automation; assessed intelligence; and adaptive intelligence. Augmented intelligence concerns augmenting and thus improving the productivity of humans. Intelligent automation is essentially about building systems that integrate humans and machines in productive ways (instead of just replacing humans entirely with machines). Assessed intelligence is all about making models robust by evaluating them rigorously and continuously. Finally, adaptive intelligence involves developing more resilient systems that can adapt to changing circumstances by shifting to a causal inference paradigm[149].

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147 *McKinsey Global Institute: "Tech for Good: Smoothing disruption, improving well-being", May 2019, p 42 and p 43.*

148 *McKinsey Global Institute: "Tech for Good: Smoothing disruption, improving well-being", May 2019, p 58.*

149 *https://www.swissre.com/risk-knowledge/risk-perspectives-blog/machine-learning-resilient-future.html*

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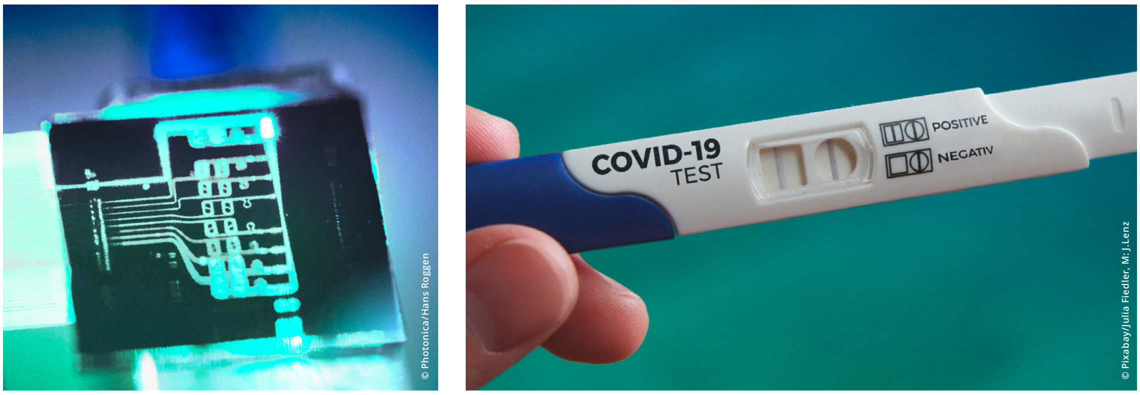
150 *LioniX, Surfix and Qurin Diagnostics (supported by PhotonDelta).*

151 *https://www.europarl.europa.eu/RegData/etudes/IDAN/2020/641543/EPRS_IDA(2020)641543_EN.pdf*



A consortium of three European SMEs[150] is developing a desktop Covid-19 testing device that will include a highly innovative photonic integrated circuit. The biosensing device will be able to yield reliable test results within 5 minutes. **F.75**

3.6.4.2.2 Key focus areas

High-priority R&D&I areas:

- Reliable and ubiquitous digital infrastructures.
- Access control/intrusion detection/surveillance.
- Provide protective environment and tools against virus infections.
- Off-grid living and emergency survival.

In the coming years, more people will work from home as the Covid-19 pandemic forced large groups of high-skill workers to do in 2020. To further enable working from home, or wherever and whenever one wants, wireless and wired infrastructures will have to be further improved (through increased reliable bandwidth, lower cost, better geographical coverage and finer granularity), security of connections will have to improve to protect the worker at home (as will the company using a distributed workforce with many internet connections) against cyber-attacks, and the theft of personal and/or company information. New functionality running in the private/public cloud will be needed to support real-time actions that may suffer from latency issues over the internet, as well as to support the worker in decision-making. Examples here are control of robotic surgical devices, remote control of robots in industrial processes, remote control of cameras in security applications and live television productions, and so on. Other professions, such as translation services, voice recognition and all kind of analytical algorithms for data analysis, also come to mind.

To create equal opportunities, innovative research should include: speech-generating devices (SGD) to help people with speech disorders; exoskeletons that empower disabled people in their everyday life; semi-autonomous vehicles that increase mobility for people with deafness and blindness; smart objects linked to geospatial information to improve women's security (e.g. invisible SOS buttons); augmentative and alternative communication tablets that help paralysed patients; VR solutions that provide realistic experiences for people with physical disabilities; and smart glasses that can be used to help people with autism on cognitive, social and emotional skills.

In 2020 we learned that Europe will need better technologies: (i) to fight and contain the rapid spread of diseases such as Covid-19; and (ii) to ensure that public health institutions can maintain their capacity to meet the ever-increasing needs caused by such a pandemic[151]. The in-depth analysis provided by the European Parliamentary Research Service's "Ten Technologies to Fight Coronavirus" identifies the importance of AI, blockchain, open source-, telehealth- and gene-editing technologies, 3D printing, nanotechnology, synthetic biology, and drones and robots for fighting pandemics. As an example, *Figure F.75* depicts a photonic Covid-19 biosensor that demonstrates agile innovation by European SMEs.

Intrinsically, technology is neither good nor bad – it is the use to which it is put that makes the difference. Malicious uses of technology include mass disinformation campaigns and cyber-attacks that seek to jeopardise national security, and cyber-fraud that targets consumers. This duality has always existed. Over the coming years, technologies such as the IoT, smart robotics, automation and AI are likely to

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major challenge 2: Facilitate empowerment and resilience	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1	COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2	EMBEDDED SOFTWARE AND BEYOND 1.3	SYSTEM OF SYSTEMS 1.4	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL 2.1	CONNECTIVITY 2.2	ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4
Reliable, dependable and secure SW and HW	X		X			X	X	X
Trustable AI/ML algorithms					X			X
Advanced cybersecurity and privacy methods and tools						X	X	X
Ensuring of safety and resilience based on ECS technologies		X	X	X	X	X	X	X
Energy-efficient and dependable HW and SW solutions (e.g. for IoT devices, wearables)	X		X	X	X		X	X
Seamlessly operating SW (e.g. for IoT devices, wearables)		X	X	X		X		
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband connectivity based on 5G systems and beyond	X	X	X			X		X
Distributed (production) systems		X		X	X	X	X	X

F.76 *Required R&D&I developments within ECS – Major challenge 2* follow the same pattern. It is up to European technology specialists to ensure that the technologies developed not only support diversity and inclusion, but also protect both the individual and groups against cyber-attacks, theft of personal information and unwanted intrusion into the personal environment.

Required R&D&I developments within ECS

To facilitate empowerment and resilience, specific R&D developments are necessary within ECS technology, as shown in *Figure F.76*.

3.6.4.3 Major challenge 3: Facilitate inclusion and collective safety

3.6.4.3.1 Status, vision and expected outcome

Ambition: safeguard collective society and wellbeing for all

- Societal and digital inclusion.
- Provide societal access for all.
- Ensure collective resilience against setbacks.

Although European countries have different types of welfare models, they also share a history of robust social protection and a focus on inclusive growth, which has been under stress in recent years[152]. There could be cracks in the sustainability of the EU social contract over the next decade caused by six trends: ageing; digital technology, automation and AI; increased global competition; migration; climate change and pollution; and shifting geopolitics. Based on these trends, inequality may rise again, and divergence within Europe could increase.

Inequality at work may emerge through a combination of: (i) automation and the substitution of labour; and (ii) corporate diffusion dynamics, leading to a competitive disadvantage among non-adopting firms. To prevent reduced employment and secure real wage growth, automation through the use of AI, robotics and other new technologies should lead to significant productivity gains. In general, occupations based on more repetitive and non-digital tasks will be taken by workers with low education and skills, who will therefore be the first to experience pressure on wages.

Collective growth and wellbeing is not only determined by equality at work, but also by individual development supported by collective interactions. Studies have shown that active social relationships increase health and longevity by improving key biomarkers of physical health. A lack of interaction causes a subtle decline in mental health by reducing attention, learning, memory and decision-making skills. In short, our bodies reward us for social interaction and punish us for isolation by negatively impacting mental and physical health. Direct interactions with family and friends, participating in

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152 *Testing the resilience of Europe's inclusive growth model, McKinsey Global Institute, December 2018, p4.*

team sports and, for instance, visiting an event with friends are very important. No technology can fully replace direct contact. However, the spread of the Covid-19 virus has shown that direct social interactions may not always be as possible as we have been used to. Thus, we will have to rethink our social interactions, and find out how we can adapt existing and new technologies to increase and improve social interactions – not just between individuals but also between individuals and groups, as well as between different groups. How can improved technologies support existing social interactions, and secure healthy digital social interactions in cases of setbacks?

In addition, collective safety can be enhanced by solutions that directly address specific communities or groups of people the individual is a member of, such as family, friends, neighbourhood, region, (sports)club or association. These solutions can either have a warning or alerting function (e.g. contamination, local fire, local air pollution, incident of violence), but can also be of a supporting nature – for instance, alerts or instructions in combination with collective supporting devices (e.g. automated external defibrillator (AED), diagnostics, measurement).

3.6.4.3.2 Key focus areas

High-priority R&D&I areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Collective safety: secure access control, surveillance, pandemic control, prevention of misinformation without limiting freedom of expression.
- Safe environment for living, working and transport: buildings and bridges resilient against earthquakes through continuous monitoring (e.g. fibre-based stress sensors).
- Emergency/crisis response solutions and services.
- Dynamics of society: systemic change.

As Europe wants to play a major role in digital inclusiveness, it is important to ensure availability and accessibility of solutions to enable remote education, learning, training and assessment of professionals, students and consumers in all regions (both cities and rural areas). Also, solutions to support social inclusiveness for people of all age should become available.

The EU has stated, in their document on orientations towards the first strategic plan for implementing Horizon Europe[153], that the interaction of science, technology, social sciences and humanities will be crucial in this respect, as will be the input of the creative sector and artists to sustainable inclusive innovation and human-oriented technologies.

153 *https://ec.europa.eu/research/pdf/horizon-europe/ec_rtd_orientations-towards-the-strategic-planning.pdf*

To facilitate inclusion, more research will be needed on education, simple human–machine interfaces and digital technology interfaces that avoid the digital split between high- and low-educated citizens. In addition, remote presence and remote connectivity to keep people connected even if they are not in the same location, trustworthy social media, serious gaming, media consumption and AR/VR will be key.

To safeguard digital inclusion, education is one of the most important research areas. Examples here are the use of AI to build personalised journeys and enhance learning outcomes, to adapt curriculum to individual student needs, digital support and nudging systems to reduce the administrative burden on teachers, tablet-based learning to improve results and decrease distress for students with dyslexia, automation of administrative tasks to free up time and resources for educational professionals, wearable devices that provide real-time support to pupils, eye-tracking solutions to adapt students' learning experiences, and use of AR/VR to provide immersive experiences to civilians in less well-served areas.

AR may improve connectedness for remote places, reducing the need for commuting or business travel. It could also enable consumers to enjoy an event together even if they are not physically at the event.

There are still several challenges to effectively take full advantage of AI in video creation and consumption. One is the size of video data. Results are only accurate when algorithms are fed with millions of observations. Technologies therefore have to be deployed and strategies have to be implemented to gather data at scale to harness the full power of AI techniques. However, size creates another challenge: datasets need to be manually labelled by humans to train the model, making the process expensive and cumbersome. New techniques that are becoming available to overcome the challenge of (expensive) data categorisation are reinforcement learning, generative adversarial networks, transfer learning and "one-shot learning". In consumer-facing applications, such as marketing and recommendation algorithms, AI models may need to be refreshed continuously due to changes in the environment that drives them. Continuous updates to AI models are expensive. Other challenges relate to data management and data gathering: to create accurate results with AI, and thus value, different types of data have to be managed in a unified manner. This includes audience data, operational data and content data (metadata). Also, "selection bias" (i.e. the data gathered is not representative of the population studied) has to be prevented to exclude wrong conclusions in a perfectly working model.

To facilitate collective safety, further research is required on secure access control, intrusion detection, (video) surveillance of security sensitive areas, and individual and collective activity tracking.

Secure access control as a service (ACaaS) is growing in relevance. This combines biometric readers and identity access management, and can be integrated with other physical security systems (e.g. video surveillance) and building automation systems. Combined with building occupancy management systems, it can deliver valuable information on the location of staff and visitors, and in the event of an emergency to rapidly clear the building.

Covid-19 has brought new physical security requirements. In addition to regular cameras, thermal cameras could be added at the entrance of buildings and venues to measure people's temperature as they enter premises. Physical access control, enriched with video security evidence, can provide important insights on where an infected individual has been, which doors they have used and who else may have come into contact with those doors and that individual. It can also provide these insights for more general security purposes.

More research on AI security solutions will ease the work of security operators. AI software can analyse images and audio from video surveillance live streams and recordings, and use image recognition algorithms to recognise faces, objects and events, more than a hundred times faster than human operators. AI algorithms can also be used to carry out event detection, scene reconstruction, video tracking, object recognition, and (re)-identification, 3D pose estimation, motion estimation and image restoration. Video surveillance may be extended with freely moving cameras mounted under drones to recognise unusual behaviour in crowds from a high altitude, to monitor hazards such as fires, floods or erupting volcanoes, and to recognise criminal faces and follow targets. Since drones are airborne, they need fast mobile and wireless communications. Low-latency broadband technologies such as 5G can improve the precision and speed of their response times, and enable high-speed communication to a nearby edge computing device.

Video quality should be further improved to support deep-learning algorithms, and to improve the video experience in media consumption: the spectral range and colour gamut can be extended, sensitivity has to increase for low light use and dynamic range for better performance under all (and changing) lighting conditions.

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major challenge 3: Facilitate inclusion and collective safety	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1	COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2	EMBEDDED SOFTWARE AND BEYOND 1.3	SYSTEM OF SYSTEMS 1.4	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTRO 2.1	CONNECTIVITY 2.2	ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4
ECS technologies for AR/VR and high-quality video/videoconferencing	X	X	X		X	X	X	
Tools, methods, SW and HW technologies for extensive and ubiquitous use of AI/ML	X		X		X	X	X	
Advanced cybersecurity and privacy methods and tools						X	X	X
Intelligent connected IoT devices using new sensors for safety and resilience of EU societies	X	X	X	X	X	X	X	X
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband connectivity based on 5G systems and beyond	X	X	X			X		X

F.77 *Required R&D&I developments within ECS – Major challenge 3*

AI video and audio algorithms will have to be transparent and explainable. Dedicated video and audio technologies will be required to prevent and trace fake video and audio used to create misinformation in (social) media.

Required R&D&I developments within ECS

To facilitate inclusion and collective safety, specific R&D developments within ECS technology are necessary, as shown in *Figure F.77*.

