E C S

Strategic Research Agenda 2020

Strategic Research Agenda
for Electronic Components & Systems
prepared on behalf of:

Aeneas
ARTEMIS Industry Association
EPoSS European Technology Platform on Smart Systems Integration

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PREFACE

A radical, digital transformation is going on and strongly influencing how we live and how we work. The innovations that lie at the heart of this transformation are founded on the rapid developments of Electronic Components and Systems (ECS)-based applications. This prompted the three industry associations – AENEAS, ARTEMIS-IA and EPoSS – that represent their members along the ECS value chain to co-author a joint ECS Strategic Research Agenda (SRA). Since 2018 this document sets the strategic priorities and technical pathways to enable European industry to become stronger and more competitive, and to have a significant and beneficial impact on society and the economy.

In the 2020 update, the authors reflect the growing importance of Artificial Intelligence, and documented the required technology developments and the impact of Artificial Intelligence across all application domains. In addition, ultra-low power consumption of electronic components and systems was identified as a mandatory element to sustain the current pace of digital innovation in the long run. Furthermore, sections on computing paradigms and software technologies were significantly expanded to underline the trend of "Artificial Intelligence at the edge", which will provide the European industry with opportunities to play a leading role in the future.

The ECS SRA aims to foster the digital transformation by supporting the development of technology solutions over the entire ECS value chain, addressing the emergence of new business models with shorter innovation cycles and new transaction mechanisms for improved trust and security. It captures the game changers that have led to a smart economy and society (smart mobility, smart health, smart energy, smart industry and smart life). In the future, new integration technologies and closer interaction with neighboring evolving technology domains like integrated photonics, bioelectronics and flexible electronics will open-up new opportunities and application fields for the European ECS industry.

The ECS SRA acts as a tool to realise the industry-driven, long-term vision of an ECS ecosystem. By focusing on strategic priorities, it aims to align and coordinate research policies in Europe as well as match the allocation of programmes and resources to different technology and policy challenges. The Research, Development and Innovation (R&D&I) strategy addresses the essential capabilities required to meet the application needs, dissolving barriers between application sectors to create a complete ecosystem of companies, universities and research institutes cooperating together to develop key technologies and applications. Finally, in establishing an adequate environment to transform the research results into successful solutions, Europe will be strengthened and become a more competitive force.

Implementing the ECS SRA will translate not only into economic value but also have profound societal impact, by contributing to meet the challenges of sustainable living and of the long-term European policy on zero carbon dioxide emissions. In the global competitive arena, the need of keeping or even bringing back manufacturing to Europe is undeniable. In terms of the societal needs arising from an ageing society, new approaches based on ECS will help maintain the living standards that have been reached in Europe. In the context of growing protectionism in the US and China, Europe has to retain its sovereignty and autonomy for the provision of its rapidly increasing needs for electronic components, embedded/cyber-physical systems and smart integrated systems. The three associations share the firm conviction that the companies, research institutes and universities should remain strongly engaged together in driving the research and innovation agenda with the ultimate goal of creating value, growth, jobs and prosperity.

Jean-Marc Chéry
President of AENEAS

Jean-Luc di Paola-Galloni
President of ARTEMIS-IA

Stefan Finkbeiner
Chair of EPoSS

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Introductory and overview chapter

0.1. WHY THIS SRA? TOWARDS A DIGITAL EUROPE

0.1.1. The digital society

Digitalisation[1] and the underlying key technologies are an essential part of the answers to many of the daunting challenges that we face today: mounting insecurity, ageing population, air quality degradation in large cities, traffic congestion, limited energy resources, unemployment, to name but a few. They impact the everyday lives of citizens, as well as all business sectors. Shaping the digital transformation of Europe opens up huge opportunities for the take-up and deployment of digital technologies – digital transformation facilitates the use of new technologies and widens the business scope worldwide with innovative digital products and services. The future of Europe must be substantially shaped by a strong European electronic components and systems (ECS) industry.

In 2018, MGI estimated that an additional $13 trillion could be added to global GDP by 2030 through digitisation, automation and AI, as these technologies will create major new business opportunities where productivity gains can be reinvested into our economies.[2]

0.1.2. ECS at the core of a digital Europe

The core enablers for this digital transformation are electronic components and systems, where the 'components' are the hardware and software parts of the systems enabled by electronics, and the word 'systems' is used in this context for the respective highest level of development targeted within the given part of the value chain. 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. These systems typically include hardware and software parts (see Figure 1 for an illustration of the concept).

Electronic components and systems are core enablers and differentiators for the development of many innovative products and services in all sectors of the economy. As shown in Figure 2, the ECS industry represents the basis of an 'inverted pyramid' on which rests a large part of the world economy.

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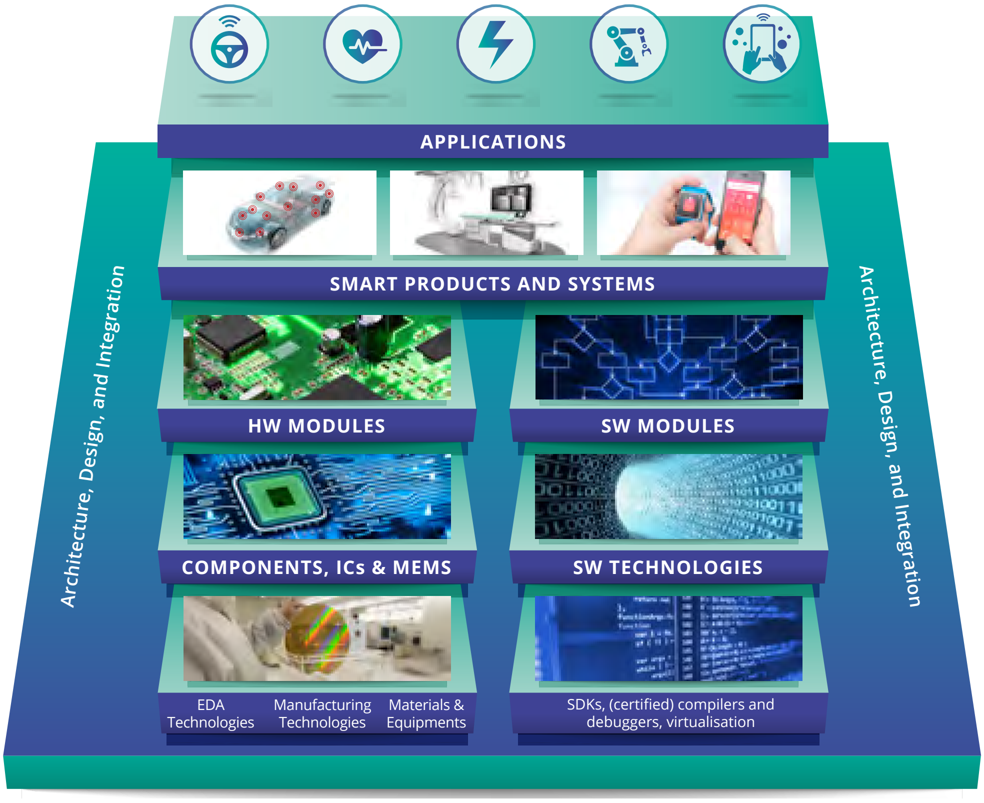
[1] For the sake of clarity, the following definitions are used in this report to distinguish between digitisation and digitalisation: 'digitisation' is the conversion of text, pictures or sound into a digital form that can be processed by a computer (i.e. from analog to digital), while 'digitalisation' is the use of digital technologies to transform business models, generate new revenue and value-producing opportunities, and interact with the world (i.e. putting the digital into practice).

[2] Quoted from McKinsey Global Institute, 2019, "Twenty-five years of Digitization: Ten Insights into How to Play it Right", May.

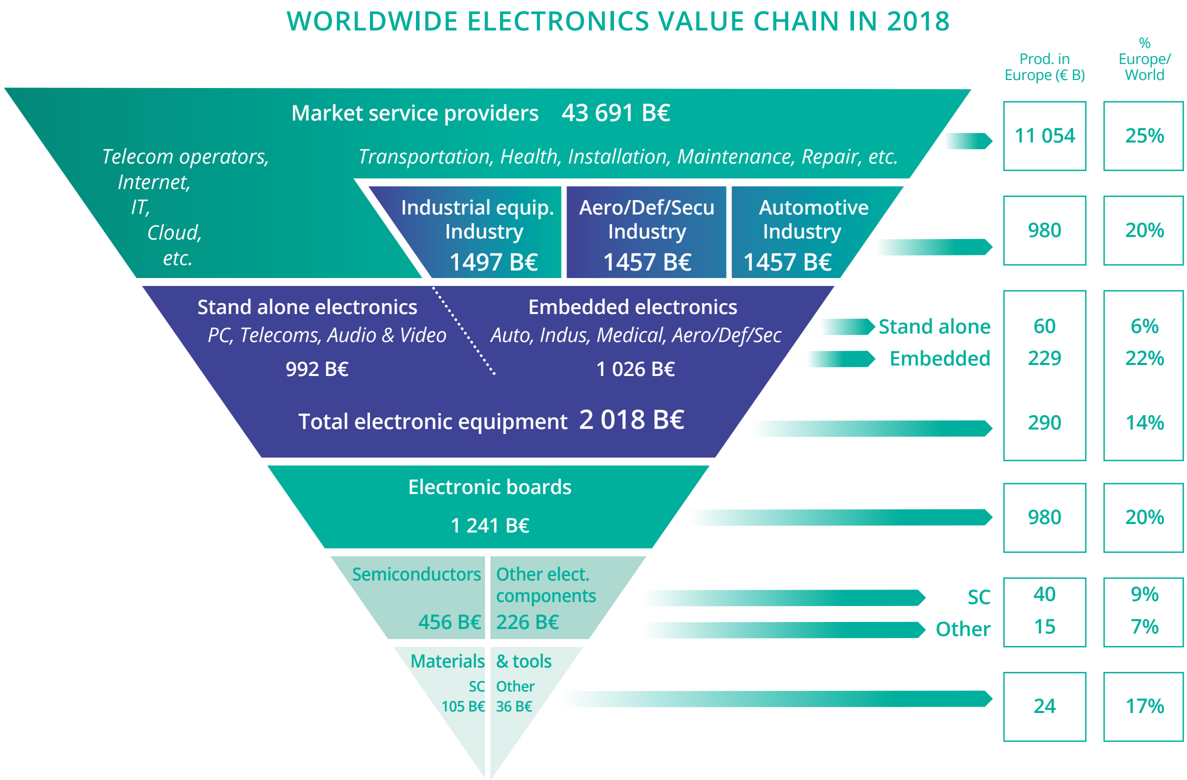


F.1 *The electronics value chain*

Europe's ECS industry remains robust: the ability to develop and produce highly performing and reliable systems to meet the needs of consumers is based on the availability of components tailored to the needs of the systems.