3.6.4.4 Major challenge 4: Facilitate supportive infrastructure and a sustainable environment

3.6.4.4.1 Status, vision and expected outcome

Ambition: contribute to a collective supportive infrastructure and environment

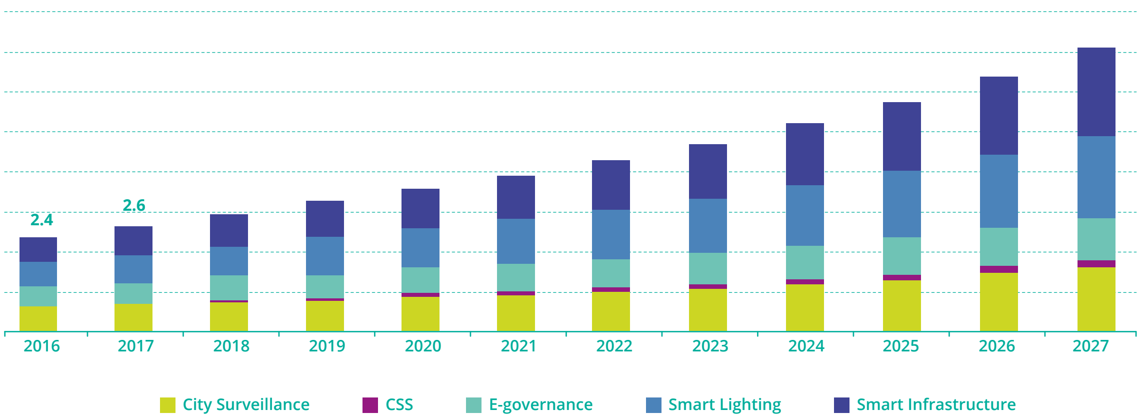
- Provide reliable and resilient infrastructure.
- Protect society against destabilising forces.
- Establish a sustainable environment.
- Secure controlled climate change.

To fully benefit from the power of digitisation, Europe must enable a supportive infrastructure and environment. Given the rapid pace of change, this requires companies to get their technology, people and culture ready to join the digital transformation. This should be achieved by providing a reliable and resilient digital infrastructure (with ubiquitous and continuous connectivity), protecting society against destabilising forces and establishing a sustainable environment. The former includes preventing harmful use of the internet (e.g. manipulation of elections, misinformation such as "deepfakes" and "cheapfakes", but also identity theft and phishing), which are covered by **Major challenge 3**. The latter includes securing controlled climate change (as stipulated in the Green Deal). Furthermore, monitoring and intelligent control of infrastructures and essential resources (especially in the urban environment) will contribute to a sustainable environment.

The vision is to introduce new digital products and services that contribute to a sustainable lifestyle in all areas of human life, including cradle-to-cradle and circular economy aspects. We are addressing the following aspects.

- Comprehensive assessment of resource usage to identify largest areas of consumption. As well as air quality monitoring systems, they need to offer solutions for lighting, heating, computing with reduced usage of energy, and other resources. In addition, solar panels and batteries, home-grown vegetables and city farming systems are key.
- Providing IoT/smart systems that support the digital business life with the minimum amount of resources (energy, water, paper, travelling, etc), ensuring a highly efficient, productive and sustainable working environment. Reduction of (food) waste in supermarkets and restaurants, as well as resource recycling.
- Smart water management to protect resources. Intelligent management of energy in public spaces such as football stadiums and railway stations, including smart street lighting. Promoting green areas in cities and enabling citizens to provide their own sustainable solutions.
- Sustainability and dealing with climate change.

U.S. SMART CITIES MARKET SIZE, BY SMART GOVERNANCE, 2016–2027 (US $ BILLION)



F.78 *Growth of US smart cities market (Source: www.grandviewresearch.com)*[154]

The European approach to working with regard to digitalisation will be focused on the preservation of our democratic system, and on values such as trust and cooperation. Ethical requirements will include fairness, accuracy, confidentiality, transparency, accountability, explainability, trustworthiness and absence of bias. This involves offering AI capability maturity programs to companies that use AI in their designs, to coach them in the best ethical points of view. In this way products will become more resilient, accessible, reliable and trustworthy, and hence ready to take part in the new European digital society.

3.6.4.4.2 Key focus areas

High-priority R&D&I areas:

- Physical infrastructure management/physical resilience.
- Intelligent infrastructure management (intelligent buildings, city-owned infrastructure, synergies with industry, etc).
- Digital infrastructure management/digital resilience.
- Smart cities: e-government/citizen support.
- Resource monitoring (air, water, etc) and feedback to enable more effective management.

To further improve digital infrastructures, investments should be aimed at enhancing infrastructure coverage and quality – for example, with broadband rollout and public Wi-Fi. Also, outcomes have to be influenced through legal frameworks and by setting standards.

Intelligent buildings will require security, eco-friendship and building management. Security systems such as access control and cybersecurity

154 *Source: Grand view Research: "Smart Cities Market Size, Share & Trends Analysis" Report by Application (Governance, Environmental Solutions, Utilities, Transportation, Healthcare), By Region, And Segment Forecasts, 2020 – 2027. See https://www.grandviewresearch.com/industry-analysis/smart-cities-market*

were covered under **Major challenge 3**, but the further development of smart lighting, air quality monitoring and control, and IoT-based real-time monitoring of electric, water and gas meters to increase the energy efficiency of buildings with the help of distributed energy systems will improve the wellbeing of occupants and reduce the carbon footprint of buildings. Smart technology (e.g. sensors placed around radiators, boilers, pumps and other machinery to detect critical levels of noise, vibration or heat) will enable facility managers to save maintenance costs by switching from a reactive to a predictive maintenance model.

Cities are very complex organisms. They combine a variety of means allowing for mobility, city infrastructure providing different types of media (gas, water, energy, etc), and citizen-oriented services that increase their quality of life. It is predicted that by 2050 between 68% and 90% of the global population might live in cities, from small municipalities right up to megacities[155]. This means that, in the near future, technical means will be required to enable digital solutions for more sustainable development in cities of all size and wealth. Available technologies from tech giants such as IBM, Microsoft, Amazon, Google and Cisco raise concerns from city managers about data privacy policies, and the very high maintenance costs caused by licence fees and the potential for vendor lock-ins[156]. Available open source solutions – such as the Red Hat integration platform, which could be used in smart city applications – can also easily be acquired by large companies such as IBM[157] to be integrated with their company product portfolio offered commercially. This means that, in such a dynamically changing world, open source solutions that are widely available, promoted and deployed within EU (such as FiWare[158]) have to be developed to protect European sovereignty and values. Additionally, due to the rich industrial heritage in many EU countries, opportunities for re-using or integrating available well-developed open source industry platforms, such as the Arrowhead Framework[159], have to be thoroughly investigated. This is especially the case since industry sites are often integrated within city areas, and therefore naturally create synergies that can influence each other. These smart city applications create natural synergies with the **System of Systems**, **Mobility** and **Digital Industry** sections.

The impact of technology on environmental sustainability is likely to be highly significant. In retail, where shifting customer habits will be key (for example, for new products such as plant- or insect-based food), IoT sensors and devices will also yield a positive impact – for example, by reducing waste through improved food temperature or expiry date management. In the manufacturing sector, smart building applications related to energy and wastewater management, as well as applications such as carbon capture and biofuel generation on industrial sites, will have a significant impact.

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155 *https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html*

156 *https://www.smartcitiesworld.net/news/news/city-governments-fear-vendor-lock-in-from-iot-platforms-3776*

157 *https://www.networkworld.com/article/3429596/ibm-fuses-its-software-with-red-hats-to-launch-hybrid-cloud-juggernaut.html*

158 *https://www.fiware.org*

159 *https://www.arrowhead.eu/arrowheadframework*

Required R&D&I developments within ECS

Development of supportive infrastructure and a sustainable environment within EU needs the following specific R&D developments within ECS technology:

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major challenge 4: Facilitate supportive infrastructure and a sustainable environment	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING 1.1	COMPONENTS, MODULES AND SYSTEMS INTEGRATION 1.2	EMBEDDED SOFTWARE AND BEYOND 1.3	SYSTEM OF SYSTEMS 1.4	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL 2.1	CONNECTIVITY 2.2	ARCHITECTURE AND DESIGN: METHODS AND TOOLS 2.3	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 2.4
Open systems and platforms for managing complex cross-connected physical infrastructure and associated processes		X	X	X			X	
Energy-efficiency oriented HW technologies and embedded SW	X		X		X	X	X	
Advanced cybersecurity and privacy methods and tools						X	X	X
Intelligent connected IoT devices using new sensors for safety and resilience of EU societies	X	X	X	X	X	X	X	X
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband low-latency connectivity based on 5G systems and beyond	X	X	X			X		X
Distributed (production) systems		X		X	X	X	X	X

F.79 *Required R&D&I developments within ECS – Major challenge 3*

3.6.5
TIMELINE

The following table illustrates the roadmaps for **Digital Society**.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2021–2025)
Major challenge 1: Facilitate individual self-fulfilment	**Topic 1.1:** Improved human–machine interaction solutions	• Intensive research on human–machine interaction solutions
	Topic 1.2: Online education and examination	• Developments of methods and solutions for online education and examination
	Topic 1.3: VR/AR training and support	• VR/AR pilots, including remote training, support and work
	Topic 1.4: Support devices (wearables, robots, cobots, chatbots, etc)	• Wearables and chatbots used for commonly used devices
	Topic 1.5: Nudging, gamification (for development or health reasons)	• New nudging, gamification systems developed for education and health
Major challenge 2: Facilitate empowerment and resilience	**Topic 2.1:** Access control/ intrusion detection/surveillance	• Classic surveillance systems
	Topic 2.2: Reliable and ubiquitous digital infrastructures	• Increased quality of service (QoS) and available bandwidth with 5G, less time-critical functions moving to the cloud
	Topic 2.3: Social media/serious gaming/AR/VR	• AR on social media moves from photos to video >80% on social media in video by 2022; in-game systems that self-adapt to guide human learning
Major challenge 3: Facilitate inclusion and collective safety	**Topic 3.1:** Digital inclusion: tools, infrastructure, training, connectivity	• Development of technologies (AR/VR, hearables, haptics, etc) for digital inclusion
	Topic 3.2: Resilient society against setbacks	• Emergency/crisis response solutions and services with ubiquitous localisation
	Topic 3.3: Societal acceptance of novel technologies	• Technologies (serious gaming, nudging, etc) for societal acceptance and adaptation
Major challenge 4: Facilitate supportive infrastructure and environment	**Topic 4.1:** Physical infrastructure management/ physical resilience	• Development of IoT and dedicated robot-based inspection systems supported by AI algorithms
	Topic 4.2: Intelligent infrastructure management	• Development of systems for intelligent management of infrastructure (water, street lighting, heat, etc)
	Topic 4.3: Digital infrastructure management/digital resilience and cybersecurity	• Acceleration of initiatives to create open, secure privacy-oriented systems; development of AI-based algorithms for increased cybersecurity
	Topic 4.4: Surveillance, homeland security and emergency response systems	• Edge/cloud solutions, IoT systems and robot-based inspection platforms, increased multimodal situational awareness, ubiquitous localisation

MEDIUM TERM (2026–2029)	**LONG TERM** (2030–2035)
• Improved human–machine interaction solutions in pilot phase	• Improved human–machine interaction solutions in the commercial phase
• Online education and examination used in most EU universities, also for education of adults	• Online education and examination widely used across the EU
• VR/AR training, support, and remote work is mature	• VR/AR training widely used across the EU
• Support devices (wearables, robots, cobots, chatbots, etc) gain more intelligence and interaction	• Support devices (wearables, robots, cobots, chatbots, etc) used in daily life
• Nudging, gamification pilots in education and health	• Nudging, gamification (for development or health reasons) is widely used across the EU
• Smart surveillance with rudimentary intrusion detection	• Smart surveillance with AI-based intrusion detection
• Bandwidth and QoS increase especially for video-based applications • Time-critical functions moved to cloud	• Bandwidth and QoS no longer an issue for video applications. • AI algorithms support supervision
• Apart from, AR also VR for videos on social media • Multimodal and multi-sensory interfaces in serious gaming • Application beyond single game. • Personal learning	• Real-time emotion state sensing • Cognitive learning
• Pilot deployments of hybrid systems for collective interactions	• Technologies for immersive collective interactions
• Trustable solutions for collective activity tracking, access control and intrusion detection	• Trustable AI-supported hybrid solutions for resilient society
• Human-oriented trustable AI systems and technologies	• Trustable AI for collective growth and wellbeing
• Pilot deployments of trustable AI-based systems relying on dependable edge/cloud IoT	• Intelligent, affordable and trustable IoT and robot-based systems are available
• Pilot deployments of trustable AI-based orchestration systems to create synergies in infrastructure management	• Smart systems for multi-domain infrastructure orchestration and management available
• Adaptation and pilot deployments of available interoperable open and reliable systems supported by trustable AI algorithms for increased cybersecurity	• Open, secure, interoperable and reliable privacy-oriented systems empowered by trustable AI-based IoT solutions available
• Deployment of trustable AI-based edge-cloud solutions, IoT systems and robot-based inspection platforms for surveillance and emergency response support	• Trustable and dependable AI-based IoT systems and robot-based inspection platforms for increased situational awareness widely available

3.6.6
SYNERGY WITH OTHER THEMES

There is synergy with several other ECS key application areas, which has been delineated as follows:

- **Mobility:** Where the **Mobility** section mainly addresses infrastructure-related aspects, **Digital Society** implies "being on the move" from time to time. The aspects addressed by the Major challenges for **Digital Society** in general therefore also apply when being on the move.
- **Digital Industry:** While sustainability is an important aspect of life in the digital society, this is also addressed in the section on **Digital Industry**.
- **Energy:** Electrical energy is a prerequisite of a digital society, as smart devices are based on it. Although in general energy generation and distribution is a different area, energy scavenging of IoT sensors and actuators, energy storage and wireless charging of smartphones and other wearables can be essential elements of a digital society.
- **Health and Wellbeing:** Where healthcare aims to cure people of diseases, wellbeing implies measures to keep healthy people healthy. The **Major challenge** "Ensuring individual empowerment and wellbeing" will contribute to the aim of keeping healthy people healthy by supportive products and services in the **Digital Society**.
- **Agrifood and Natural Resources:** The protection of natural resources can be considered part of ensuring environmental sustainability; for the rural, this is addressed in the section on **Agrifood and Natural Resources**, while the urban lies more in the scope of **Digital Society**.

There is also synergy with some other ECS technology sections:

- **Quality, Reliability, Safety and Cybersecurity**: There are relevant Major challenges in that section that link to this section on **Digital Society**: quality and reliability, ensuring dependability in connected SW, privacy and cybersecurity, safety and resilience, and human–systems integration.
- **Connectivity:** Homeland security and cybersecurity of the digital society needs reliable connectivity infrastructure.
- **System of Systems:** Smart city topics require reliable digital solutions that can handle a variety of many interconnected systems within cities.

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i For GAIA-X see https://www.data-infrastructure.eu

ii Cobots, are collaborative robots intended for direct human robot interaction.

4

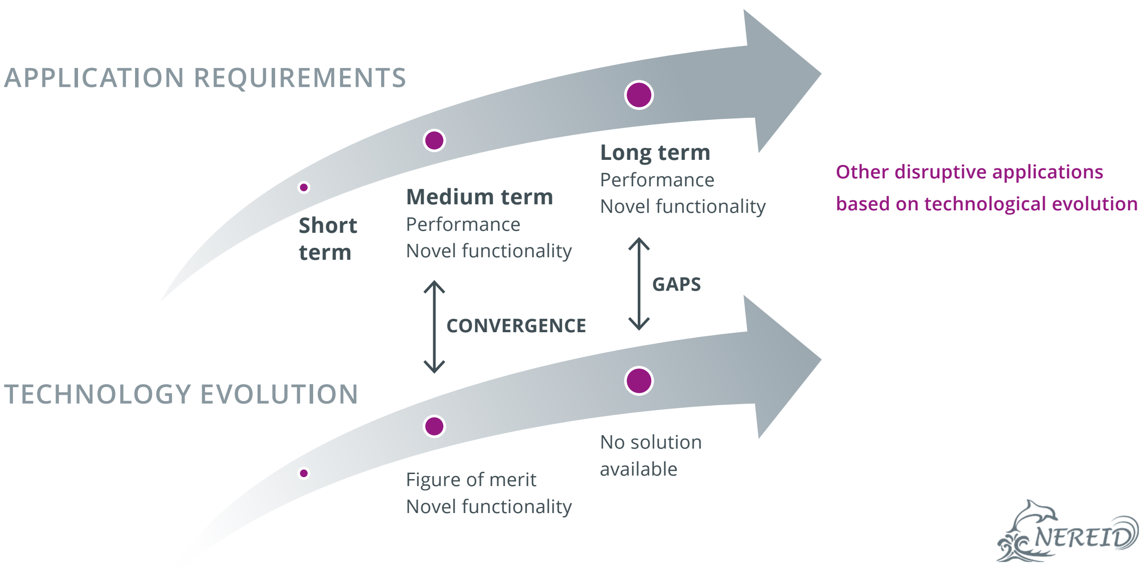
Strategic Research and Innovation Agenda 2021

LONG-TERM VISION

The objective of this chapter is to identify the research subjects that will need to be addressed as foundation and preparation for developments in European industry over the next decade. Based on the trends and plans described in the previous chapters, the long-term industrial requirements will be determined so that research programmes can be initiated to provide hardware, software and system solutions for the continuous improvement of European innovation. As the lead time from scientific breakthrough (TRL1) to the market launch of a product based on this approach (TRL9) is typically around 10 years, identifying the early signs of emerging industrial trends is a determining factor for the success and speed of innovation. In projecting these trends, general societal developments (growth of population, urbanisation, etc) have also to be taken into account.

The long-term vision for European technological success is built upon an anticipated relationship between the evolution of technology and the requirements for its application (see *Figure F.80*). Future applications will be enabled by enhanced performance and novel functionalities generated by new technology options (in both hardware and software), as projected in the technology application roadmaps. In addition, there have always been disruptive developments in the field of technology that were not anticipated in the roadmaps available at the time. Nevertheless, these unexpected developments may have a tremendous impact. They might even lead to a paradigm shift in the way we conduct business or organise our daily life – the unpredicted emergence of the internet in the early 1990s is a very prominent example of this. Current developments, such as in the domains of Artificial Intelligence and the Internet of Things, may give rise to similar disruptive innovations. To ensure that the precursors of the next technology revolution are identified early so that its opportunities can be of benefit, close cooperation between academic, institutional and industrial stakeholders along the value chain is a prerequisite. This cooperation is traditionally strong in Europe, as exemplified by the European Framework Programme and public/private partnerships over the last 30 years, and this will remain a valuable European strategic asset in the coming years.

This strength is based on the availability of numerous research facilities with extensive experience in the ECS domain. This comprehensive ecosystem of universities, RTOs and industrial research organisations



Technology evolution and application requirements (Source: NEREID) F.80

across many countries in Europe forms an effective incubator for pioneering new breakthrough technologies that can enable the creation of hyper-smart, safe, secure and resource-efficient electronic components and systems. This ecosystem is the foundation for maintaining the competitiveness of the European ECS industry now and into the future. It enables increasingly networked scientific research, and offers the best opportunities for coping with growing interdependencies and interdisciplinarity through a strong coupling of basic and applied research within the European Framework Programme. This, in turn, creates the fertile soil from which industry can achieve breakthrough technological solutions with minimal time to market and thus maintain European technological leadership in this area. It is no exaggeration to state that long-term European technological leadership is the cornerstone for prosperity and peace on our continent.

Over the last few decades, the ECS domain has evolved from being technology-driven to an environment where societal needs and application requirements guide the research agendas of the centres of expertise. The European competences in both "More Moore" and "More than Moore"[160] have been instrumental in bringing about this change, resulting in a strong European position in markets that require complex multifunctional smart systems. There is no doubt that the safeguarding and further extension of these competences, while adapting state-of-the-art findings from other scientific domains, is essential for a continuous offering of disruptive technologies that will ensure the preservation of Europe's competitive position.

A list of anticipated disruptive technologies can, by its very nature, never be complete. In this chapter, the main research trends that are of particular importance for the European strategic research and innovation agenda will be addressed. These are described within the scope of four main common objectives (see *Chapter 0*), aligned with European strategic targets:

01. Boost industrial competitiveness through interdisciplinary technology innovations.
02. Ensure EU strategic autonomy through secure, safe and reliable ECS supporting key European application domains.
03. Establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal.
04. Unleash the full potential of intelligent and autonomous ECS-based systems for the European digital era.

It should be noted that most research and innovation topics contribute to the achievement of several of these main common objectives. Therefore, the assignment of a research subject to one section in this Long-Term Vision chapter does not mean that the benefits of the advances on that topic will be limited to the strategic goal under which it is discussed.

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160 *IRDS™ More than Moore White Paper IRDS™ 2020: More than Moore – IEEE International Roadmap for Devices and Systems™*

4.1
INDUSTRIAL COMPETITIVENESS

Industrial competitiveness is not only determined by the availability and continuous development of state-of-the-art technologies, but also by novel solutions that result from interdisciplinary technology innovation. Consequently, all subjects discussed in this chapter are relevant for European industrial competitiveness. In this section, the focus will be on a set of capabilities that are essential for the preservation and advancement of European innovation strength:

- Connectivity.
- Process technology, equipment and materials.
- Digital industry.

4.1.1 Next-generation connectivity

With mobility being everywhere, connectivity and interoperability have become key enablers for supporting the development of innovative applications in various markets (e.g. consumer, automotive, digital manufacturing, network infrastructure). The availability of new innovative connectivity technologies (e.g. IoT, 5G, car-to-car) will enable and enhance a wide range of new business opportunities for European industry, and will also significantly contribute to unleashing the full potential of intelligent and autonomous ECS-based systems for the European digital era (main common objective 4).

Long-term roadmaps for connectivity and interoperability will guide a seamless integration of various technologies (hardware and software) for the development of complex connected systems in an effective manner.

Three **Major challenges** will have to be addressed in the connectivity roadmap until 2050.

Major challenge 1: Meeting future connectivity requirements leveraging heterogeneous technologies
Vision: Targeting systems and applications, it is important to consider the interconnection between subsystems, and there should be a focus on individual component technology development according to needs identified at a system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is crucial.

Major challenge 2: Enabling nearly lossless interoperability across protocols, encodings and semantics
Vision: To fully leverage this heterogeneous integration at the hardware level, software interoperability is a parallel challenge to provide connectivity that allows for System of Systems (SoS) integration. Thus, an additional **Major challenge** is to enable SoS integration through nearly lossless interoperability across protocols, encodings and semantics. Dedicated software tools, reference architecture and standardisation are key to supporting SoS integration, thereby enabling the provision of a scalable and evolvable SoS. As it remains very difficult to assume that highly customised embedded systems will be built based on a single, unified, high-level modelling principle and toolset, there is a quest for consolidation, or even the standardisation of basic run-time frameworks, component libraries and subsystem interfaces that will facilitate the deployment of interoperable components into generic, domain-specific solutions and architectural frameworks in a bottom-up approach. This 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.

Major challenge 3: Ensuring secure connectivity and interoperability
Vision: Data protection has to be ensured at an appropriate level for each user and functionality regardless of the technology. Ensuring security interoperability across any connectivity anticipates the usage of different technologies in connectivity networks. Technology differences impose security incompatibilities that can lead to increased engineering costs. Therefore, the development of an innovative hardware and software security solution that supports and provides correctness and safety is of fundamental importance. Such a solution will have to be linked to the previous **Major challenges** to facilitate SoS engineering, deployment and operation in a seamless way.

Security assessment is also a significant issue considering the criticality of applications. Standards and directives are required not only for technology transfer and system evaluation, but also for legal purposes in conjunction with the GDPR legal framework and emerging laws regarding European and national cybersecurity requirements. Approaches are required to continuously verify that security, safety and integrity are maintained in the overall system[161].

4.1.2 Future ECS and their process technology, equipment and materials

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

In the More Moore field, there are strong interests in Europe for specific activities that involve very low power devices, leading to possible disruptive applications – for instance, for future IoT systems, embedded memories, 3D sequential integration or application-driven performance (e.g. high temperature operations in the automotive industry).

New materials (strained semiconductors, Ge, III-V, 2D such as transition metal dichalcogenides or phosphorene, 1D such as carbon nanotubes (CNTs) or nanowires, ferroelectric, magnetic, etc), ultimate processing technologies (EUV, immersion multiple patterning, multi e-beam, imprint lithography, self-assembly, etc) and novel nanodevice architectures (gate-all-around, horizontal or vertical nanowire FETs with co-integration of different channel materials, nanosheet devices, CNT FETs, negative capacitance FETs, tunnel FETs, NEMS, hybrid devices such as tunnel FETs (TFETs) with ferroelectric gate, non-charge-

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161 *Ani Bicaku, Markus Tauber, Jerker Delsing (2020), Security standard compliance and continuous verification for Industrial Internet of Things. International Journal of Distributed Sensor Networks. https://doi.org/10.1177/1550147720922731*

based memories, 3D integration, etc) are mandatory for different applications, as well as new circuit design techniques, architectures and embedded software. Some of these nanostructures are also very interesting for advanced sensors (e.g. 1D and 2D materials, nanowires, CNT or TFET architectures) with high sensitivity or high performance energy harvesters (e.g. nanowires). All of these are key for future high performance/ultra-low power terascale 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 have to be addressed to ensure successful application of these nanotechnologies. A number of these are described briefly below.

- For nanowires, which are very useful for very low-power nanoscale devices (and therefore important for European innovation), the best material and geometry options for logic (high speed as well as low power) need to be identified. Millimetre-wave front-ends with III-V MOSFETs have to be developed (with applications in communications, radar, etc), including 3D aspects of processing.
- For negative capacitance field-effect transistors (NCFETs), which are suitable for very low power devices, it is key to identify the maximum switching speed and optimal dimensions, and to develop thin hafnium-based ferroelectric layers and investigate the scaling potential of these devices.
- For TFETs, which are promising steep subthreshold slope devices in the "beyond CMOS" domain, the development of novel materials and device architectures to overcome driving current limitations is crucial.
- For nano-electro-mechanical FETs (NEMS-FET), low voltage reliable devices have to be developed.
- For carbon nanotube FETs (CNT-FETs), which are useful for very fast, and possibly ultimately scaled, transistors for logic applications, and which could be produced by self-assembly based fabrication, solutions have to be developed to lower the Schottky barrier at source/drain. In addition, solutions are required to remove metallic CNTs, and a quicker process is desirable. Design strategies also have to be developed to deal with the variability induced by m-CNTs and doping fluctuation. The gate stack architecture is a particular challenge for these fully passivated surfaces.

In the field of alternative memories, resistive RAM, magnetic RAM and ferroelectric RAM/FeFET will be key for driving the limits of integration and performance beyond that afforded by existing non-volatile, DRAM and SRAM memories:

- Resistive random-access memory (RRAM): Offers advantages in speed and density, and is compatible with CMOS. Research is vital on materials, reliability and maintainability.
- Metal oxide-resistive RAM (OxRAM): High resistance state (HRS) broadening is the challenge here. New materials and programming schemes should be investigated.
- Conductive-bridging RAM (CBRAM): The issues to be investigated here are the same as with OxRAM, with additional special focus on data retention, which is probably the most challenging area for CBRAM.
- Magneto-resistive RAM (MRAM), especially spin-transfer torque (STT): Integration problems in this area (e.g. etching) can be much harder to solve than expected. The high current consumption can also be a serious drawback for practical applications (in particular, the IoT).
- Ferroelectric field-effect transistor (FeFET): Widening the material screening is key, in addition to the standard $Si:HfO_2$. Much research is required on the interface between channel and Fe layer.

In addition to components managing information, devices aimed at directly monitoring the condition of people, assets, processes and environments will be essential. The demand for these devices will extend to a wider diversity of application scenarios, and will be required to have a faster response, greater sensitivity, more robustness, larger functionality and lower energy consumption. This will bring higher levels of heterogeneity and hybridisation of More than Moore processes and materials. Recently, the 5e federation was launched to appraise the potential interaction of European ecosystems in nanoelectronics, electronic smart systems, and flexible, organic and printed electronics[162]. Combinations of nanoelectronics and flexible organic and printed electronics that provide functionalities to electronic smart systems will lead to novel solutions. This trend towards the concept of functional electronics is characterised by the following aspects.

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

A 3D place-and-route tool needs to be developed for 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). 3D sequential processes 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 the communication of health problems, environmental quality and security, secure transport, building and industrial monitoring, entertainment, education, etc.

For modelling/simulation, characterisation and reliability, which are also strong European domains, new tools are required that take into account all the new materials, technologies and device architectures to speed up technology optimisation and reduce the cost of development.

4.1.3 Digital industry

Essential for Europe's economic autonomy is the preservation of a competitive manufacturing industry. This can only be achieved by continuous innovation, based upon an uninterrupted development of novel leading-edge ECS technologies.

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162 *https://5e-project.eu*

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163 *https://www.spire2030.eu/what/walking-the-spire-roadmap/spire-Roadmap*

164 *https://www.effra.eu/factories-future-roadmap*

165 *https://www.effra.eu/connectedfactories*

Manufacturing industries can essentially be classified into two main categories: process industry and discrete product manufacturing. Process industries transform material resources (raw materials, feedstock) during a (typical) (semi-)continuous conversion into a new material that has significantly different physical and chemical performance than the starting substance. Discrete manufacturing refers to the production of distinct items, such as automobiles, furniture, toys, smartphones and airplanes. The resulting products are easily identifiable and differ greatly from process manufacturing, where the products are undifferentiated (e.g. oil, natural gas and salt).