The key differentiators for the success of European systems are:

- application-specific semiconductor technologies ('More-than-Moore technologies') such as RF, MEMS and power semiconductors, as well as the very low power CMOS technologies (e.g. FD-SOI) where European companies are global market leaders;
- the traditional European strength in smart cyber-physical systems, and the ongoing revolution of ubiquitous computing that presents an opportunity to position European players as world-class leaders;
- highly complex, efficient and reliable software solutions operating from micro-controllers up to complex products such as aircraft, satellites, cars and trains;
- highly miniaturised and tailored ECS packaging and assembly technologies that integrate the heterogeneous components of electronics, photonics and MEMS technologies (micro-fluidics, micro-nano-bio-systems, etc) into low-space, energy-efficient packages to create the HW basis for digitalisation;



Worldwide ECS value chain in 2018[3]

Source: DECISION Etudes & Conseil

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- a world-leading equipment industry that serves not only the local S/C industry, but also manufacturers of high-volume standard products such as microprocessors and/or memories that are produced mainly outside Europe but whose performance and reliability form the basis of successful SW within any ECS;
- world-class industry sectors in aeronautics and space, automotive, health, automation, robotics and energy.

The importance of such capabilities for the success of European ECS-based systems will dramatically increase as European Society undergoes a digital transformation, so it is essential to boost innovation here in order to support this transformation.

Continued European digitalisation represents a great opportunity, as well as a pressing need, to undertake ambitious R&D&I to generate market products and services that benefit citizens, businesses and society. This requires a wide range of research and innovation topics that address the entire ECS value chain, from equipment, materials, production technologies, packaging and assembly technologies, embedded software through architecture and design tools, modelling

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[3] *Revenues from the sales of stand-alone SW modules shown in Figure 1 are not included.*

and models, libraries and complete functional blocks over the different levels of abstraction, up to the level of smart system integration[4] and complex cyber-physical systems,[5] or even systems of systems such as aircraft, cars, networks of robotic production facilities and ECS manufacturing clusters, but also smart home solutions (smart city and smart grid), and low power, high-performance data and computing centres. Europe has to recognise the opportunities as well as the threats provided by the digital society if it is to maintain those key technologies and capabilities in-house.

0.1.3. Aligning R&I priorities across technologies and applications

This ECS-SRA aims to foster digital transformation by supporting the development of technology solutions over the full ECS value chain. It focuses on the strategic priorities to bring innovation through smart digitised applications, products and services in a large variety of activity sectors.

The pan-European ECS Strategic Research Agenda is a tool for realising the industry-driven, long-term vision on ECS. By focusing on strategic priorities, it aims to help align and coordinate research policies in Europe, and to match the allocation of programmes and resources to different technology and policy challenges, and ultimately to strengthen European stakeholders in ECS.

Until the turn of the century, electronics industry advances were mainly powered by Moore's law and the concurrent progress in software engineering. As transistors became smaller, they became cheaper, faster and less power-consuming. Whatever the application required (performance-, cost- or energy-driven), miniaturisation was the answer. As a result, the technology development roadmaps for integrated circuits could be largely decoupled from the application roadmaps.

As scaling is approaching physical and economic limits, new technologies to improve functionality that are no longer so 'market-agnostic' grew in importance. In particular, the European ecosystem (industry, RTOs and academia) took a leadership position in the development of market-specific components and technologies, as described in the section on 'game changers'. New functions and figures of merit have emerged, and technology and application roadmaps are now increasingly interrelated; in addition to higher-processing and larger memories application needs co-determine the technology development priorities, while applications base their development roadmaps on expected new technological capabilities. Consequently, this document was augmented by bringing together over 250 experts from both applications and technology domains across the whole R&D&I spectrum, from university labs to large companies, and from RTOs to SMEs.

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4 *Smart system integration combines multiple technologies, functions and materials that utilise nanoelectronics, micro-electro-mechanic, magnetic, photonic, micro-fluidic, acoustic, bio and chemical principles, radiation and RF, as well as completely new technologies to form smart systems that are reliable, robust and secure. These are also often miniaturised, networked, predictive, and can learn and become autonomous. They bring together sensing, diagnosing, managing, actuation, communication and collaborative capabilities to enhance the quality of life and address societal challenges.*

5 *Cyber-physical systems are 'embedded intelligent ICT systems' that make products smarter, more interconnected, interdependent, collaborative and autonomous. They provide computing and communication, monitoring and control of physical components and processes in various applications. Harnessing these capabilities in time and across space creates applications with enormous and disruptive new functionalities that offer unprecedented societal impact and economic benefit for both citizens and societies.*

0.2.
GAME CHANGERS

Innovation, along with rapid developments across all ECS-based application areas, are creating the foundation for transforming the way we work and live. The falling cost of all semiconductor components, the advent of artificial intelligence, the rise of broadband, ubiquitous connectivity, the omnipresence of autonomy and virtualisation, the efficiency increase in power management, 'clean' mobility and miniaturised systems, the use of sensors and actuators as environment connectors, the novel human-machine interfaces (graphical, touch, holographic, voices, gesture, etc.) with the outer digital world have combined to create the dawn of a digital era filled with the accelerating evolution of technologies.

In addition, the emerging ecosystems around embedded intelligence and artificial intelligence technologies, blockchain and security, the Internet of Things (IoT),[6] high-performance computing, ever-growing miniaturisation, as well as increasing physical and functional integration into devices and smart systems, among others, have quickly moved from emerging to being on the verge of mainstream, thus creating new paradigms. In parallel with this change to daily life through available technologies, the challenges regarding sustainable living and the fulfilment of a long-term European policy on zero carbon dioxide emissions and zero casualties in road transport demand disruptive solutions. In the global competitive arena the aim to keep, or even bring back, manufacturing in Europe through initiatives such as 'Industry 4.0', 'Industrie du Future' and the like are supporting the digitalisation of European industry. For the societal needs of an ageing society, new approaches based on ECS will pave the way for maintaining the living standards we have achieved in Europe. We review these main trends[7] below, which we call 'game changers'" due to their disruptive nature.

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[6] IoT: McKinsey & Company Global Institute in its report: Internet of Things: Mapping the value beyond the hype – June 2015 define IoT as: sensors and actuators connected by networks to computing systems. These systems can monitor or manage the health and actions of connected objects and machines. Connected sensors can also monitor the natural world, people and animals. They exclude systems in which all of the sensors primary purpose is to receive intentional human input, such as smartphone apps where data input comes primarily through a touchscreen, or other networked computer software where the sensors consist of the standard keyboard and mouse.

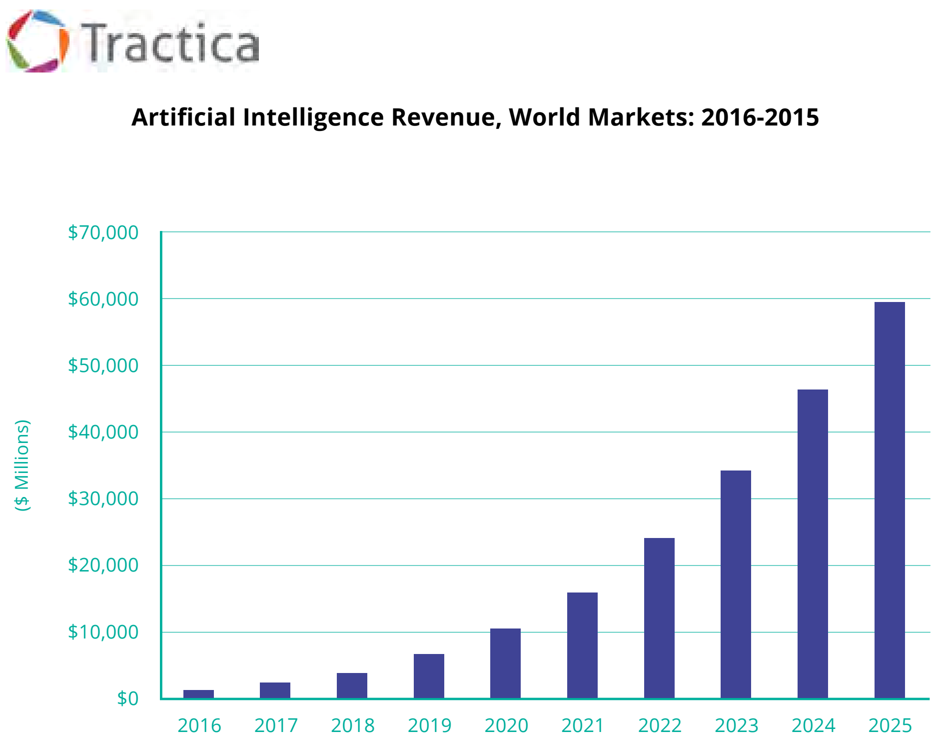
[7] Only generic game changers, affecting most or all technology and application domains covered by the SRA, are included in this chapter. If they exist, domain-specific game changers are also mentioned in the relevant domain chapter.