Another meaningful way to distinguish between manufacturing industries is by dissecting the domain by its end-product categories, such as energy, chemicals, petrochemicals (oil and gas), food, pharmaceuticals, pulp and paper, steel industry (process industries), as well as car manufacturing, machines, robotics and semiconductors. These subdomains constitute significant industrial areas for Europe, and are increasingly demanding and major consumers of ECS technologies – such as sensors, big data, Artificial Intelligence, real-time systems, digital twins, safety and security, computing systems, lifecycle engineering, human–system integration, etc. ECS technologies are essential parts of most of the advances in these domains.

The industries' perspective is presented in the SPIRE Roadmap 2030 and the SPIRE Vision 2050, which lists the following targets[163].

- Replacement of fossil-based materials by bio-based materials requiring completely new processes.
- Re-use of waste streams that require complete redesign of materials, products and related production processes.
- New resource-efficient applications that require completely new designed processes.
- Complete redesign of industrial parks to realise industrial symbiosis.

These are overall targets, which translate into diverse and much more practical targets in each domain, and which also lead to a number of technology challenges in the ECS-SRIA.

The Factories of the Future roadmap, produced by the European Factories of the Future Research Association (EFFRA), summarises its vision as follows[164].

- Agile value networks through lot-size one/distributed manufacturing.
- Excellence in manufacturing through advanced manufacturing processes and services for zero-defect and innovative processes and products.
- The human factor, to develop human competences in synergy with technological progress.
- Sustainable value networks through manufacturing driving the circular economy.
- Interoperable digital manufacturing platforms that support an ecosystem of manufacturing services.

EFFRA's Connected Factories project also forecasts the emergence of new manufacturing concepts are emerging, such as[165]:

- Hyperconnected factories.
- Autonomous factories.
- Collaborative product-service factories.

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 a need to invest in technology research and innovation projects on the following topics.

- The rise of AI and an increasing focus on powerful edge and cloud computing networks. Methods and algorithms will be required to evolve for more complex, reliable and dependable AI.
- A greater amount of measurement-originated data, images and videos, 3D design, animation, data, and more heterogeneous and unstructured data.
- New production schemes, such as:
  - Modular factories (i.e. smaller standard units to be assembled according to need, also mobile units).
  - More end-user driven agile production (i.e. end-users more connected to production and logistics chains).
  - Hyperconnected factories.
- Towards closer-to-customers production through new production technologies (e.g. 3D printing and other novel manufacturing methods).
- Extending closed-loop production lines to closed-loop regions (e.g. extensive recycling, net energy, zero emissions and waste, close to end-users).
- From autonomous to human–machine co-work as a means to enable flexibility and reduce excessive complexity.

Over the next decade, digital industry will increasingly become a producer and enabler of "green electronics", with electronic components and systems being recycled as much as possible.

4.2 EUROPE'S DIGITAL AUTONOMY

In the changing political and economic landscape worldwide, unrestricted access to goods and free exchange of knowhow and information, protected and regulated by multilateral agreements, can no longer be taken for granted. This implies the EU will need to have policies to protect its strategic autonomy and sustain its competitiveness. This is particularly the case for the ECS industry, which constitutes the backbone of the digital society.

This section addresses the **Major challenges** required to ensure that European competence in ECS will be preserved going forward to 2050.

4.2.1 Digital autonomy

Digital autonomy – the ability of the EU to maintain a high level of control and security of its products, and to respond quickly if potential vulnerabilities are perceived – is of the utmost importance. This is especially relevant in view of the fact that, for the major economic drivers of digitisation and connectivity, Europe is very dependent on the supply of hardware and software from countries outside Europe. This challenge has to be addressed, both in the short and long term, by research programmes on the following topics.

- The development of rigorous methodologies, supported by evidence, that demonstrate a system is secure and safe to achieve the highest level of trustworthiness. These methodologies should be supported by certificates of extensive testing, a new code covering metrics (mutation testing), security testing (fuzzing), and formal methods for providing guarantees of trustworthiness.

- Privacy and data integrity are fundamental to data protection and correct computations that enable computer-based or computer-supported decisions. Methods for security-by-design and safety-by-design need to be developed to reduce cyberattack and emerging problems. The extension of CPS to include AI and ML components makes the requirement for data integrity even stronger since it also affects algorithmic correctness in light of adversarial attacks. The scalability of IoT and its inclusion of cloud applications constitute a challenge that needs new solutions that not only address open cloud security issues but also involve standardisation and certification. As CPS and IoT are increasingly affecting our everyday lives, especially in domains such as health, driving, etc, legal and social aspects need to be researched as well.
- Trustworthiness represents a major challenge over the next decade. Ensuring this will require "modular certification of trustable systems and liability" where a system could include AI functionality. A long-term vision should address more mature liability, where formal methods, supported by evidence, are used to provide guarantees of trustworthiness and dependability. Moreover, such a vision should embrace the development of explainable AI models for both human interaction and system interaction, and also for certification. In addition, trustworthiness should include communications, as mentioned in *section 4.1.1.* in regard to **Major challenge 3:** "Ensuring secure connectivity and interoperability".
- Radical AI developments will enable unprecedented integration of quality, reliability, safety and security in digital data and digital processes, and especially drive model-based engineering and contributing to reducing the development cycles of robust ECS. AI-enabled distributed software will be executed in edge and cloud architecture, allowing for seamless and ubiquitous integration of the cyber-physical intelligent systems with real processes and systems.

4.2.2 Digital healthcare

ECS will continue to be key enablers in realising the continuum of healthcare, notably by linking wellbeing, diagnostics, therapeutic approaches and rehabilitation issues. In addition to providing tools for the personal management of individual health and monitoring of health conditions, ECS and smart systems will play an active role in assistive technologies with the goal of reducing inequalities associated with impairments originating from loss of physiological or anatomical structure or function after a disease or accident. "Ambient Assisted Living" (AAL) is also a high-priority objective for Europe to support its increasingly ageing population.

Beyond 2030, personalised and patient-tailored healthcare will be at the forefront of technology advancement. The key challenges here are not only technological, dealing with subjects such as reliability, safety and privacy, but also include issues such as regulation and uptake by practitioners, especially when dealing with procurement policies.

A priority here 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.

Further miniaturisation of biomedical devices and integration of smart integrated systems (e.g. smart catheters, electroceuticals) will have significant impact on point-of-care diagnosis and treatment. Real-time localised detection of disease and minimally invasive targeted drug delivery will be a key priority.

Achieving enhanced reliability and building stakeholder confidence in these technology advancements will be crucial 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 greater focus on tailored patient diagnosis and treatment.

Digital medicine

Improvements in medicine over the years has greatly benefited from advancements in other disciplines. It has evolved from "mechanical" medicine (surgery) towards "chemistry" medicine, and more recently "biotech" medicine. Developments in ICT and digitisation are having an important impact on the way healthcare is addressed. Ten years from now "digital medicine" will be deployed that will complement, although not necessarily replace, the tools offered to medicine to benefit both patients and medical professionals.

These tools may, for instance, be in silico human models allowing for "digital twins". However, ECS will also play a crucial role in ensuring the necessary link between digital and real twins. Sensor signal processing, especially related to data collection from on-body IoT sensors, is a key technology that will advance existing wearables that provide real-time sensory information, and enable identification and prediction of a person's health condition. The use of AI technologies, based on extended measurement data, will also provide significant advances in this area. Furthermore, the deployment of smart automated solutions for healthcare will improve clinical outcomes and professional proficiency.

Finally, progress in interfacing electronic components and systems with biological systems will offer seamless connection to the body for continuous monitoring, as well as for electro-stimulation purposes. Results from the flagship Human Brain Project will provide input for improved deep brain stimulation. In addition, electroceuticals and nerve stimulation will enhance the treatment of diseases and partially replace pharmaceutical treatments, thus avoiding side effects.

Some developments in this area are presented below.

- Fully personalised medicine will be enabled by the smart monitoring of health parameters, including factors from the molecular to the environmental level: Developments in healthcare will provide prediction of health evolution and preventive treatment through the concept of digital twins. Drug development will be assisted by emerging methodologies such as organ-on-a-chip. Fully personalised and accurate health data will be available anywhere, anytime.
- 3D bioprinting: Medicine is greatly benefiting from advances in other disciplines, such as genomics and 3D printing. Combining the 3D printing of living material and electronic systems will develop a bottom-up approach to medicine, with advanced and personalised prosthetics and implants increasing biocompatibility, solving the problem of powering and increasing quality of life.
- Cyborgisation: Future brain–computer interface (BCI) technology will enable new modes of communication, including for people with severe disabilities. By the 2040s, wearable or implantable BCI technology could well make smartphones obsolete. Due to the massive exposition of physical and biological worlds in cyberspace, BCI systems will incorporate new means for the protection of technology, data and consciousness – such as heartbeat, venous system, functional magnetic resonance imaging (fMRI) and "brainprints" – as the main security measures.

Innovation in the medical domain can be accelerated by the creation of ECS-based technology platforms for medical applications. The following list of emerging medical domains was compiled by the Health.E Lighthouse initiative[166].

- Bioelectronic medicines.
- Organ-on-a-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.

The list of challenges that ECS will face over the next decade is changing, and new challenges linked to the developments described above will need to be addressed. Security and reliability will remain major issues to guarantee the safety and integrity of medicine, and regulation has to be developed to tackle these concerns. Furthermore, ethical issues may become increasingly critical in the uptake of patients, which may lead to fundamental decisions on how medicine will evolve.

4.2.3 Cities of the future

The cities of the future are expected to be secure, safe and reliable. A comprehensive definition describes smart cities as "innovative cities that use ICT and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that they meet the needs of present and future generations with respect to economic, social, environmental, as well as cultural aspects"[167]. Digital transformation is crucial to identify the directions that a smart city should follow to shift from being an isolated environment to an intelligent municipality[168, 169].

To make the cities of the future intelligent, the first step is represented by the definition and deployment of a reliable connectivity infrastructure, supported by heterogeneous networking, allowing information exchange in the most flexible way[170]. Devising a smart city should improve the life quality of citizens, also through the use of IoT-oriented (or, more generally, SoS) technologies,[171] thus increasing the efficiency of services. This should also include efforts to make the best use of existing resources (e.g. managing food production, congestion and pollution) to maximise the safety and security of citizens[172, 173]. Such digital transformation is expected to provide European cities with the ability to interact and support each other efficiently, thus fostering European

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166 *https://www.health-lighthouse.eu/emerging-medical-domains*

167 *S.E. Bibri, J. Krogstie, "Smart sustainable cities of the future: An extensive interdisciplinary literature review." Sustain. Cities Soc. (2017) 31, 183–212.*

168 *M. Hämäläinen, "A Framework for a Smart City Design: Digital Transformation in the Helsinki Smart City." in Entrepreneurship and the Community: A Multidisciplinary Perspective on Creativity, Social Challenges, and Business; Springer International Publishing: Cham, Switzerland, 2020; pp. 63–86.*

169 *K. Tomicic Pupek, I. Pihir, M. Tomicic Furjan, "Smart City Initiatives in the Context of Digital Transformation—Scope, Services and Technologies." Management) 2019, 24, 39–54.*

170 *L. Belli, A. Cilfone, L. Davoli, G. Ferrari, P. Adorni, F. Di Nocera, A. Dall'Olio, C. Pellegrini, M. Mordacci, and E. Bertolotti, "IoT-enabled smart sustainable cities: challenges and approaches", Smart Cities, vol. 3 (2020), no. 3, pp. 1039–1071. DOI: 10.3390/smartcities3030052.*

171 *M. Lederer, J. Knapp, P. Schott, "The digital future has many names—How business process management drives the digital transformation" in Proceedings of the 2017 6th International Conference on Industrial Technology and Management (ICITM), Cambridge, UK, 7–10 March 2017; pp. 22–26.*

172 *E. Crisostomi, R. Shorten, F. Wirth, "Smart Cities: A Golden Age for Control Theory?" IEEE Technol. Soc. Mag. (2016), 35, 23–24.*

173 *S. Musa, "Smart Cities—A Road Map for Development" IEEE Potentials (2018), 37, 19–23.*

autonomy at the urban level and paving the way to more secure and safer European urban scenarios. Furthermore, a European effort in developing corresponding technologies will reduce dependency on others in realising these cities.

4.2.4 Digital farming

Over the following decades the global population will increase, rising to an estimated peak of 9.78 billion by 2064[174]. By the middle of the century, about two-thirds of the population will live in urban areas[175]. This will require new digital approaches to supply the growing number of people with food, which will involve a great threat to food security for certain countries and especially for large cities. Digitalisation has already helped initiate open field farming through precision agriculture, but there are other ways of targeting this issue, especially by the emerging areas of "digital farming" and "vertical farming". In this form of farming, plants are grown in vertical arrays, inside buildings, where growing conditions can be optimised. Crops are supplied with nutrients via a monitored system under artificial lighting and can thus be grown year-round. This method makes it possible to grow plants without soil and natural sunlight, with optimal growth conditions being created artificially. The full potential of this approach can only be achieved with the help of information technology (IT) and IoT components and paradigms such as AI and Industry 4.0, which all still need to be adopted for this purpose. With these digital farming approaches, it will be possible to secure food supply autonomy and food safety for large parts of the EU. Furthermore, investigation into the provision of corresponding technologies and approaches will enhance the strategic autonomy of Europe.

4.3 SUSTAINABILITY AND THE GREEN DEAL

Since climate change and environmental degradation is posing an existential threat to Europe and the world, a strategy known as the European Green Deal has been defined with the objective to make the economy of the EU sustainable in the long term[176]. By 2050, a modern resource-efficient and competitive economy must be in place, characterised by:

- zero net emissions of greenhouse gases.
- economic growth decoupled from resource use.
- no person and no place being left behind.

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[174] *DESA, UN (2018): World urbanization prospects: the 2018 revision, key facts. New York: NY. Available online at: https://population.un.org/wup/Publications/ (Accessed 12.05.2020)*

[175] *S.E. Vollset, et al., Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study, https://www.thelancet.com/pdfs/journals/lancet/PIIS0140-6736(20)30677-2.pdf*

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

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[177] *https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf*

The ECS community will be instrumental in the realisation of the European Green Deal. In particular, the many challenges associated with energy management can only be tackled by ECS-based solutions. This, of course, implies that ECS devices themselves should be increasingly energy-efficient.

4.3.1 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 stabilisation of the power grids with an increased share of fluctuating renewable energy sources.
- highly efficient, variable speed, motor drives.
- energy-efficient and low-emission mobility with hybrid and full electric vehicles.
- energy-saving lighting technology.
- efficient recovery of braking energy.
- energy management of batteries.
- control appliances and building management systems via the grid interface (smart grids).

The estimated energy savings that can be achieved by introducing state-of-the-art and future power electronics components into systems 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. 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 band gap 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, three **Major challenges** were identified:[177]

Major challenge 1. Ensuring sustainable power generation and energy conversion
Vision: The ultimate goal is loss-free energy conversion and generation. The target is to achieve approximately 99% efficiency by 2030.