0.2.1. New Technological Paradigms

Advent of Artificial intelligence and data analytics

After a period of disillusion, artificial intelligence has recently been scoring huge public successes, with machines now defeating humans in many fields, from general culture (such as Jeopardy) to strategy games (Go, chess and poker). This technology aims to have a disruptive impact in many of the domains covered by the Strategic Research Agenda, whether in our daily life (with apps such as cloud-based advanced assistant systems – Alexa, Siri, Google Home, Cortana, etc.) or in specialised domains such as healthcare (e.g., advanced systems to help provide clinical support for healthcare professionals), energy, industry (e.g., preventive and predictive maintenance, control, optimisation, decision support), and autonomous cars and domestic appliances. In general, data and data science are a new sort of material that fuel the AI applications, and together also represent a significant driver of the research strategy of the essential capabilities, e.g., requiring adaptation of the computing models being developed.

According to a Market forecast report by Tractica, the revenues generated by the direct and indirect application of AI software will grow from USD1.4 billion in 2016 to USD59.8 billion by 2025 (see Figure 3).



F.3 *Forecast of AI revenues until 2025* Source: Tractica

In addition to intensive embedded intelligence capabilities, autonomous cyber-physical systems (ACPS) are developing new ways to interface with the real world in general, and humans in particular: virtual reality, augmented reality, brain–computer interfaces, home assistant, etc. Deep learning and cognitive computing are changing the way humans interact with the digital world in a more natural manner with voice or gestures, and assignments to autonomous systems, and which are driving research and innovation priorities. In providing a range of novel functionalities offered by artificial intelligence, smart systems may also become a major force behind almost all product innovations in nearly every application field: transportation, health, domestic activities, manufacturing, energy, natural resources and security, by optimising the resources, energy and improving the efficiency of processes.

Humanoid robots, able to interpret human body language and read emotion, will support the improvement of patient care and wellbeing, and could even have an impact beyond that in our daily lives as well as on the factory floor.

While this major game-changer represents a clear opportunity for improving our lives, it also carries a threat for Europe, since many of the current big players in hardware and software are non-European, and also in the future when decision-making could move out of human control.

The arrival of radically new paradigms for computing provides an opportunity for Europe to become stronger in that field, in terms of both hardware and software technologies. In particular, the emergence of neuromorphic and quantum solutions will open new opportunities for computing hardware and software platforms. This represents an emerging playing field, in which a window of opportunity exists for Europe to take leadership in computing if it acts fast. Additionally, several initiatives are seeking to strengthen European excellence in AI research and innovation, with a strong focus on human-centred AI and ethical AI, and to establish world-wide brand recognition for 'AI made in Europe. Such initiatives can hopefully provide the groundwork with which the European ECS industry will be able to build leadership, as well as perspectives for industry/science collaboration, see Figure 4. Finally, it is crucial that the developments in artificial intelligence are accompanied by R&D in security, safety, data protection (in view of industrial intellectual property rights) and data privacy of the AI-powered systems, if those systems are to be trusted and deployed. The leadership position of Europe in safety and security can hopefully be leveraged to provide our continent with an edge in the AI race.

The importance of ongoing and future breakthroughs in artificial intelligence, the technology developments they require and their impact across all application domains are visible throughout this Strategic Research Agenda and are a recurring theme of the report.

Advances in computing: Facing new software and hardware complexity – moving computing and AI to the edge

Market projections clearly indicate that large-scale system of systems (SoS) solutions will be the market pull for the current ECS value chain. This market pull points toward a move to market value networks that evolve from existing technologies and their value chains. Here, distributed, dynamic and flexible computing integrated by seamless connectivity will allow the value-based exchange of information to support societal objectives related to environmental footprints, efficient resource utilisation, etc.

The major technology push for highly distributed computing is the energy cost of data communication compared to computing, which is pushing computing to the edge – i.e., to embedded devices, see Figure 5. With the expansion in AI and data analytics, the development of a European strategy to become the world leader in edge AI and edge data analytics should be the next step. Such progress will build on advancement for

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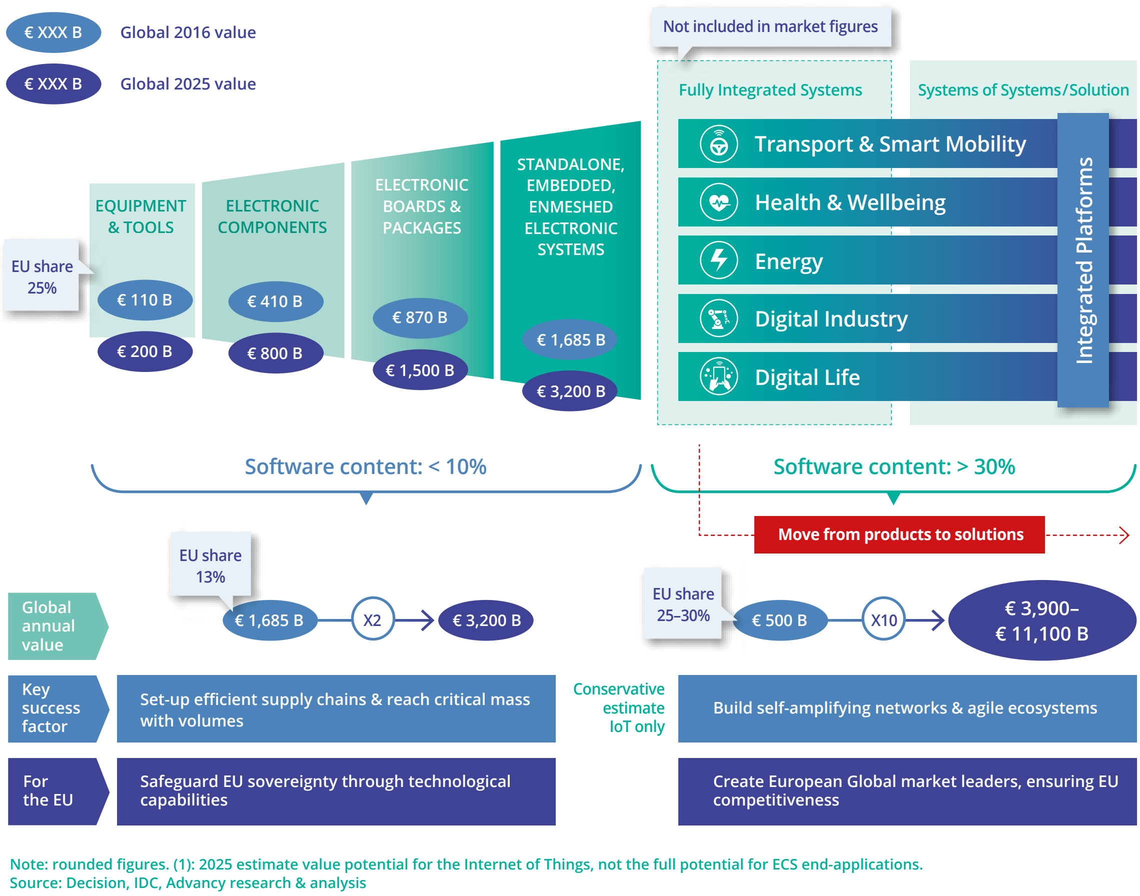
[8] *See, e.g., CLAIRE, "Confederation of Laboratories for Artificial Intelligence Research in Europe", https://claire-ai.org/.*

embedded computing based on traditional digital computing hardware and new computing paradigms like neuromorphic hardware.

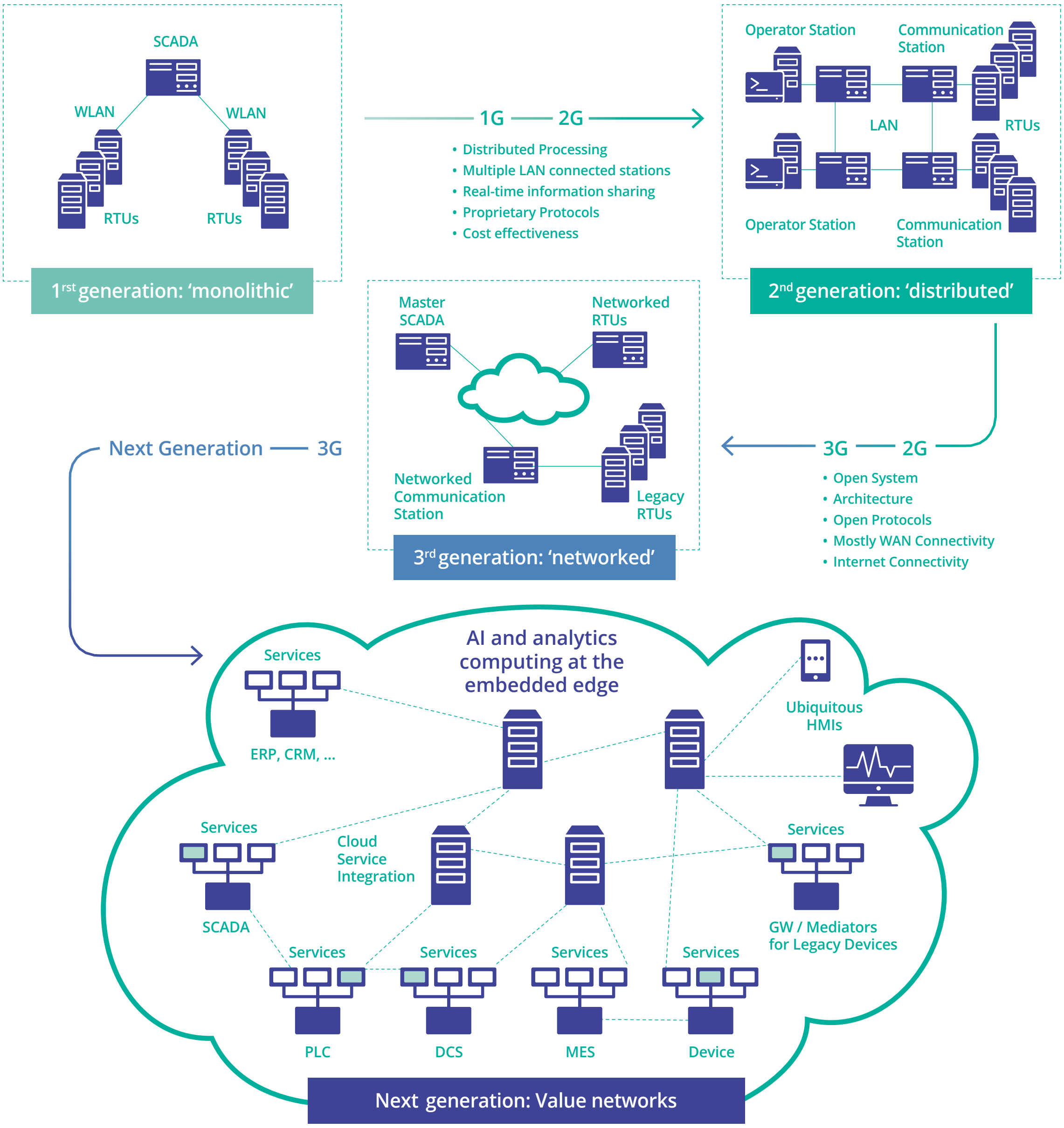
Today, and into the near future, artificial intelligence will rely almost entirely on advanced logic and memory technologies to process the exponentially growing data stream. The advancing miniaturisation of semiconductor structures is currently the only way to reduce the relative power consumption of logic components (see Figure 6) while simultaneously increasing their performance.