Major challenge 2. Achieving efficient community energy management
Vision: The decentralisation of energy sources, opportunities with networked systems, limitations in peak electricity supply, oversupply times, new demand for electric energy supply for urban mobility, and the introduction of storage systems will lead to new challenges in energy management and distribution for communities and cities.

Major challenge 3. Reducing energy consumption
Vision: The vision for 2030 is to achieve the current EU policy target of 30% savings by utilising innovative ECS-based solutions.

4.3.2 Transport and mobility

The EU has issued ambitious policy statements regarding transport and smart mobility[178].

- Emissions from transport should 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 that is safe, connected and clean.

To realise this vision, possible scenarios include the projection that mainly autonomous and electrically driven vehicles 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 powerful edge nodes (mobile edge computing, MEC), will enable highly effective vehicular communications for traffic management and safety applications. Where latency can be still a problem for swift decisions based on networked information, smart systems-based autonomous response should take over. 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. New concepts of electric propulsion aerial vehicles for personalised short-range movements will be introduced, creating a massive push for technological advances.

4.3.3 Digital support for sustainability

Sustainability is supported by digital farming, where plants are being produced in a fully controlled environment with the help of IT, IoT components and AI, as this will reduce requirements for water, pesticides and chemicals in the production of plants.[179] Food supply chains produce vast amounts of CO_2 in transporting essential foods to the consumer. Smart farming would tackle this form of greenhouse gas emissions through producing food locally.[180] A shorter route from harvesting to consumer can be achieved, but will require new approaches in logistics and the distribution of food. In addition, Industry 4.0 approaches, where operational technology (OT) meets IT, could be adopted for this purpose. Nevertheless, as traditional farming cannot be replaced in all areas, further investigation into continuously improving the production of food via digital tools should remain on the agenda.

The cities of the future are expected to be sustainable and inclusive. More generally, the proper digital transformation process for a smart city is further related to the need to collect data produced by heterogeneous sources (e.g. data streams from bicycle sharing schemes, car parks, air quality sensor data)[181, 182], and to analyse these in a close to real time way[183, 184], so that city planners can employ the most up-to-date predictive models for their planning activities. As an example, the following are associated with activities that may be of interest for municipalities looking to improve their sustainability level.

- Strategic Environmental Assessment Plan (SEAP): Targets a reduction of CO_2 emissions of a certain percentage.
- Sustainable Urban Mobility Plan (SUMP): Aims to reduce private car usage, re-design public transport networks, develop intermodality and interconnection with different urban transfer systems, improve environmental quality, and reduce transport costs, energy consumption and waste of resources.
- Sustainable Energy and Climate Action Plan (SECAP): Aims at mitigating the environmental problems through the decarbonisation process, adapting to climate changes, and increasing energy efficiency for secure and sustainable energy management.

There are already several smart city deployments based on custom systems and solutions, but these are not always suitable for other cities around the globe, and in some cases are only a subset of the various aspects that need to be considered. A long-term vision of the cities of the future calls for common digital paradigms for sustainability to be applicable to the largest possible set of urban scenarios.

4.4 INTELLIGENT AND AUTONOMOUS ECS FOR THE DIGITAL AGE

“Digital age” is the generic term for the trend that industrial, societal and economic activities will increasingly be enabled and characterised by microelectronics and ICT-based technologies. This development began with the invention of the solid-state transistor and the production of integrated circuits in the second half of the 20th century, which gave rise

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178 *https://ec.europa.eu/transport/road_safety/home_en*

179 *C. Gnauer, H. Pichler, , C. Schmittner, M. Tauber, K. Christl, J. Knapitsch, M. Parapatits, "A recommendation for suitable technologies for an indoor farming framework", e&i Elektrotechnik und Informationstechnik 137 (2020), 370–374*

180 *P. Pinstrup-Andersen, R. Pandya-Lorch, M.W. Rosegrant, “Global food security”’ in The unfinished agenda, IFPRI, Washington (2001), pp. 7–17)*

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181 *V. Okrepilov, S. Kuzmina, S. Kuznetsov, “Tools of quality economics: Sustainable development of a ‘smart city’ under conditions of digital transformation of the economy” IOP Conf. Ser. Mater. Sci. Eng. (2019), 497, 012134.*

182 *I.O. Pappas, P. Mikalef, M.N. Giannakos, J. Krogstie, G. Lekakos, “Big data and business analytics ecosystems: Paving the way towards digital transformation and sustainable societies”, Inf. Syst. E Bus. Manag. (2018), 16, 479–491*

183 *M.N.I. Sarker, M. Wu, M.A. Hossin, “Smart Governance through Bigdata: Digital Transformation of Public Agencies”, in Proceedings of the 2018 International Conference on Artificial Intelligence and Big Data (ICAIBD), Chengdu, China (2018); pp. 62–70*

184 *M. Scriney, M. Roantree, “Efficient Cube Construction for Smart City Data", in Proceedings of the Workshops of the EDBT/ICDT 2016 Joint Conference, EDBT/ICDT Workshops 2016, Bordeaux, France, (2016), pp. 1–5*

to the semiconductor-based technology drive as described by Moore's Law and entered the consumer domain in an increasingly wide range of applications, from personal computers to mobile phones and the internet. Whereas this technology drive could be seen as a determining factor for electronic innovation up to the 1990s, the "digital society" that has been evolving in the new millennium is much more characterised by the requirements of emerging applications in a wide range of economic and societal domains (industrial production, healthcare, transportation, infrastructure, communication, etc). All these applications require highly sophisticated hardware- and software-based intelligent systems with high levels of autonomy with advanced adaptability and reconfiguration capabilities that enable completely innovative products and services targeting all aspects of our society.

The challenges that the digitalisation of society brings have to be addressed, not only in the next few years but also in the longer term, since the growing complexity of these challenges will have to be anticipated, understood and solved by extensive research programmes incorporating novel domains (e.g. AI, cyber-physical systems, the Internet of Things and next-generation computing). This has to be achieved through a comprehensive approach that ensures these technological directions are fully integrated, demonstrated in real life, and embedded in applications with seamless interoperability, connectivity and hardware/software integration. Some long-term trends that are indicative for the digital age are discussed below.

4.4.1 Embedded intelligence

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

In the domain of embedded intelligence, the following trends can be identified.

- Ubiquitous AI.
- AI in the cloud and at the edge.
- Intelligent data-driven industrial processes/production lines.
- AI in silicon.
- Massive optimisation in real time.
- Advanced perception based on multidimensional data streams in close to real time.
- Autonomous AI re-usability.
- New concepts of AI-based processes for learning and reasoning.

The **Major challenges** are discussed in the chapter on **Artificial Intelligence, Edge Computing and Advanced Control**. In this section, only the long-term aspects of these **Major challenges** will be summarised.

Increasing the energy efficiency of computing systems serving AI

- Computing systems are most efficient if data processing is done as close as possible to where it is created. This requires a dynamic instantiation of multi-paradigm computing resources according to the specifications of the tasks to be performed. This includes automatic interfacing, discovery and interfacing of resources, which is an essential AI capability.

- Quantum computing will be explored for its possible use in AI-based concepts. Neuromorphic and other advanced hardware architectures will require hybrid system solutions through the integration of multiple computing paradigms (classical, deep learning, neuromorphic, photonic, etc) in the same package. Complete 2.5D ecosystems (incorporating chiplets and interposers) will re-use chiplets in different designs, with tools increasing productivity.
- Automatic interoperability is to be achieved at all levels, from chip to systems, adapting to data structures and physical interfaces with respect to communication characteristics. Global reconfiguration of the resources to satisfy the functional and non-functional requirements (latency, energy, etc) should be possible.
- Linear and/or functional scalability should be feasible for AI towards 2030 and beyond. Functionalities will be simulated as digital twins.
- Semi-automated co-design of algorithms, hardware, software and topologies should enable auto-configuration of a distributed set of resources to satisfy both functional and non-functional application requirements.

Managing the increasing complexity of embedded intelligent systems

- A balanced mechanism between the performance and interoperability of complex embedded intelligent systems should be achieved by partitioning through standard interfaces.
- The adaptation of new models has to be enabled and stimulated by a generic model-based digital development system for embedded intelligence.
- AI-based techniques must provide solutions in complexity management. This requires the development of modelling simulation tools for digital twins.

Interdisciplinarity for domain-specific AI applications

- New application domains such as smart cities and digital farming will consist of multiple autonomous components that must be able to adapt to changing external condition without human intervention. In such a complex environment, approaches are required that take into account interdisciplinary between IT/OT and domain experts for autonomously resolving potential conflicts[185].
- Fully autonomous SoS that impact our daily lives will also have ethical aspects, which have to be included in the design of policies for such systems.

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185 *J. O. Kephart and D. M. Chess, "The vision of autonomic computing," in Computer, vol. 36 (2003), no. 1, pp. 41–50, doi: 10.1109/MC.2003.1160055*

4.4.2 Next-generation computing

It is imperative to assess the potential of the emerging computing technologies, new state variables and computing paradigms to provide efficient approaches to information processing, either for distributed computation within the expanding IoT or to realise accelerators on top of CMOS platforms to increase processing speed. Furthermore, fundamental issues such as heat dissipation at the nanoscale, one of the most critical bottlenecks in information processing, need to be addressed. These "beyond CMOS" activities represent medium- and long-term research, with the cutting edge residing in case-specific and tailored performance that can enhance information processing and reduce power consumption. The scaling of CMOS devices and circuits is facing a rather fundamental problem arising from dissipation, so-called "heat death", which has led to the saturation of the clock frequency, "dark silicon" (i.e. idling parts of the chips to reduce heat production) and to multicore processors. This is shifting the paradigm of today's generic data processors towards specific processing units, driven by application requirements.

Potential solutions to solve the "heat death" problem and reduce dissipation include the use of new materials such as 2D materials in the switches, alternative computing paradigms or different state variables, spins, photons, phonons or mechanical switches, instead of charge. In addition, in the context of new computing paradigms, especially in the IoT, novel circuit-level and system-level architectural techniques are required for reduced processing – e.g. sensor signal processing and efficient communication among cooperating objects. This is especially important considering the emerging requirements for application security and distributed computations of IoT devices. However, most of the R&D needed to exploit these novel approaches is only taking place in academic laboratories, as there is much research still required at the material exploration level.

Emerging technologies cover a wide range of TRLs (1–4) with a large variety of device concepts and materials, some of which are compatible with the current CMOS platform, and novel information-processing paradigms in the timeframe of five to ten years, and beyond. In the long run, it is expected that these innovative concepts will be taken up more broadly by academia, and eventually be transferred to industry. There is already relatively strong demand and indirect support for the new approaches in Europe through the existing and forthcoming flagships that focus on 2D materials, neural networks and quantum technology.

The scope of "beyond CMOS" activities in Europe covers several emerging technologies aimed at identifying their potential, challenges and shortcomings when applied to information processing. These technologies include spintronics, neuromorphic computing, heat transport at the nanoscale and photonic computing, 2D materials, topological insulators, Weyl semi-metals, nano-optomechanics and molecular electronics. In addition to the already expected support for quantum technologies, spintronics and neuromorphic computation, dissipation and entropy computation should be investigated as key potential components of the long-term scenario in Europe. These technologies are fundamental not only because they provide apparently useful applications, but because they augment critical infrastructures in all areas (e.g. health, transportation and manufacturing), indicating the need for concurrent progress in functionality, performance and safety.

The emerging semiconductor and device components will provide the basic modules of the next-generation embedded and cyber-physical systems (CPS). New tools are necessary for the architecture and design of efficient, power-aware CPS that provide security and safety properties in new generations of IoT and IIoT. The new computing paradigms (e.g. neuromorphic, approximate and quantum) will also lead to highly complex software components. Software engineering and tools for embedded software are becoming increasingly important for the development of efficient and dependable systems that continue to integrate an increasing number of functions of different criticality (e.g. safety, security).

The development of reliable and safe applications and services over distributed embedded systems, often including virtualised components, requires new languages and tools for application software development as well as for efficient distributed middleware platforms. The penetration of AI and ML across heterogeneous technologies from devices to applications indicates the need to develop methods and tools for efficient and secure AI/ML component development, and also for effective integration in systems developed by developers without AI/ML expertise. As OT is a major portion of CPS application, design tools and methods are equally important to run-time methods and tools for efficient and dependable systems. Run-time verification and testing, as well as run-time confirmation of certification compliance due to multiple stakeholders, constitute significant process-dependent challenges for constrained continuous, fail-safe and real-time operation. Continuous software integration, field updates and reconfigurability in real time, distributed and/or safety-critical systems require new approaches for the constrained CPS environment.

Strategic Research and Innovation Agenda 2021

APPENDIX

GLOSSARY

INTRODUCTION

The scope of the ECS SRIA is very broad and spans many disciplines, each of which has developed a specific understanding of some of the terms used in this report. As a result, the same term can have different meanings for specialists in different ECS domains. This glossary defines some of those terms in an exclusive way to ensure there are no inconsistencies across the various chapters. Although there may be readers that feel uncomfortable with a few of the definitions provided here if they differ from what they commonly mean in their own areas, we feel that developing a common language is important in building a strong and integrated ECS community.

SRIA DEFINITIONS

3D integration: A vertical stack of circuitry or integrated circuits (ICs) for meeting electronic device requirements such as higher performance, increased functionality, lower power consumption, and a smaller footprint. In general, 3D integration is a broad term that includes technologies such as: 3D wafer-level packaging; 2.5D and 3D interposer-based integration; 3D stacked ICs (3D-SICs), monolithic 3D ICs; 3D heterogeneous integration; and 3D systems integration.

3D printing: Also known as additive manufacturing, this is the construction of a three-dimensional object from a computer-aided design (CAD) model or digital 3D model. The term "3D printing" can refer to a variety of processes in which materials are deposited, joined or solidified under computer control to create a three-dimensional object, with typically the materials (such as liquid molecules or powder grains being fused together) being added on a layer-by-layer basis.

5G: Fifth-generation wireless (5G) is the latest iteration of cellular technology, engineered to greatly increase the speed and responsiveness of wireless networks. With 5G, data transmitted over wireless broadband connections can travel at multi-gigabit speeds, with potential peak speeds as high as 20 gigabits per second (Gbps) by some estimates. These speeds exceed wireline network speeds and offer latency of 1 millisecond (ms) or lower, which is useful for applications that require real-time feedback. 5G will enable a sharp increase in the amount of data transmitted over wireless systems due to more available bandwidth and advanced antenna technology. 5G networks and services will be deployed in stages over the next few years to accommodate the increasing reliance on mobile and internet-enabled devices. Overall, 5G is expected to generate a variety of new applications, uses and business cases as the technology is rolled out.

Ambient Assisted Living (AAL): Information and communication-based products and services that integrate modern technologies (sensors, microcontrollers, connectivity, secure elements, Artificial Intelligence, etc) into the homes and lives of disabled persons, and vulnerable or older adults. These technologies aim to improve the lives of those facing some of the challenges of ageing, and those who care for older people if they need help. An impact of AAL is also in reducing the costs of health and social care.

Artificial Intelligence (AI): The theory and development of information processing systems able to perform tasks usually requiring human intelligence (such as visual perception, speech recognition, decision-making, and translation between languages) with a certain degree of autonomy.

Augmented reality (AR): An interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.

Autonomous system (AS): Performs desired tasks in unstructured environments without continuous human guidance.

Biologic drugs: Products that are produced from living organisms or contain components of living organisms. Biologic drugs include a wide variety of products derived from human, animal or microorganisms by using biotechnology. Types of biologic drugs include vaccines, blood, blood components, cells, allergens, genes, tissues and recombinant proteins.

Blockchain: Decentralised, chronologically updated database with a consensus mechanism created from a network for the permanent digital securitisation of property rights.

Brain–computer interface (BCI): A direct communication interface between a (biological) brain and a technical (IT- and/or ECS-based) system. A BCI can transfer information in both directions – e.g. enabling the brain to control the technical system or enhancing human perception (such as hearing) with additional information from the technical system (e.g. hearing aid).

Care pathway: The sequence of health and care services a patient receives after entering the care system during an episode of care.

Cath lab: Examination room in a hospital or clinic with diagnostic imaging equipment used to visualise the arteries of the heart and the chambers of the heart.

Cloud: The on-demand availability of computer system resources, especially data storage (cloud storage) and computing power, without direct active management by the user. The term is generally used to describe data centres available to many users over the internet (from Wikipedia).

Component: A combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case. A component is not self-contained in all its functions, as it requires the close support of other components for operation (e.g. in data processing, power handling, embedded software).

Computer-aided design (CAD): The use of computers (or workstations) to aid in the creation, modification, analysis or optimisation of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

Contract-based design: A design methodology where the system, itself as well as its constituents (subsystems, components, modules, etc), are described by contracts that are formalised by specifications of their functional behaviour and properties. This is often given in a “assume-guarantee” format (e.g. for a certain software module a contract could be: “If the other components of the system guarantee the availability of input data at certain, well-defined times and if the hardware platform on which this module is running guarantees the availability of certain processing and memory resources (assumptions), then (guarantee) this module will produce its output within a certain, guaranteed time interval”). In this methodology, a designed system is “correct” if (informally): (i) all assumptions of all constituents are met by guarantees of other constituents; and (ii) the contracts of all constituents together imply the contract of the complete system.

Coopetition: A neologism for the act of cooperating and competing at the same time. Companies that compete in the market with their products might still cooperate on topics that are either pre-competitive or non-product differentiating. Typical examples here are interoperability, standards and development processes.

Cyber-physical system (CPS): An ECS in which a physical artefact is controlled or monitored by algorithms. A CPS is the result of tight intertwined hardware and software components capable of creating a link between the physical world and the digital world, to operate on different spatial and temporal scales, exhibit multiple and distinct behavioural modalities, and interact with each other in ways that depend on the context. Examples of CPS include smart grid, autonomous automobile systems, medical monitoring, industrial control systems, robotics systems and automatic pilot avionics.

Cybersecurity: The protection of information against unauthorised disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).

Deep edge: The farthest extreme node where subsystems (sensors, actuators, data loggers) interface with the real world. This node is connected to the cloud, but the connection can be intermittent or absent for long periods of time. The emergence of "tiny machine learning" is based on this premise to enable AI in performance-constrained environments (ultra-low power, limited memory size and calculation power), but always very close to the subsystem.

Deep learning (DL): A special form of machine learning based on artificial neural networks, DL is where the system is able to automatically discover the representations needed for feature detection or classification from raw data. The adjective "deep" in deep learning comes from the use of multiple layers in the network (from Wikipedia).

Deeply embedded software: Software that runs on dedicated hardware and not on standard microprocessors. In its simplest form, it is called "firmware".

Dependability: According to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here can be a device, component, module or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01-27) and maintenance support performance (192-01-29), and in some cases other characteristics, such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).

Development or design tools, development or design frameworks, design flow: Design tools are software tools supporting engineers with different tasks during system designs. Ideally, these tools are integrated into frameworks that: (i) provide a uniform user interface to all tools; (ii) "sort" the tools according to the different steps in the design process; and (iii) ensure interoperability between the integrated tools. Regardless of whether the tools used are integrated into a framework or not, the order in which the tools are used is called the "design flow".

Device: In the context of the SRIA, and if it is not further qualified, a device will designate a "packaged chip", whether it is a packaged integrated circuit (e.g. system on a chip, memory, processor, microcontroller) or a micro-electromechanical system (MEMS)/micro-opto-electro-mechanical system (MOEMS). A device performs a general electrical, electronic or electrical/electronic-physical transduction role.

Digital infrastructure: Foundational services necessary to the IT capabilities of a nation, region, city or organisation.

Digital twin: A digital replica of a living or non-living physical entity. Digital twin refers to a digital replica of potential and actual physical assets, processes, people, places, systems and devices that can be used for various purposes. The digital representation provides both the elements and the dynamics of how the physical entity operates and "lives" throughout its lifecycle. To be useful in systems engineering, digital twins need to be executable (i.e. engineers must be able to use them in simulations as representatives of the actual physical entity) and/or amendable to formal analysis methods. The more aspects of the physical entity are represented in a digital twin, the more useful it becomes.

Divide and conquer strategy: A strategy in systems engineering where a large problem (i.e. designing and building a complex system or even System of Systems) is iteratively broken down ("divided") into smaller problems (i.e. designing subsystems, modules and components), which are then divided further or solved ("conquered"). The results of each step are then integrated into a solution for the next-level larger problem. Divide and conquer typically leads to hierarchical designs; it is also a strategy well suited for distributed developments within supply chains and platform economies.

Edge computing: A computing paradigm where computation and data storage are close to the location where they are needed, to improve response times, save bandwidth and increase independence. It can also include the gateway between deep edge devices and other edge devices (organised in a federation of devices, see fog computing), or with the cloud (modified from Wikipedia).

Embedded (or edge) high-performance computing: Provides supercomputing processing performance in rugged, compact and easily deployable computing architectures optimised to work in harsh environments in the field. Bringing high-performance computing capabilities from data centres to field-deployable applications means reducing space, weight and power absorption, increasing resistance, robustness and reliability while maintaining the same advanced computational performance and energy efficiency. Embedded (or edge) high-performance computing is an enabling technology for many vertical domains, such as autonomous driving, UAV, and security and surveillance systems.

Embedded software: The software that runs on embedded and cyber-physical systems, providing the low-level functionalities required to use the available hardware resources, dedicated operating systems, run-time environments, virtualisation and containerisation platforms, application software, micro-services, etc. Embedded software is specifically conceived to optimally exploit the limited hardware resources of embedded and cyber-physical systems. For deeply embedded software, see the separate definition.

Embedded system: An ECS generated from the combination of a microprocessor(s) or system on a chip memory and input/output peripheral devices that have a dedicated function within a larger mechanical or electrical system.

Extended reality (XR): Refers to all real and virtual combined environments and human–machine interactions generated by computer technology and wearables, where the "X" represents a variable for any current or future spatial computing technologies.

Fog computing: An architecture that uses edge devices to carry out a substantial amount of computation, storage and communication locally, and routed over the internet backbone (from Wikipedia).

Functional safety: The ability of a system or piece of equipment to control recognised hazards to achieve an acceptable level of risk – such as maintaining the required minimum of operation even in case of likely operator errors, hardware failures and environmental changes – to prevent physical injuries or damages to the health of people, either directly or indirectly.

Prosthetics: The branch of medicine or surgery that deals with the production and application of artificial body parts.

Healthcare: The preservation of mental and physical health by preventing or treating illness through services offered by the health profession.

Heterogeneous integration: Refers to the integration of separately manufactured components into a higher-level assembly (system in a package) that, in the aggregate, provides enhanced functionality and improved operating characteristics. In this definition, components should be taken to mean any unit, whether individual die, MEMS device, passive component or assembled package or subsystem, that are integrated into a single package. The operating characteristics should also be taken in its broadest meaning to include characteristics such as system-level performance and cost of ownership (from ITRS Assembly & Packaging chapter).

Industry 4.0: The application of technology to digitally transform how industrial companies operate. These technologies include the industrial Internet of Things (IoT), automation and robotics, simulation, additive manufacturing, and analytics. Industry 4.0 is driven by a need to boost efficiency, become more agile to respond to market unpredictability, improve quality, and to enable new business models.

In silico clinical trials: In silico means performed on a computer or via computer simulation. The term characterises biological experiments carried out entirely on a computer. Although in silico studies represent a relatively new avenue of inquiry, they have begun to be used widely in studies that predict how drugs will interact with the body and with pathogens.

In vitro diagnostics: The technique of performing a given procedure in a controlled environment outside of a living organism. Many experiments in cellular biology are conducted outside of organisms or cells. One of the abiding weaknesses of in vitro experiments is that they fail to replicate the precise cellular conditions of an organism, particularly a microbe.

In vivo clinical trials: Experimentation using a whole living organism as opposed to a partial or dead organism. Animal studies and clinical trials are two forms of in vivo research. In vivo testing is often employed over in vitro because it is better suited for observing the overall effects of an experiment on a living subject. Integrated practice unit: Involves a shift from the current siloed organisation by specialty department and discrete service to being organised around the patient's medical condition. Care is delivered by a dedicated multidisciplinary team of clinicians who take responsibility for the full cycle of care for the condition, encompassing outpatient, inpatient, and rehabilitative care, and supporting services (e.g. nutrition, social work, behavioural health). The team measures processes and outcomes as a team not individually, and accepts joint accountability for outcomes and costs.

Integrated circuit: An electronic circuit formed on a small piece of semiconducting material, performing the same function as a larger circuit made from electronic building blocks.

Integration platform: An ECS allowing the integration of different systems, applications and services into a single system. They can be found on all layers of the design hierarchy, ranging from "communication backplanes" in hardware design to "reference architectures" and "middlewares" in system engineering, to distributed service platforms in System of Systems. Integration platforms are an important basis for: (i) standardisation; and (ii) platform-based economies.

Internet of Things (IoT): The set of technologies that bring intelligence to objects, enabling them to communicate with other objects or with other devices. IoT describes the network of physical objects – "things" – that perform functions. For example, with these technologies, billions of sensors embedded in everyday devices can be designed to record, process, store and transfer data, and to interact with other devices or systems that use the network's capabilities.

Interoperability: The capability of computing systems to exchange information that can be understood and used by the receiving system.

Key digital technologies: Electronic and photonic components, and the software that defines how they work. These technologies underpin all digital systems, including Artificial Intelligence and the Internet of Things.

Lab-on-a-chip (LOC): A miniaturised device that integrates one or several biological or chemical analysis functions on a single chip (e.g. detecting specific proteins).

Large-area electronics (LAE): Electronics fabricated utilising printing and roll-to-roll fabrication methods that, as opposed to integrated circuit technologies, can be used on significantly larger substrates. Inorganic and organic inks and pastes are used for printing conductors and active components such as transistors. Substrates in LAE are typically flexible, such as plastic films or paper, giving rise to the term "flexible electronics".

Machine learning: Ability for a machine to learn by example without being explicitly programmed to perform the target function. This is one method for implementing Artificial Intelligence.

MEMS, MOEMS, NEMS, MNS, MNBS: Micro-electromechanical systems (MEMS) originally referred to miniaturised devices that provided a precise mechanical output (typically a small vertical, horizontal, or rotary displacement) upon an electric excitation (e.g. a microrelay), or vice versa, or an electronic signal from a mechanical excitation (e.g. a microaccelerometer or gyroscope). When the objective of such displacement was to interact with light (e.g. a micromirror), the term "micro-opto-electromechanical systems (MOEMS) was used. Gradually, the transduction domain was extended beyond the mechanical one and chemical and biological mediation were also considered. The overall size of MEMS devices could be in the mm or cm range, the term "micro" referring to the dimension of the device's internal features to be mastered for the device to be functional. The term "nanoelectromechanical systems" (NEMS) is used when such critical dimension falls back into the nano domain. The terms "microsystem", "micro-nanosystem" (MNS), or "micro-nano-bio system" (MNBS) were alternatively introduced for those small devices amenable to such generalised transduction principles. This kind of device could be fabricated in principle with different materials, but silicon technologies provided a micromachinable material and a miniaturised technology responsive to the integration of the electronic signal to be conveyed or transduced. MEMS, MOEMS, NEMS, MNS and MNBS are very successful means of interaction between the physical and digital worlds, providing information systems with the means to interact with their environment, sensing it, actuating on it or being powered by it.

Model-based design: Where design artefacts (the system, subsystems, component, modules, as well as their connections and the environments in which they will be used), are represented by models that are abstract descriptions of certain aspects of such artefacts (typically, their functional behaviour, timing properties, etc). Ideally, these models are: (i) executable, thus usable in simulation and early verification and validation (V&V); and (ii) detailed enough to be usable in formal analysis and test methods.

Module: Ensemble of properly integrated components so that their reunion embodies a definite functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and software, making it interchangeable between systems, and allowing higher abstraction level in systems design.

Molecular biology: Study of phenomena in terms of biology molecular (or chemical) interactions. Molecular biology emphasises chemical interactions involved in the replication of DNA, its "transcription": into RNA, and its "translation" into or expression in protein – that is, in the chemical reactions connecting genotype and phenotype.

Open source hardware: The blueprint of hardware artefacts that is (partially) freely available and which anyone can use, modify or enhance (depending on different licences associated with the blueprint).

Open source software: Software with source code that is (partially) freely available and which anyone can use, modify or enhance (depending on different open source licensing models existing).

Operational design domain (ODD): Comprises the "operating conditions under which a given […] system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain [environmental] characteristics" (Surface Vehicle Recommended Practice — Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE: J3016, 2018).

Optical coherence tomography (OCT): A non-invasive imaging test that uses light waves to take cross-section pictures of the retina to help with diagnosis. They also provide treatment guidance for glaucoma and diseases of the retina such as age-related macular degeneration (AMD) and diabetic eye disease.

P4 medicine: A shift in medicine from a reactive to a proactive discipline that is focused on predictive, personalised, preventive and participatory (P4). P4 medicine will be driven by system approaches to disease, emerging technologies and analytical tools.

Patient-generated health data (PGHD): Health-related data created, recorded or gathered by or from patients (or family members or other caregivers) to help address a health concern.

Personalised medicine: Tailoring of medical treatment for patient cohorts to be treated in a unique manner depending on their health status and previous course of a disease and analysis of personal characteristics.