F.4 *Global and European value chain 2016–25 (Source: Embedded Intelligence : Trends and Challenges, A Study by Advancy, Commissioned by ARTEMIS Industry Association, March 2019).*

To this end, pure dimensional scaling (by patterning and circuity shrink) is supplemented by three further scaling engines – i.e., circuit scaling (by 3D, system-on-chip and advanced packaging), device scaling (by new devices and materials) and architecture scaling (by solutions optimisation). To explore the potential of these domains, Europe has a unique ecosystem of RTOs and semiconductor industries available, particularly pilot line providers and equipment, material and (design) tool makers. It has achieved a leading position in this sector, and will therefore continue to make an indispensable contribution to the advancement of AI. The aim is to strengthen and expand this position in the future.

The challenges of transforming current client–server application software into this projected computing and connectivity future should not be underestimated. Europe has to move from its current leading position using



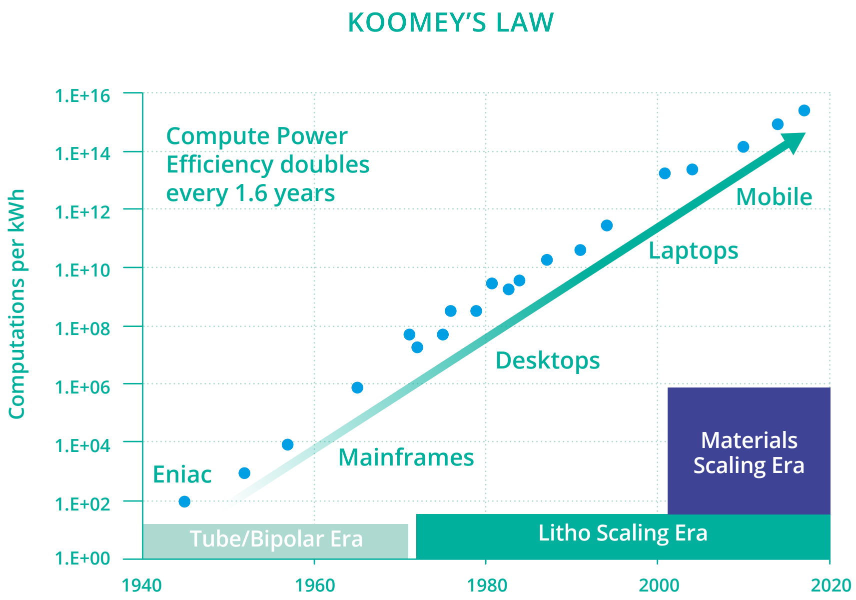
Evolution of the control systems from different computing architecture generations (monolithic, distributed, networked) to an edge computing one where data analysis, based on AI, is performed close to the end-devices and/or subsystems. F.5

legacy technologies for embedded real-time client software into highly distributed, edge and heterogenous embedded computing.

The distribution of computing to the edge and heterogenous embedded hardware will require widespread usage of new software paradigms such as service-oriented architectures and software–agent technologies, adaptation of cloud software technologies to the edge and embedded platforms and new embedded software technologies suitable for real-time distributed AI and analytics. These new tools should support a continuum of computing between clients, edge and the cloud, where data processing is more efficient. In addition, new and highly efficient engineering tools and tool chains are necessary to meet the projected market demands at SoS solutions.

The upcoming neuromorphic computing[9 10 11 12] architectures and hardware radically reduce the energy cost of computing for deep-learning applications. Energy reduction of a magnitude of two or three times is being widely published. However, software for neuromorphic architectures and hardware is a rather unexplored domain, and thus becomes both an opportunity and a threat to European industry. To exploit combined digital and neuromorphic computing hardware, radically new approaches to software and software development are needed. A strong commitment in this direction will further strengthen application areas currently dominated by Europe.

The projected move of computing and AI from the cloud to clients and the edge also creates new requirements for connectivity at the edge. Heterogenous usage of legacy and new (5G) communication channels will be integrated in a seamless manner while ensuring that data security is maintained and energy consumption kept as low as possible at a global level. Within the edge, key focus is needed on high-performance high efficient gateways (upper link gathering the raw data coming from sensor nodes, aggregating, local processing and transmitting them). Edge computing is a method of optimising cloud computing systems by performing data processing at the edge of the network, near the source of the data. This reduces the bandwidth needed for communication between sensors and the central data centre (cloud or private cloud) by performing analytics and knowledge generation at or near the source of the data. [13 14]



F.6 *Koomey's law: Computing power efficiency doubles every 1.6 years due to progress in logic and memories technology.*

Increased connectivity

The trend towards integration of individual systems into networks of systems puts new demands on connectivity, e.g., in terms of seamless interoperability, latency, security, safety, flexibility, manageability and evolution. Full support for such requirements has the potential to transform our economy and personal lives even further. While this represents huge opportunities, it is not exempt from threats: as previously isolated safe systems are becoming connected to the outside world, novel integrated approaches are required to ensure both safety and robust security for products.

Increased connectivity has a potentially strong impact on the energy consumption of the communication networks. To avoid an explosion in energy consumption, energy per transmitted data unit must be cut radically. Intelligent beam-forming techniques to limit radio signals only to directions of active user terminals, efficient communication protocols and network management algorithms will be developed, as well as highly efficiency electronic components.

Application-specific semiconductor technologies

In recent years, application-specific semiconductor technologies have played an ever-increasing role in our day-to-day lives; without advances in sensor and actuator technologies, passive and active safety solutions in cars or the 'smartness' of smartphones would be unthinkable. Similarly, the introduction of the renewable energies, minimised chargers and electric powertrains in vehicles are all dependent on the capabilities of achieving higher power densities and far less dissipation loss to enable ever smaller form factors.

Those technologies are evolving towards smaller but more heterogeneous components, fabrication on larger wafer diameters, continuous cost reductions, and improved performance, all of which enables further developments in the market for ECS.

Those advanced application-specific technologies were made possible thanks to the development of processes and materials (such as SiC and GaN for RF and power devices), as well as the necessary equipment. They enable innovative emerging applications while leveraging synergies with processing and manufacturing technologies of More-Moore devices.

Heterogeneous Integration/comprehensive smart miniaturised systems

The realisation of smart electronic components and systems for Europe's critical applications requires complementing logic, memories, communication and power electronics with a large number of additional features for functions such as sensing (e.g., MEMS, photonics and RADAR imagers), actuating, data protection and energy management. To a growing extent, the heterogeneous functionalities can be integrated monolithically. These system-on-chip (SiC) components can have substantial embedded memory but also mixed-signal and smart power capabilities. However, the highest complexity still necessitates multichip components and the use of system-in-package (SiP) integration technologies. Here, 3D stacking and multi-level fan-in or fan-out wafer-level packaging are the most advanced concepts today, with a clear trend pointing towards finer structures, smaller pitches and higher diversity of the features integrated.

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[9] *Neuromorphic computing uses architecture and design principles based on those of biological nervous systems. It might mimic non-conventional coding of information such as spikes while using classical CMOS devices, or resort to new hardware implementations (such as oxide-based memories).*

[10] *Carer Mead, Neuromorphic Electronic Systems, Proceedings of the IEEE, 78(10), October 1990.*

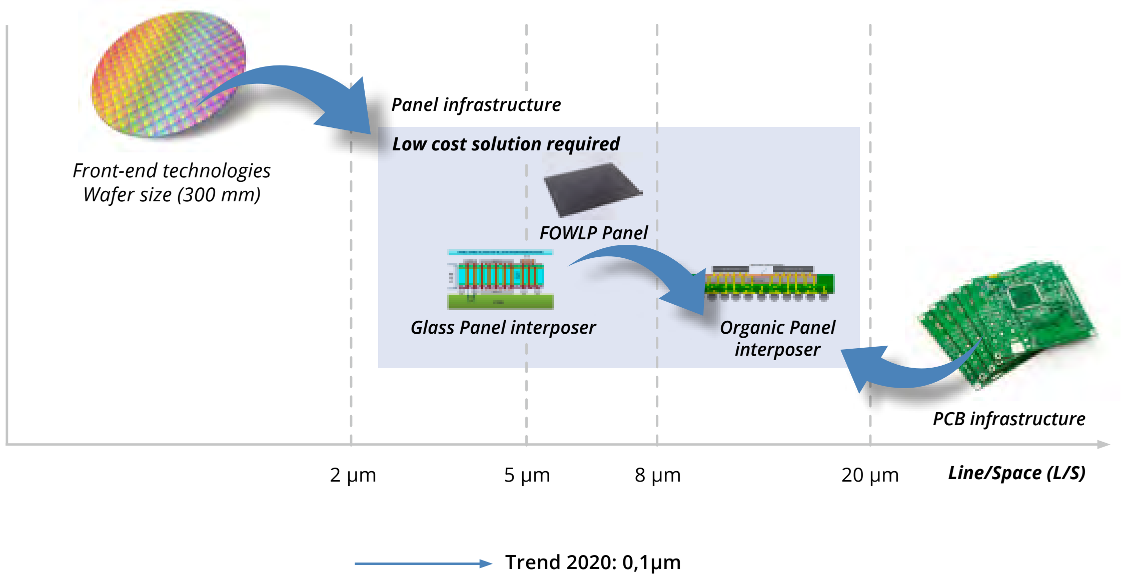
[11] *Monroe, D. (2014). "Neuromorphic computing gets ready for the (really) big time", Communications of the ACM, 57(6): 13–15, doi:10.1145/2601069.*

[12] *Neuromorphic Computing: The Machine of a New Soul, The Economist, 2013-08-03.*

[13] *Gaber, Mohamed Medhat; Stahl, Frederic; Gomes, Joao Bártolo, 2014, Pocket Data Mining – Big Data on Small Devices (Springer International Publishing).*

[14] *David Greenfield, blog on "Fog Computing vs Edge Computing: What's the difference?" https://www.automationworld.com/fog-computing-vs-edge-computing-whats-difference.*

Heterogenous integration combines dies with different process nodes and technologies with die-to-die interconnect distances starting to become so close that they mimic the functional block interconnect distances inside a SoC. This requires new assembly and packaging materials, as well as compatible chip/package interfaces. In addition, the packaging architectures must consider electro-magnetic compatibility and also temperature and thermo-mechanical constraints in order to keep the applications robust and reliable. The combination of all these challenges, which must be addressed simultaneously, makes research and innovation in heterogeneous integration and packaging/assembly technologies a key issue for the performance/reliability and cost of the ECS as a whole.



F.7 *The heterogeneous integration domain in electronic components merges the conventional PCB with the wafer-level technologies (Source: Fraunhofer IZM).*

Beyond components, this game-changer impacts R&I strategy in many domains covered by the SRA, such as the following.

- Computing and storage that leads to research on hardware/software specialisation according to the task at hand, and for the management of heterogeneity and complexity.
- Module- and system-level integration, where the aim is to combine sensing, decision-making, actuation, communication with energy management locally and with all the necessary software functionalities in a highly comprehensive way, and to develop knowhow that enables solutions suitable for high-volume fabrication based on a multitude of different systems or sub-systems.
- Connectivity and interoperability, whose R&I priorities include the development of methods and tools enabling the use of heterogeneous protocols over heterogeneous hardware.
- Physical integration at all levels, in which the use of 3D architectures provides opportunities for increasing the functional density and improving the performance of the devices.
- Physical integration at system level, whereby energy autonomy[15] becomes an important consideration for IoT schemes, as well as the local versus global split of computing/data treatment capabilities in relation to functional autonomy and response time of the overall distributed system and its individual nodes.

These new technologies enable the creation of autonomous systems that are comprehensively capable of sensing, diagnosing, deciding and actuating in a communicative and collaborative way. These systems are already often highly miniaturised, and operate in networks, feature predictive and energy autonomy capabilities, constituting the embodiment of what is now known as the Internet of Things. In the future, they will increasingly integrate physical artificial intelligence, feature self-organising, self-monitoring, and self-healing and truly cognitive functionalities. They will be designed to meet the growing requirements in terms of reliability, functional safety and security that result from the new applications, and also the demanding environments in the fields of personal and freight transport, digital industry, health and wellbeing, smart energy and digital life. At the same time, many of these systems will be fabricated for the business-to-business sectors and the general public – i.e., at costs appropriate to the markets of both commercial and individual end-users. With this large penetration, these new systems will address and substantially contribute to the mastering of the societal challenges.

Additive manufacturing/3D printing

The constraints of current manufacturing infrastructure, optimised for low-cost/high-quality products that are mass produced in enormous quantities in Asia, lead to standardised components and product designs, limited freedom of shape, a rigid supply chain and pressure to minimise variation to allow the high fixed manufacturing costs to be amortised over many produced units. Additive manufacturing techniques have the potential to introduce a major paradigm change in the industry, enabling Europe to regain leadership in the fabrication of the increasingly customised products demanded by today's segmented markets. One striking example is the health sector, where these technologies enable the fabrication of patient-specific anatomical models. Beyond that, they could even disrupt supply chains and business models, as parts made centrally and subsequently shipped across the world could be 3D-printed in decentralised locations.

Micro Nano Bio Systems (MNBS)

Combined with the continuous development of new materials (such as graphene and metamaterials for medical devices) and 3D printing using biological materials, computerised numerical control machining could allow the printing of implants and prosthetics adapted to the individual. Leveraging the latest advances in energy harvesting and power management will enable devices that may never need to be replaced.
Nano devices will change diagnostics, targeted drug treatment and local treatments. Bio-sensing, molecular biology and genomics will also provide greater insight for personalised treatments.

One step further, the in vitro technologies used today to develop organs on a chip should lead to in vivo implantable organs on a chip

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[15] *low-power operation (sensing/acting, computing, communicating) coupled to feasible unwired power (energy harvesting and storage)*

or implantable organs in a package that could substitute for donor organs or assist ailing deficient organs. These will help lead the way in regenerative medicine, aiming to restore degenerated, diseased or damaged tissues and organs, thereby increasing vital functioning and reducing the cost of healthcare.

Integrated Photonics

Integrated photonics uses light particles (photons) instead of electrons for the instantaneous transport of data, related data processing and sensing, for example. Integrating multiple photonic functions on a (photonic) chip creates an impact similar to that of IC's revolutionised microelectronics in the 1980s, resulting in mass producible products that are cheaper, lighter, faster, smaller and greener (having significantly less energy consumption). Recent progress in technology already allows to integrating the translation between light and electrical signals in both directions. In these so-called active optical cables, the amplification of light is possible, and the conversion between light and optical signals can be realised by the connectors. The first applications in very high-speed data processing at very low energy consumption using photons as information carriers are already commercially available. However, more research and innovation is required to take advantage of the full potential of this merging of nano-electronics and photonics.

Photonic IC's are currently emerging in applications where information is already available as light, such as in data transport, processing and communication systems using glass fibres (e.g., data centres) and light sensors (medical, agro-food, climate, mobility), as well as niche applications in quantum computing and security.

Photonics for societal megatrend applications

Photonic technologies are a major development in solving many societal challenges. Some examples are in the following.

- **Health:** (optical) Sensing technologies for the early detection of diseases, assistance in surgery, and remote medical care.
- **Agro-food and food safety:** Sensing ripeness and contamination of food along the supply chain from farm to fork, and ultimately finding uses in smartphones.
- **Communication:** In data centres and 5G networks, photonic ICs can route information streams from fibre to fibre without conversion to electronics with an energy efficiency that brings substantial savings to the global electric energy consumption and at speeds that can keep pace with the exponentially growing data levels. This meets a pressing need, as in data centres alone traffic is doubling on average every three years, while in the fastest-growing hyperscale data centres traffic is doubling every year.
- Mobility: Light-radar (LiDAR – Laser Imaging Detection and Ranging) for (semi)-autonomous vehicles can be made compact, low power, robust and affordable using photonics. Airplanes can become more energy-efficient and safer with fibre-based load and stress sensors in their landing gear, wings and body.
- **Construction:** Bridges and tall buildings can become safer through continuous monitoring with fibre-based stress sensors.
- **Climate:** Optical sensors for monitoring air and water quality.
- **Industry 4.0:** Optical sensors and low-EMC optical networks; LiDAR for robotics.
- **Quantum and security:** Photonics is a key enabler for quantum computing and quantum-safe security.

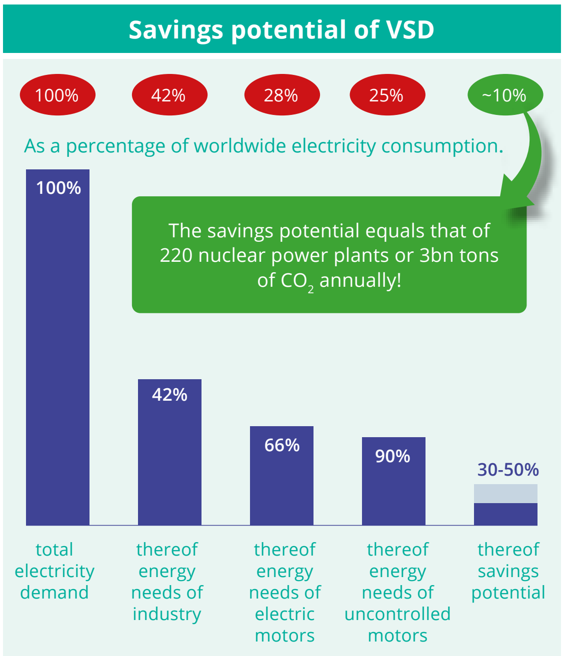
Energy landscape

The ambition to achieve zero emissions towards 2050 is driving the need for change in the energy landscape through distributed variable renewable energy sources and bidirectionality in the grid landscape. ECS supports the development of this landscape with the lowest dissipation losses, integrated intelligence and smallest form factors.

By way of complementing its contribution to more efficient energy generation and distribution, ECS, and in particular power technologies, also have a huge potential impact for energy consumption in the industry domain, as illustrated by Figure 8.

FACTORY AUTOMATION:
HUGE SAVINGS POSSIBLE WITH VARIABLE SPEED DRIVES (VSD)

- About 300 million electric motors are in use worldwide
- Rising electric energy cost and ErP (Energy-related Prodcts) directive force energy efficiency
- Rising labor cost in low labor cost countries drives automation level.
- “Mechanic goes electric”; e.g. hydraulic is replaced by electric motors.