Plug and play components: Component with a specification that facilitates the discovery of a hardware component in a system without the need for physical device configuration or user intervention in resolving resource conflicts.

Point of care: The location at which patient services are delivered (excluding hospital, doctor's office, patient's home).

Point-of-care testing (POCT or bedside testing): Performance of clinical laboratory testing at the site of patient care rather than in a laboratory, often by non-laboratorians.

Point of need: New model of having critical data and information when and where it is needed rather than at the point of care. These are diagnostics that can be done anytime, anywhere, for anyone – for instance, as a vital part of managing a chronic disease over time, resulting in improved treatment and patient outcomes.

Predictive maintenance: Techniques designed to help determine the condition of in-service equipment to estimate when maintenance should be performed.

Product lifecycle management (PLM): Process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products.

Prognostics (a.k.a. health management): A method that permits the assessment of the reliability of the product (or system) under its application conditions. It predicts the occurrence of an event based on current and future operational and environmental conditions to estimate the time at which a system no longer fulfils its function within desired specifications ("remaining useful life").

Prosthetics: The branch of medicine or surgery that deals with the production and application of artificial body parts.

Quality: In this SRIA, quality is defined as "the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (burn-in) but no other type of testing". In this way, reliability, dependability and cybersecurity, which some readers may have expected to be included under quality, will be treated separately.

Quantum computing: An area of computing focused on developing computer technology based on the principles of quantum theory, which explains the behaviour of energy and material on the atomic and sub-atomic levels. A quantum computer utilises quantum entanglement between qubits to solve a set of computationally complex problems efficiently. The computational power of quantum computers is estimated to grow faster than classical computers in the future.

Quantum sensing: Sensor technologies that make use of quantum technology.

Quantum technology: The creation, manipulation and detection of single particle quantum states accurately, enabling the use of quantum superposition and entanglement, where quantum states of several particles cannot be described independently, even when spatially separated. Currently, quantum effects typically require very low temperatures and the use of cryogenic technologies.

Recommender-based (methods and) tools: Methods and tools in which the current status of a system under design is analysed and evaluated by design-supporting software, which then gives recommendations to the engineer as to possible further steps and/or options for completing the design, ideally together with an evaluation of the pros and cons for each option.

Reliability: The ability or probability, respectively, of a system or component to function as specified under stated conditions for a specified time (ISO 25010).

Safety (a.k.a. functional safety): Freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or the environment (IEC 61508).

Security of ECS (a.k.a. IT security/cybersecurity): In this SRIA, security of ECS is defined as the prevention of illegal or unwanted penetration, intentional or unintentional interference with the proper and intended operation, or inappropriate access to confidential information. Security is considered to be composed of confidentiality, integrity and availability (ISO 21549-2).

Self-X: In self-X, X stands for adaptation, reconfiguration, etc. Usually in self-reorganising systems the major issue is how to self-reorganise while preserving the key parameters of a system, while being coherent with the initial requirements (e.g. performance, power consumption, real time constraints). Self-adaptation and self-reconfiguration has an enormous potential in many applications.

Smart city: An urban area that uses different types of electronic methods and sensors to collect data. Insights gained from that data are used to manage assets, resources and services efficiently; in return, that data is used improve the operations across the city (from Wikipedia).

Smart drug delivery system (SDDS): An advanced method of drug-targeted (DT) delivery. The smart drug delivered by this system must fulfill the following criteria: (i) increase the doses of delivered drug to the targeted body part of interest (tissue/cells/organs); (ii) not be degraded by any of the body fluids; (iii) diminish side effects by improving the efficacy of drug treatment; (iv) absorption of the delivered drug must cross a biological membrane; and (v) drug is released in appropriate dosages to the body part of interest. SDDS is highly complex and involves an integration of various disciplines, such as biology, chemistry and engineering.

Smart systems integration (SSI): (Integrated) smart systems incorporate sensing, actuation and control up to cognitive functions to describe and analyse a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. The enabling principles of these functions include nanoelectronics, micro-electromechanics, magnetism, photonics, chemistry and radiation. SSI is an assembly of technologies that: build products from components; combine functions in products and systems; connect and network systems to other systems; and, importantly, enable systems to receive and store a “knowledge base” – the software that makes them “smart”.

System: For the purpose of this SRIA, a system is a set of electronic-based constituents (subsystems, modules and components, realised in hardware, software, or both) that are integrated in a way to together allow the system to perform a desired (set of) function(s).
Note that:

- Due to ECS typically being constructed hierarchically, a (e.g. camera or other sensor) “module” being part of the electronic “system” in an autonomous car might itself be referred to as a "system" when designing it (e.g. while integrating lower-level components to together achieve the "camera function") (see also: system in a package, system on a chip, and others).

- The difference between a "system" (comprising subsystems, modules and components) and a "System of Systems" (also comprising subsystems) is that the constituents of a system are chosen and integrated during design-time (i.e. completely under control of the engineers), while in a System of Systems the constituent (sub)systems are independent and dynamically form (and disband) a System of Systems at run-time.

System in a package (SiP): A number of integrated circuits and other electronics building blocks (e.g. MEMS, antennas) enclosed in one single package.

System on a chip (SoC): An integrated circuit that incorporates multiple building blocks of an electronic system, including processors, memory units, accelerators, and input/output ports, and which covers the complete functionality of an electronic system.

System of Systems (SoS): A collection of independent and distributed embedded and cyber-physical systems dynamically composed to generate a new and more complex system, provided with new functionalities and driven by new goals not present in the constituent embedded and cyber-physical systems individually. An SoS must satisfy five characteristics: operational independence of constituent systems; managerial independence of constituent systems; geographical distribution; emergent behaviour; and evolutionary development processes. A system that does not satisfy these characteristics (specifically the first two) is not considered an SoS.

Teleoperation: Teleoperation (or remote operation) indicates operation of a system or machine at a distance. It is similar in meaning to the phrase "remote control" but is usually encountered in research, academia and technical environments. It is most commonly associated with robotics and mobile robots, but can be applied to a whole range of circumstances in which a device or machine is operated by a person from a distance.

Telepresence: The use of virtual reality technology, especially for remote control of machinery or for participation in distant events.

Tracking mode simulation: Adapting simulation by respective measurements of the real counterpart.

(Technical) Trustworthiness: Having some reasonably well thought-out assurance that the technical realisation of a system is worthy of being trusted to satisfy certain well-specified requirements (e.g. safety, security, reliability, robustness and resilience, ease of use and ease of system administration, and predictable behaviour in the face of adversities, such as high-probability real-time performance).

Value-based healthcare: A healthcare delivery model in which providers, including hospitals and physicians, are paid based on patient health outcomes. Under value-based care agreements, providers are rewarded for helping patients improve their health, reduce the effects and incidence of chronic disease, and live healthier lives in an evidence-based way.

Verification and validation (V&V): Independent procedures that are used together for checking that a product, service or system meets requirements and specifications, and that it fulfills its intended purpose. Verification checks whether the development implemented the specified requirements of a product correctly ("are we building the product right"), while validation is a system test checking whether a product can fulfil its intended purpose in a real environment ("are we building the right product?").

Virtual commissioning: The practice of using "virtual" simulation technology to "commission" – design, install or test – control software with a virtual machine model before it is connected to a real system.

Virtual reality (VR): Computer technology that makes a person feel like they are somewhere else. It uses software to produce images, sounds and other sensations to create a different place so that the user feels they are really part of this other place. Applications of virtual reality can include entertainment (e.g. video games) and educational purposes (e.g. medical or military training).

Wearables: Wearable technology is a category of electronic devices that can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin.

X-in-the-loop: Where "X" can be hardware-, software-, models-, systems-, etc. The term is used when testing ECS (or parts of an ECS). The system (e.g. component, module) to be tested is called "system-under-test" (SUT). This SUT is embedded into a testbed (or test environment) that provides the necessary input data (according to a specific test scenario), and which then monitors its outputs, comparing these actual outputs to the expected/specified ones. Within these testbeds, data flow therefore forms a "loop" (from the testbed through the SUT back to the testbed). Depending upon the realisation of the SUT (e.g. as a hardware component/module, software module, simulation model, complete system), different testbeds are needed and the resulting test process is called "hardware-in-the-loop", "software-in-the-loop", etc, or when referred to in a general way "X-in-the-loop".

ACRONYMS

USED IN THE DOCUMENT

5G	*Fifth-generation communication network*
6G	*Sixth-generation communication network*
A&P	*Assembly and packaging*
AAL	*Ambient Assisted Living*
ACA	*Anisotropic conductive adhesive*
ACES	*Autonomous, connected, electric and shared*
ACK	*Alexa Communication Kit*
ADAS	*Advanced driver-assistance system*
AF-EAF	*Air Force Enterprise Architecture Framework*
AFIoT	*Architecture Framework for the Internet of Things*
AFM	*Atomic force microscopy*
AI	*Artificial Intelligence*
AIN	*Aluminium nitride*
AIOTI	*Alliance for the Internet of Things Innovation*
AIoT	*Artificial Intelligence of things*
ALU	*Arithmetic logic unit*
AMD	*Age-related macular degeneration*
AMS	*Analogue/mixed signal*
API	*Application programming interface*
AR	*Augmented reality*
AS	*Autonomous system*
ASIC	*Application-specific integrated circuit*
AUTOSAR	*AUTomotive Open System Architecture*
B2B	*Business-to-business*
B2C	*Business-to-consumer*
BATX	*Baidu, Alibaba, Tencent and Xiaomi*
BCI	*Brain–computer interface*
BDVA	*Big Data Value Association*
BEOL	*Back end of line*
BEV	*Battery electric vehicle*
BGA	*Ball grid array*
BiCMOS	*Bipolar CMOS*
BIST	*Built-in self-test*
BOM	*Bill of materials*
BOX	*Buried oxide*
C&K	*Competence and knowledge*
CAD	*Computer-aided design*
CAFCR	*Customer Objectives, Application, Functional, Conceptual and Realisation Model*

CAGR	*Compound annual growth rate*
Cath lab	*Catheterisation laboratory*
CAV	*Connected autonomous vehicle*
CB	*Conductive-bridge*
CBRAM	*Conductive-bridging RAM*
CCAM	*Connected, Cooperative and Automated Mobility*
CDR	*Carbon dioxide removal*
CFD	*Computational fluid dynamics*
CMOS	*Complementary metal–oxide–semiconductor*
cMUT	*Capacitive micromachined ultrasound transducer*
CNN	*Convolutional neural network*
CNT	*Carbon nanotube*
CPS	*Cyber-physical system*
CPU	*Central processing unit*
CrMMC	*Carbon-reinforced metal matrix composites*
CT	*Computed tomography*
CVD	*Chemical vapour deposition*
D2D	*Device-to-device*
DCS	*Distributed control systems*
DfA	*Design for assembly*
DfM	*Design for manufacturing*
DfR	*Design for reliability*
DfX	*Design for excellence*
DL	*Deep learning*
DNN	*Deep neural network*
DRAM	*Dynamic random access memory*
DSA	*Directed self-assembly*
DSL	*Domain-specific language*
DSS	*Decision-support system*
DT	*Drug-targeted*
DUV	*Deep ultraviolet*
E/E	*Electrical/electronic*
EC-RAM	*Error correction RAM*
ECPS	*Embedded and cyber-physical system*
ECS	*Electronic components and systems*
ECSO	*European Cyber Security Organisation*
ECU	*Electronic control unit*
EDA	*Electronic design automation*

EFFRA	*European Factories of the Future Research Association*
eHPC	*Embedded high-performance computing*
EHR	*Electronic health record*
EIP-AGRI	*European Innovation Partnership "Agricultural Productivity and Sustainability"*
EMC	*Electromagnetic compatibility*
EMI	*Electromagnetic interference*
EMR	*Electronic medical record*
EMS	*Energy management systems*
eNVM	*Embedded non-volatile memory*
EOL	*End-of-life*
EP	*Engineering process*
EPI	*European Processor Initiative*
ERP	*Enterprise resource planning*
ERTRAC	*European Road Transport Research Advisory Council*
ESAAF	*European Space Agency Architecture Framework*
ESS	*Electronic smart system*
ETP	*European Technology Platform*
ETP4HPC	*European Technology Platform for High Performance Computing*
EU	*European Union*
EUV	*Extreme ultraviolet*
EV	*Electric vehicle*
FAIR	*Facebook AI Research*
FAIRness	*Findability, accessibility, interoperability and reuse*
FCC	*Federal Communications Commission*
FDSOI	*Fully depleted SOI*
Fe	*Ferroelectric*
FEM	*Finite element method*
FEOL	*Front end of line*
FET	*Future and emerging technologies*
FFT	*Fast Fourier transform*
FinFet	*Fin field-effect transistor*
FLOPS	*(flops or flop/s) Floating point operations per second*
FMEA	*Failure mode and effect analysis*
FMI	*Functional mock-up interface*
FMIS	*Farm management information system*
fMRI	*Functional magnetic resonance imaging*
FMU	*Functional mock-up unit*
FPGA	*Field-programmable gate array*

GAFAM	*Google, Apple, Facebook, Amazon and Microsoft*
GaN	*Gallium nitride*
GDPR	*General data protection regulation*
GHG	*Greenhouse gas*
GPS	*Global Positioning System*
GPU	*Graphics processing unit*
HAD	*Highly automated driving*
HCI	*Human–computer interaction*
HEMT	*High-electron-mobility transistor*
HEV	*Hybrid electric vehicle*
HF	*High-frequency*
HIL	*Hardware-in-the-loop*
HIR	*Heterogeneous Integration Roadmap*
HMI	*Human–machine interface*
HMLV	*High mix low volume*
HPC	*High-performance computing*
HTA	*Hexagon Tensor Accelerator*
HVAC	*Heating, ventilation and air conditioning*
HVDC	*High-voltage direct current*
HW	*Hardware*
I/O	*Input/output*
IC	*Integrated chip*
IC	*Integrated circuit*
ICT	*Information and communications technology*
IDM	*Integrated device manufacturer*
IEA	*International Energy Agency*
IGBT	*Insulated-gate bipolar transistor*
IIA	*Industrial Internet Architecture*
IIoT	*Industrial IoT*
IIRA	*Industrial Internet Reference Architecture*
INCOSE	*International Council on Systems Engineering*
iNEMI	*International Electronics Manufacturing Initiative*
IoMT	*Internet of Medical Things*
IoT	*Internet of Things*
IP	*Intellectual property*
IP	*Internet protocol*
IPCEI	*Important project of common European interest*
IPM	*Integrated pest management*