Energy-saving potential of S/C power technologies (Source: ABB. 2013) **F.8**

The fourth industrial revolution

The first industrial revolution used water and steam power to mechanise production. The second used electric power to create mass production. The third used electronics and information technology to automate production. Now, the fourth industrial revolution (supported by initiatives such as ‘Industry 4.0’, ‘Industrie du Futur’ and ‘Digitising European Industry’) heralds a fusion of technologies in which the lines between the physical, digital and biological spheres are becoming blurred.

In parallel or combination with the new manufacturing technologies for automation mentioned above, advances in information and communication technology (ICT) are also allowing for large horizontal integration across multiple value chains on processes, data and companies, as well as vertical integration among corporate levels, from the enterprise resource planning (ERP) level down to the field level (robots, sensors and actuators, shop floor). Connected enterprises can attain increased efficiency in processes, performance and output, giving rise to virtual network enterprises.

In addition, the concept of mass customisation (a.k.a 'agile value networks' or 'lot size 1') – i.e., by manufacturing only what the customer wants – will significantly reduce the waste and inefficiency of current mass market production, directly decreasing environmental impact and increasing responsible consumption and production, one of the sustainable development goals of the European Union.

EU companies that focus on high-quality and personalised products/services could provide them at significantly lower costs, while maintaining the attention to design and functionality that makes companies successful. This could give a significant competitive advantage to EU manufacturers compared to low-cost mass manufacturers. All these changes are an opportunity for Europe to reverse the current trend of shifting production to countries with low labour (and other societal) costs thanks to flexible and cost-effective production enabled by electronic components and systems technologies.

As with the earlier revolutions, the fourth industrial revolution has the potential to raise global wealth and improve the quality of life for populations around the world. Its full impact on business, governments and people will be as unprecedented as it will be unpredictable.

0.2.2. New Business Model Paradigms

Everything as a service: New business models/Internet economy

Initiated in the IT world, the trend of replacing ownership with a pay-per-use system – also known as 'everything as a service', or XaaS – is now entering the physical space. For example, mobility-as-a-service (MaaS) will increasingly catalyse the public–private co-development and co-delivery of mobility and transport systems and services, as well as shared and open use of public space, data and infrastructure.

The mobility market is now regarded as multimodal, combining all kinds of transport means, including mobility data and information, as well as access to it. European industry is well-positioned to provide the required electronic components and systems to enable these new business models.

Faster and shorter innovation cycles

The challenge is to cope with the adversary requirements of the ever-decreasing time to market and the need for a longer 'time on market', which directly impacts technology requirement definitions. However, the challenge can be met, such as by providing upgradable ECS for later adaptation at the customer's site.

New transaction mechanisms for improved trust and security: Blockchain

Initially confined to the world of security experts, distributed ledger technology (blockchain) has the potential to enable innovation across the economy.

- In healthcare: Health and life insurers are among the many players scrambling to determine how blockchain can be adapted to improving how we maintain health records, execute transactions and interact with stakeholders.
- For energy: To enable transactions and micro-trading in the new smart distributed energy resource grids.
- For the cashless economy: Virtual currencies and crypto-currencies.

Vertical integration and leadership

Hyper-scale businesses are vertically extending their range of activities by creating customer lock-in over the complete value chain. For example, in the domain of consumer electronics, companies that have gained control over the complete value chain (from silicon design through retail or internet shops up to end-user applications) have recently shown a high level of success, and seem to be more resilient to economic crises as they have created ecosystems and customer lock-in over the complete value chain.

The vision of 'virtual vertical integration' encourages market leaders to define the conditions for successful business innovation by building on emerging technological developments, and vice versa, to coordinate technological platform developments (hardware and manufacturing to system design and software engineering). At an organisational level, the subset of horizontally specialised European industry segments should work towards vertical ecosystems. Based on this assumption, this SRA highlights the importance of the contribution to standardisation activities and setting adequate new standards, as standards are essential enablers for scalability and interoperability functionalities. Also important is the development of design environments that efficiently cover the ECS design process over the whole value chain.

When consumers become prosumers

New technologies enable consumers to become co-designers and/or actors of the services and products they are using. In health, patients can provide first-level self-diagnosis. A consumer of digital content has evolved into a prosumer due to the advent of social media platforms such as YouTube. A home owner installing a solar panel is as much a supplier as a customer of an electricity utility company. Companies may even turn to their end-customer for the design of new products. However, this trend requires that products be designed with in-field personalisation in mind.

Energy and power management are clear examples of where these new paradigms are being developed.

- At the macro level, the growth of alternative energy sources such as solar and wind power, and the importance of efficient energy management for the development of smart cities, are changing the nature of the world's power grids. The increasing distribution of power generation is moving from today's unidirectional to a distributed and bidirectional power flow, requiring smart grids and the development of new electricity storage solutions. Emerging wide bandgap semiconductor[16] and integration technologies are key enabling factors for these new electrical architectures.
- At the micro level, the development of ultra-low power sensing and data processing capabilities, combined with new energy harvesting technologies, are allowing for the creation of systems that are energy autonomous over their entire lifetime – i.e., they are able to produce all the energy they need to consume. This will have a profound impact on many application domains, such as health, where lifelong implantable devices can now be envisioned

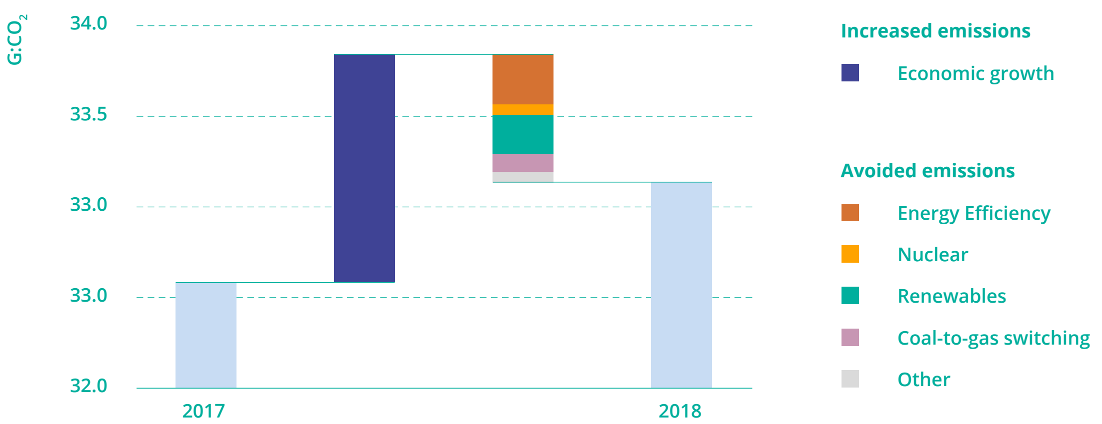
0.2.3. New Non-Technical, Societal Paradigms

The game-changers considered so far are technology- or business-related. However, other major trends are at work in shaping our future that need to be considered when deriving a strategy for European ECS industry research and innovation:

- **Political:** We are witnessing an era of increasing economic protectionism, which makes it all the more important for Europe to secure access to essential technologies and to avoid strategic and economic critical dependencies, such as the restrictions imposed by US export control laws.

These latter, due to their extra-territorial application, can constrain European companies from selling products, including US technology, to third countries (see Appendix to Chapter 0 for more detail). Regions and territories also intend to play a greater role in the technological roadmap and implementation.

- **Economic:** Developing economies in Asia and Africa represent both an opportunity (expanding markets) and a threat (increased competition). They also prompt us to develop new approaches to innovation, where ECS technology can be a key enabler.
- **Societal:** The European population is ageing, putting a strain on already constrained health budgets, changing the nature of the digital services needed, and also having an impact on our production infrastructure. This is to be viewed both as a threat and as an opportunity, since it forces us to solve now challenges that other regions around the world will face in the future. Increased urbanisation also requires new approaches (in energy management, transport and mobility, etc) that, once developed for Europe, will find new markets beyond our borders.
- **Environmental:** The impact of climate change and the need to safeguard the environment are raising challenges that cannot be solved without the ECS industry. On the other hand, the ECS industry needs to continue its efforts to reduce or eliminate the use of non-environmentally friendly materials, such as the use of rare earth materials.
- **Feeling safe and secure:** Faced with many threats in their daily lives, from terrorism to disruptive changes to their way of living due to food and health crises, the citizens of Europe are increasingly demanding the safety, security and protection of their privacy and personal data. ECS technology should be part of this solution, but at the same time it needs to consider this requirement at the design phase if it doesn't want to add to the problem (e.g., unprotected IoT devices providing entry doors to hackers and privacy breaches).
- **Legal:** Local legislation has a major impact on the deployment of some ECS-driven applications, such as autonomous driving and micro-bio-nano systems. Discrepancies between the rules applicable in various European countries might hamper the development of these technologies, and the corresponding European-based industry, compared with what happens in regions that benefit from a unified legal framework. Adequate legal environments are required to achieve the full potential of future ECS systems for European citizens.



Increased use of renewables in 2018 had an even greater impact ob CO2 emissions, avoiding 215 Mt of emissions, the vast majority of which is due to the transition to renewables in the power sector.

F.9 *Change in global energy-related CO_2 emissions and avoided emissions (2017–18).*

0.3. COMPETITIVE SITUATION

0.3.1. Key application areas

European industry has many strengths in several vertically integrated markets where ECS are the main driver of performance, such as transportation (automotive, railroad, aerospace), energy, health, urban services (from building construction to water provisioning) and industrial digitalisation.

Transport and smart mobility:

- **Automotive:** The EU is among the world's largest producers of motor vehicles and the sector represents its biggest private investor, providing jobs for 13.3 million people (including 3.4 million manufacturing jobs[16]) and accounting for 6.8% of the EU GDP.
- **Rail:** The overall rail sector in the EU, including rail operators and infrastructure managers, employs approximately 1.8 million people with an estimated 817,000 dependent individuals. The European rail supply industry employs nearly 400,000 people and is a top exporter, accounting for nearly half of the world's market for rail products and with a market share of 84% in Europe and a total production value of €40 billion (2010). The railway management systems market is expected to grow from €29.27 billion in 2016 to €57.88 billion by 2021.
- **Aerospace:** The European aerospace industry is a world leader in the production of civil and military aircraft, helicopters, drones, aero-engines and equipment, exporting them all over the world. Aerospace within the EU provides more than 500,000 jobs and generated a turnover of €140 billion in 2013. The aircraft flight control systems market is projected to grow from $11.85 billion to $16.59 billion by 202.

Health and wellbeing

Healthcare spending as a percentage of gross domestic product (GDP) should rise slightly, from an estimated 10.4% in 2015 to 10.5% In 2020. Government healthcare expenditure as a percentage of GDP is projected to rise more quickly in low income countries than for other income groups. Global healthcare expenditure is projected to reach €8.7 trillion by 2020, from €7 trillion in 2015, driven by improving treatments in therapeutic areas coupled with rising labour costs and increased life expectancy.

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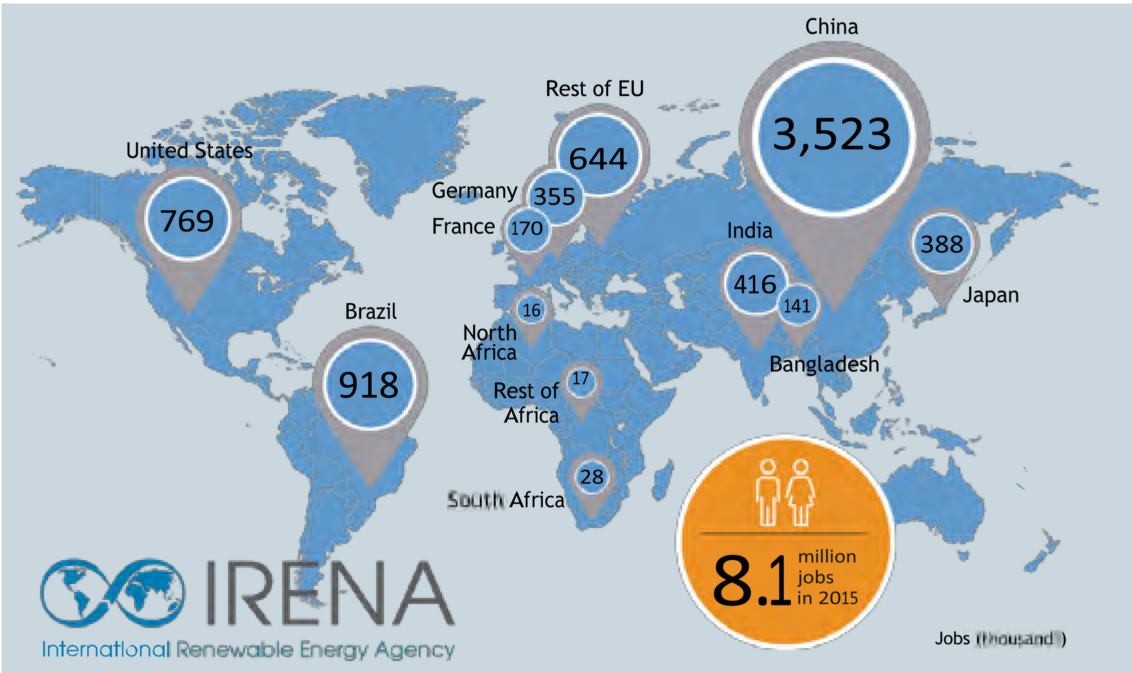
16 https://www.acea.be/automobile-industry/facts-about-the-industry

The healthcare sector accounts for 10% of all employment and is expected to grow by a further 1.8 million jobs by 2025. The healthcare IT market is projected to reach €200 billion by 2021 from €115 billion in 2016.

Energy

More than 9.8 million people were employed in the renewable energy sector in 2016, according to a recent report by the International Renewable Energy Agency (IRENA).[17] In 2015, Europe was employing close to 1.2 million people in this fast-growing sector.



F.10 *Renewable energy employment in countries and regions* [17]

In 2015, the worldwide renewable energy generation amounted to 5512TWh, of which Europe provided 1168TWh, or 21%.

Sustainable Production

The manufacturing sector accounts for 15% of GDP and provides around 33 million jobs in Europe. Europe is a frontrunner in manufacturing excellence, with its vision of smart and connected factories swiftly becoming a reality. The industrial control and factory automation market, comprising control system manufacturers, field components manufacturer, systems integrators and software manufacturers, is projected to reach $153.3 billion by 2022. By 2025, additive manufacturing is expected to create a €6.3 billion opportunity in the consumer electronics, automotive and aerospace industries.

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[17] *Source: IRENA International Renewable Energy Agency. Renewable Energy and Jobs Annual Review 2016*

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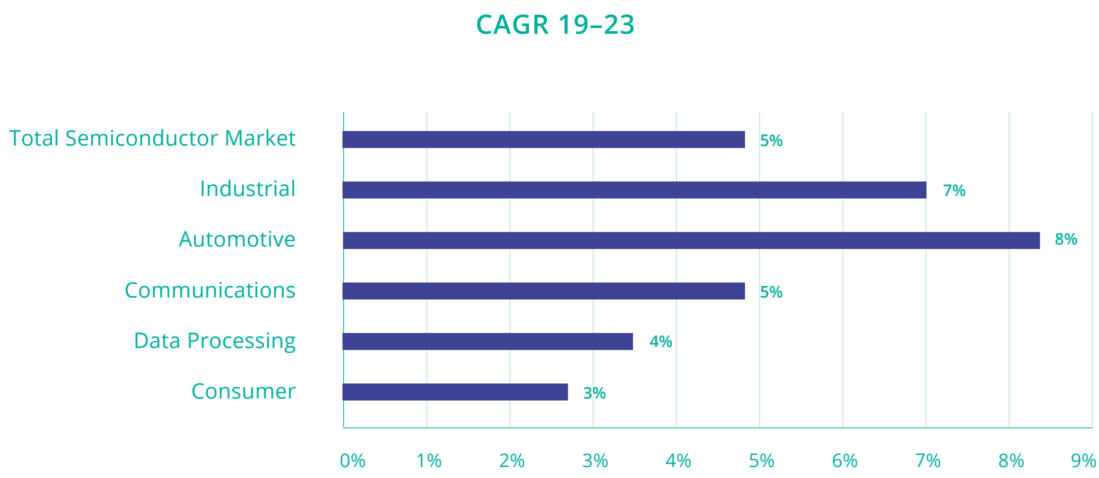
[18] *Source: IHS 2019*

[19] *Source WSTS forecast, August 2017*

Application domains, where Europe has a leadership position (as for automotive and industrial), have resulted in relatively high average growth for ECS components:



Overall annual growth rate for ECS demand.[18]

F.11

Overall, the annual growth rates in the demand for ECS components in Europe is expected to be higher than for other regions.

Spring 2017 - Q2 Update	Amounts in US€M				Year on Year Growth in %			
	2016	2017	2018	2019	2016	2017	2018	2019
Americas	65,537	79,555	83,464	83,116	-4.7	21.1	4.9	-0.4
Europe	32,707	37,760	39,639	39,998	-4.5	15.4	5.0	0.9
Japan	32,292	36,005	37,331	37,358	3.8	11.5	3.7	0.1
Asia Pacific	208,395	243,328	253,087	250,621	3.6	16.8	4.0	-1.0
Total World - €M	338,931	396,649	413,522	411,094	1.1	17.0	4.3	-0.6
Discrete Semiconductors	19,418	21,299	22,168	22,744	4.3	9.7	4.1	2.6
Optoelectronics	31,994	33,403	34,574	35,405	-3.8	4.4	3.5	2.4
Sensors	10,821	12,336	13,135	13,899	22.7	14.0	6.5	5.8
Integrated Circuits	276,698	329,11	343,645	339,045	0.8	19.1	4.3	-1.3
Analog	47,848	51,663	54,284	56,129	5.8	8.0	5.1	3.4
Micro	60,585	62,829	65,173	66,907	-1.2	3.7	3.7	2.7
Logic	91,498	99,558	102,579	105,088	0.8	8.8	3.1	2.4
Memory	76,767	115,561	121,597	110,921	-0.6	50.5	5.2	-8.8
Total Products - €M	338,931	396,649	413,522	411,094	1.1	17.0	4.3	-0.6

Comparison of European growth rates to the rest of the world [19]

F.12

0.3.2. Essential capabilities

The development of these key application areas relies heavily on the availability of, and further research into, ECS essential capabilities:

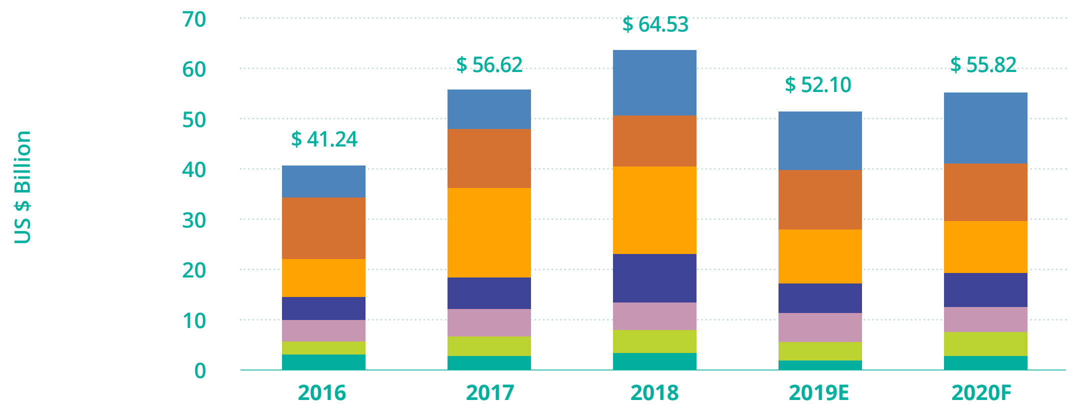
- systems and hardware/software components for architecture, design and integration;
- connectivity and interoperability;
- safety, security and reliability;
- computing and storage;
- process technology, equipment, materials and manufacturing for ECS.