IPSR	*Integrated Photonic Systems Roadmap*
IR	*Infrared*
IRDS	*International Roadmap for Devices and Systems*
ISOC	*Internet Society*
IT	*information technology*
IVD	*in vitro diagnostic*
IXP	*Internet exchange point*
JU	*Joint undertaking*
KDT	*Key Digital Technologies*
KFI	*Key failure indicator*
KPI	*Key performance indicator*
LAE	*Large-area electronics*
LCA	*Lifecycle assessment*
LCP	*Liquid crystal polymers*
LCOE	*Levelised cost of electricity*
LoC	*Lab-on-a-chip*
LV	*Low voltage*
M2M	*Machine-to-machine*
MaaS	*Manufacturing as a service*
MaaS	*Mobility-as-a-service*
MCM	*Multi-chip module*
MCU	*Microcontroller unit*
MDM	*Multi-dimensional metrology*
MEC	*Multi-access edge computing*
MEC	*Mobile edge computing*
Medtech	*Medical technology*
MEMS	*Micro-electromechanical systems*
MES	*Manufacturing execution system*
MES	*Multi-energy system*
MIL	*Model-in-the-loop*
ML	*Machine learning*
MM-ENS	*Multimodal energy system*
MNBS	*Micro-nano-bio system*
MNS	*Micro-nanosystems*
MODAF	*Ministry of Defence Architecture Framework (UK)*
MOEMS	*Micro-opto-electro-mechanical system*
MOF	*Metal–organic framework*
MOOC	*Massive open online course*

MOSFET	*Metal–oxide–semiconductor field-effect transistor*
MPU	*Microprocessing unit*
MRAM	*Magnetic RAM*
MUT	*Micromachined ultrasonic transducer*
MV	*Medium voltage*
NB	*Narrowband*
NEMS	*Nano-electromechanical systems*
NFV	*Network functions virtualisation*
NFVI	*Network functions virtualisation infrastructure*
NLU	*Natural language understanding*
NPU	*Neuromorphic processing unit*
NVM	*Non-volatile memory*
OCT	*Optical coherence tomography*
ODD	*Operational design domain*
OECD	*Organisation for Economic Co-operation and Development*
OEM	*Original equipment manufacturer*
OOC	*Organ-on-a-chip*
OSI	*open systems interconnection*
OSS	*Operations support system*
OT	*Operational technology*
OTA	*Over-the-air*
OXRAM	*Oxide-based RAM*
P2P	*Peer-to-peer*
P4	*Predictive, preventive, personalised, participatory*
PAD	*Productivity-aware design*
PCB	*Printed circuit board*
PCM	*Phase-change memory*
PCRAM	*Phase-change RAM*
PDMS	*Polydimethylsiloxane*
PEALD	*Plasma-enhanced atomic layer deposition*
PFI	*Physical and functional integration*
PGHD	*Patient-generated health data*
PHM	*Prognostic health management*
PIII	*Plasma-immersion ion implantation*
PI	*Polyimide*
PLC	*Programmable logic controllers*
PLM	*Product lifestyle management*
PMIC	*Power management integrated circuit*

PMUT	*Piezoelectric micromachined ultrasound transducer*
PoC	*Point-of-care*
PoCT	*Point-of-care testing*
PoF	*Physics of failure*
PPAC	*Power, performance, area and cost*
PPE	*Personal protective equipment*
ppm	*Parts per million*
PPP	*Public/private partnership*
PSiP	*Power source in a package*
PTEMM	*Process technologies, equipment, materials and manufacturing*
PV	*Photovoltaics*
PVD	*Physical vapour deposition*
PwrSiP	*Power system in a package*
PwrSoC	*Power source on a chip*
PZT	*Lead zirconate titanate*
QIP	*Quantum information processing*
QoS	*Quality of service*
QRSC	*Quality, reliability, safety and cybersecurity*
Qubit	*Quantum bit*
qZSI	*Quasi-impedence source inverter*
R&D	*Research and development*
R&D&I	*Research and development and innovation*
RAM	*Random-access memory*
RAMI 4.0	*Reference Architecture Model for Industry 4.0*
ReRAM	*Resistive RAM*
RES	*Renewable energy system*
RF	*Radio frequency*
RFID	*Radio-frequency identification*
RL	*Reinforcement learning*
RNN	*Recursive neural network*
ROHS	*Restriction of Hazardous Substances Directive*
ROI	*Return on investment*
RPA	*Robotic process automation*
RRAM	*Resistive RAM*
RT-PCR	*Real-time reverse transcription polymerase chain reaction*
RTE	*Run-time environment*
RTO	*Research and technology organisation*
RUL	*Remaining useful life*

SaaS	*Software as a service*
SAC	*Conventional SnAgCu*
SAC	*Tin-silver-copper alloy (SnAgCu)*
SAE	*Society of Automotive Engineers*
SCADA	*Supervisory control and data acquisition*
ScAlN	*Scandium aluminium nitride*
SCM	*Storage class memory*
SCM	*Supply chain management*
SDDS	*Smart drug delivery system*
SDG	*Sustainable Development Goal*
SDK	*Software development kit*
SDN	*Software-defined networking*
SDR	*Software-defined radio*
SEAP	*Strategic Environmental Assessment Plan*
SECAP	*Sustainable Energy and Climate Action Plan*
SEES	*Self-powered electrochemical energy storage system*
SGD	*Speech-generating device*
SiC	*Silicon carbide*
SIL	*Software-in-the-loop*
SiP	*System in a package*
SKC	*Skills, knowledge and competence*
SME	*Small and medium-sized enterprise*
SoA	*Service-oriented architecture*
SoC	*System on a chip*
SoCPS	*System of cyber-physical systems*
SOI	*Silicon-on-insulator*
SoS	*System of Systems*
SOT	*Spin-orbit torque*
SOTIF	*Safety of Intended Functionality*
SPIRE	*Sustainable Process Industry through Resource and Energy Efficiency*
SRAM	*Static RAM*
SRGM	*Software reliability growth models*
SRIA	*Strategic Research and Innovation Agenda*
SSI	*Smart systems integration*
STDP	*Spike-timing-dependent plasticity*
STEM	*Science, technology, engineering and mathematics*
STS	*Socio-technical system*
STT	*Spin-transfer torque*

SUMP	*Sustainable Urban Mobility Plan*
SUT	*System-under-test*
SW	*Software*
SWM	*Smart Water Management*
TCP	*Transmission control protocol*
TEV	*Through-encapsulant via*
TOPS	*Tera operations per second*
TOU	*Time of use*
TPU	*Tensor processing unit*
TPU	*Thermoplastic Polyurethane*
TRL	*Technology readiness level*
TSMC	*Taiwan Semiconductor Manufacturing Company*
TSN	*Time-sensitive network*
TSO	*Transmission system operator*
TSV	*Through-silicon via*
TV&V	*Testing validation and verification*
UAV	*Unmanned aerial vehicle*
UAV	*Unmanned autonomous vessel*
ULP	*Ultra-low power*
UN	*United Nations*
UPS	*Uninterruptible power supply*
UXV	*Unmanned vehicle*
V&V	*Verification & validation*
V2G	*Vehicle to grid*
V2X	*Vehicle-to-everything*
VCMA	*Voltage-controlled magnetic anisotropy*
VIL	*Vehicle-in-the-loop*
VLSI	*Very large-scale integration*
VOC	*Volatile organic compound*
VR	*Virtual reality*
WBG	*Wide bandgap*
WHO	*World Health Organization*
WLP	*Wafer-level packaging*
WLTP	*Worldwide Harmonised Light Vehicle Test Procedure*
XR	*Extended reality*

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MAIN OBJECTIVES:

AN ANALYSIS OF ALL MAJOR CHALLENGES

In this ECS-SRIA, for the first time, the **Major challenges** identified by the different chapter teams were analysed and finally merged into **Main common objectives** for the ECS community as shown in the following tables.

EC STRATEGIC TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
ECS R&I OBJECTIVES	**Boost industrial competitiveness through interdisciplinary technology innovations** Interdisciplinary Technology Innovation	**Ensure EU sovereignity through secure, safe and reliable ECS supporting key European application domains** Secure, Safe and Reliable ECS	**Establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal** Sustainable and Resilient ECS	**Unleash the full potential of intelligent and autonomous ECS-based systems for the European Digital Era** Intelligent and Autonomous ECS
Major Challenges in ECS Research and Innovation	**1.1.1** Advanced compute, memory and compute-in-memory concepts **1.1.2** Novel devices and circuits that enable advanced functionality **1.1.3** Advanced heterogeneous integration and packaging solutions **1.1.4** World-leading and sustainable semiconductor equipment and manufacturing technologies **1.2.2** Materials **1.2.3** Technologies, manufacturing and integration processes **1.4.2** SoS interoperability **1.4.5** Open "system of embedded and cyber-physical systems" platforms	**1.4.2** SoS interoperability **1.4.3** Composability of embedded and cyber-physical systems in SoS	**1.1.4** World-leading and sustainable semiconductor equipment and manufacturing technologies **1.2.4** Decarbonisation and recyclability **1.3.5** Green Deal and embedded software **1.4.2** SoS interoperability	**1.1.1** Advanced compute, memory and compute-in-memory concepts **1.1.2** Novel devices and circuits that enable advanced functionality **1.3.4** Embedding data analytics and Artificial Intelligence
	2.1.1 Increasing the energy efficiency of computing systems **2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain **2.2.2** Investigate innovative connectivity technology (new spectrum or medium) and new approach to improve existing one in order to maintain EU long-term leadership **2.3.2** Managing new functionality in safe, secure and trustable systems **2.3.4** Managing diversity	**2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity **2.4.1** Ensuring HW quality and reliability **2.4.2** Ensuring dependability in connected software	**2.1.1** Increasing the energy efficiency of computing systems **2.1.3** Supporting the increasing lifespan of devices and systems **2.1.4** Ensuring European sustainability in AI, edge computing and advanced control **2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity **2.4.4** Ensuring safety and resilience	**2.1.1** Increasing the energy efficiency of computing systems **2.1.3** Supporting the increasing lifespan of devices and systems **2.1.4** Ensuring European sustainability in AI, edge computing and advanced control **2.2.3** Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics **2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

	3.1.5 Challenge 5 (real-time data handling): Achieve real-time data handling for multimodal mobility and related services. **3.2.2** Energy management from on-site to distribution and transmission systems **3.2.4** Cross-sectional tasks for energy system monitoring and control **3.4.1** Enable digital health platforms based upon P4 healthcare **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system **3.5.3** Environmental protection and sustainable production **3.5.4** Water resource management **3.5.5** Biodiversity restoration for ecosystems resilience, conservation and preservation **3.6.1** Facilitate individual self-fulfilment **3.6.2** Facilitate empowerment and resilience **3.6.3** Facilitate inclusion and collective safety **3.6.4** Facilitate supportive infrastructure and a sustainable environment	**3.1.1** Challenge 1 (climate and energy): Enable electrification and sustainable alternative fuels for CO_2-neutral mobility **3.1.2** Challenge 2 (safety): Enable affordable safe and environment neutral light mobility (bikes, tricycles, wheelchairs, small drones) and mobile machinery (as smart farming) **3.1.5** Challenge 5 (real-time data handling): Achieve real-time data handling for multimodal mobility and related services. **3.2.2** Energy management from on-site to distribution and transmission systems **3.2.3** Achieving clean, efficient and resilient urban/regional energy supply **3.4.1** Enable digital health platforms based upon P4 healthcare **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game-changing technologies **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system **3.4.5** Ensure more healthy life years for an ageing population **3.5.1** Food security **3.5.2** Food safety **3.6.3** Facilitate inclusion and collective safety	**3.1.1** Challenge 1 (climate and energy): Enable electrification and sustainable alternative fuels for CO_2-neutral mobility **3.1.2** Challenge 2 (safety): Enable affordable safe and environment neutral light mobility (bikes, tricycles, wheelchairs, small drones) and mobile machinery (as smart farming) **3.1.3** Challenge 3 (automation): Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water **3.2.1** Smart & Efficient managing energy generation, conversion, and storage systems **3.2.3** Achieving clean, efficient and resilient urban/ regional energy supply **3.3.1** Responsive and smart production **3.3.2** Sustainable production **3.4.1** Enable digital health platforms based upon P4 healthcare **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game-changing technologies **3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system **3.4.4** Enhance access to personalised and participative treatments for chronic and lifestyle-related diseases **3.4.5** Ensure more healthy life years for an ageing population **3.5.3** Environmental protection and sustainable production **3.5.4** Water resource management **3.5.5** Biodiversity restoration for ecosystems resilience, conservation and preservation **3.6.2** Facilitate empowerment and resilience **3.6.4** Facilitate supportive infrastructure and a sustainable environment	**3.1.3** Challenge 3 (automation): Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water **3.1.5** Challenge 5 (real-time data handling): Achieve real-time data handling for multimodal mobility and related services. **3.2.1** Smart & Efficient managing energy generation, conversion, and storage systems **3.3.1** Responsive and smart production **3.3.3** Artificial Intelligence in digital industry **3.3.6** Autonomous systems, robotics **3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies **3.4.4** Enhance access to personalized and participative treatments for chronic and lifestyle-related diseases **3.4.5** Ensure more healthy life years for an ageing population **3.5.1** Food security **3.5.3** Environmental protection and sustainable production **3.5.4** Water resource management

EC STRATEGIC TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
	Ensure engineering support across thentire lifecycle of complex ECS-based systems lifecycle engineering support			
Major Challenges in ECS Research and Innovation	**1.2.1** Physical and functional integration **1.3.1** Efficient engineering of embedded software **1.3.2** Continuous integration of embedded software **1.3.3** Lifecycle management of embedded software **1.4.1** Architectures **1.4.3** Composability of embedded and cyber-physical systems in SoS **1.4.4** Systems of embedded and cyber-physical systems engineering	**1.3.2** Continuous integration of embedded software **1.3.3** Lifecycle management of embedded software **1.4.1** Architectures **1.4.4** Systems of embedded and cyber-physical systems engineering **1.4.5** Open "system of embedded and cyber-physical systems" platforms	**1.3.1** Efficient engineering of Embedded software **1.3.2** Continuous integration of embedded software **1.4.5** Open "system of embedded and cyber-physical systems" platforms	
	2.1.2 Managing the increasing complexity of systems **2.4.5** Human–systems Integration **3.3.5** Digital twins, mixed or augmented reality, telepresence	**2.1.2** Managing the increasing complexity of systems **2.3.2** Managing new functionality in safe, secure, and trustable systems **2.3.3** Managing complexity **2.3.4** Managing diversity **2.4.3** Ensuring cyber-security and privacy	**2.1.2** Managing the increasing complexity of systems **2.3.3** Managing complexity **2.3.4** Managing diversity **2.4.5** Human–systems integration	**2.1.2** Managing the increasing complexity of systems **2.3.1** Extending development processes and frameworks (to handle connected, intelligent, autonomous, evolvable systems) **2.3.3** Managing complexity
		3.1.4 Challenge 4 (validation): Provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility **3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation	**3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation	**3.1.4** Challenge 4 (validation): Provide tools and methods for validation & certification of safety, security and comfort of embedded intelligence in mobility **3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation **3.3.5** Digital twins, mixed or augmented reality, telepresence