Europe displays valuable assets in many of those basic technologies and integration knowhow.

Process technology, equipment, materials and manufacturing for ECS

The semiconductor market is expected to grow from $469 billion in 2018 (source: WSTS[20]) to $548 billion in 2023 (source: Decision), driving up the global semiconductor equipment (SCE) market. In 2018, the SCE market reached a high of $65 billion (source: SEMI Equipment Market Data Subscription, September 2019, see Figure 13). After a slump in 2019 due to memory correction and market volatility, it is expected that growth will resume in 2020, with China overcoming Taiwan as the largest equipment market.

SEPTEMBER TOTAL EQUIPMENT FORECAST



	2016	2017	2018	2019E	2020F
China	6.46	8.23	13.11	11.58	14.04
Taiwan	12.23	11.49	10.17	12.00	11.64
Korea	7.69	17.95	17.71	10.97	10.47
Japan	4.63	6.49	9.47	5.69	6.82
North America	4.49	5.59	5.83	6.02	5.03
Europe	2.18	3.67	4.22	3.43	4.63
SEA/ROW	3.55	3.2	4.04	2.41	3.18

F.13 *September total equipment forecast.* [21]

The lithography content, which was around 18% of the wafer processing equipment global market in 2017, moved up to 22% in 2018–H1 2019,[22] driven mainly by new technology nodes.
In the past, the market has been extremely volatile with year-on-year variations as large as +/–30%. More recent data shows that the industry and market have become more stable. Nevertheless, a high total R&D investment is required to keep up with the ever-changing industry, and in this sector R&D investment rates as high as 10–20% of total revenue are no exception.

As a result, in some areas European industry is dominant, such as in lithography where it has a market share in excess of 80%, and in other areas it has significant presence, especially on the high-end side (high-resolution imaging, atomic layer depositions, assembly and packaging, etc). Furthermore, over the last few decades the European ecosystem (industry, RTOs and academia) has invested heavily in 'More than Moore' technologies. It now has a leadership position in the global markets for MEMS technology-based sensors and actuators, power semiconductors and systems-in-package, while FD SOI, a technology developed in Europe, is enabling the development of ultra-low power processors.

The strength of the European semiconductor equipment ecosystem finds its roots in the above-mentioned consistency in R&D investments in the areas of lithography, imaging, deposition and assembly technologies. Moreover, this ecosystem taps into a strong knowledge base in research institutes, academia and industry, combined with a world-class interconnected supply chain.

This knowledge base includes fields such as light-, electron- and EUV-optics, plasma physics, surface physics and chemistry, heat and fluid transport, precision mechanics, electronics, applied mathematics, materials science, vacuum technology, contamination control, embedded system technology, thin-film technology and fast data processing.

Safety, security and reliability

European industry is playing a key role in handling security at the component and system level. As well as being an essential capability, this sector also represents a huge market. Figure 14 shows the size of this market in France, Europe and worldwide, split between products and services on the one hand, and public and private on the other. As noted earlier (section 0.2.1, advent of artificial intelligence and data analytics), this European strength in security-related technologies represents an invaluable asset in the world race towards leadership in AI.

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[20] *https://www.wsts.org/76/Recent-News-Release*

[21] *Source: SEMI 2019*

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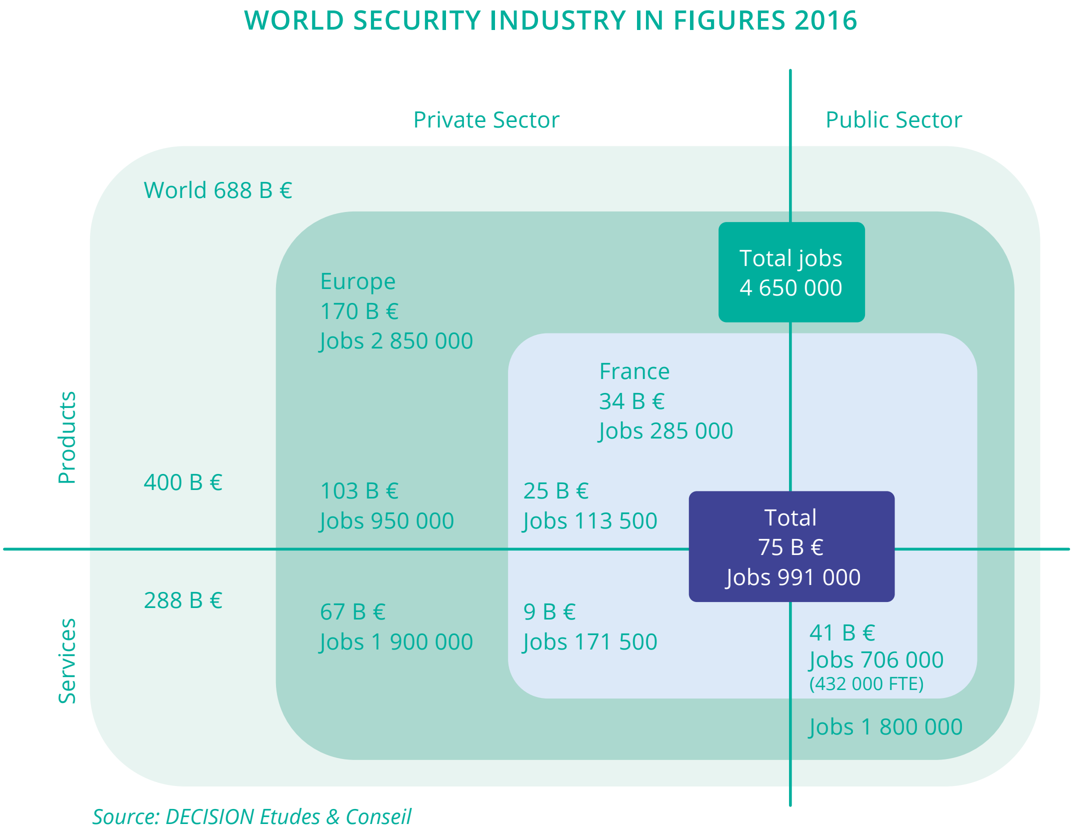
[22] *Source: SEMI Equipment Market Data Subscription, September 2019*



F.14 *Safety and security markets* [23]

Systems and components architecture, design and integration

Traditionally, European industry has had a leading position in systems engineering, allowing it to build ECS-based products that meet customer expectations in terms of innovative functionality and quality. Design technologies – processes and methods for the development, testing and ensuring the qualities of hardware, the embedded software and the complete system, as well as efficient tools supporting these – are a key enabler for this strong position. In facing the new requirements and game-changers detailed above, it is of the utmost importance for these industries to put significant resources into R&D&I activities to maintain and strengthen this leading position, and to enable them to satisfy the needs of the different domains while reducing development cycles and costs.

Europe also has very strong system houses that produce complex, innovative high-tech designs for products in the areas of aeronautics, automotive, industrial applications and manufacturing, healthcare, and communications. To maintain this world-leading position, a continuously push for improved electronic systems at increasing levels of automation is essential while simultaneously sustaining high quality.

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[23] *Security industries in this figure encompass all security products from physical security products (vehicles, access entrance systems, etc), electronics security (authentication, identification, detection, communication and surveillance systems, cameras, etc.) and cybersecurity products and services as well as private security services*

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[24] *EU industry here means the full Large Industry + SME + RTO + University eco-system*

Large electronic design automation (EDA) companies currently provide the tools and methodologies for specific design domains (digital macros, analogue and RF macros, SW, package, PCB) that are not very closely linked and mostly not focused on European needs in design technology. Higher design levels are not well covered, although some initiatives for supporting higher levels of abstraction do exist. A comprehensive, seamless open and extendable open design ecosystem across the whole value chain must therefore be created, especially for supporting heterogeneous applications.

0.4.
SWOT

The various factors listed in sections 0.2 and 0.3 can be summarised in the following Figure 15 – SWOT analysis for the European ECS industry.

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU ECS industr[24]	**Strengths:** **Key application markets:** Transportation, Energy, Health, Urban Services, Industry Automation; **Essential capabilities:** Security, Sensors, MEMS, low power devices, power semiconductors, Physical and functional integration capabilities from IC to Systems of Systems World-class semiconductor industry World-class Equipment and Materials Industry, incl. Manufacturing Tools for sub-10 nm node ICs RTOs and Universities Collaborative Skills	**Weaknesses:** No sub-10 nm node IC-factories Very few industry leaders for new IT technology
External factors To the EU ECS industry	**Opportunities:** Need for alternative performance approaches besides miniaturization Advances in AI, Machine Learning and Human-Computer Interfaces creating new solutions and market opportunities Ubiquitous connectivity / 5G deployment solutions New security paradigm (blockchain) Internet of Things New energy paradigm Solutions for zero fatalities in road transport Disruption in design, manufacturing and business models Societal changes requiring ECS-based solutions	**Threats:** Advances in AI and HCI are largely led by companies outside Europe Economic protectionism Increased competition Societal changes: ageing population, increased urbanization Environmental changes Fragmented legislations

SWOT analysis **F.15**

0.5. VISION, AMBITION

Our vision and ambition is for Europe to take a leadership role in digital transformation by developing the capability to provide digital innovation and technologies Europe requires to generate growth, create value, jobs and prosperity, and safeguard Europe's competitiveness and sovereignty.

To achieve this vision and ambition, the European ECS industry, supported by public authorities at European, national and regional levels, must:

- address the major technological challenges identified in this SRA;
- pool research efforts on a number of shared priorities to avoid fragmentation and reach critical mass, setting greater synergies across the complete ECS value chain and its eco-system for a high return on investment;
- foster innovative business models, coupled with adequate funding schemes for a faster go-to-market.
- Proper execution of the above will support the EU-based ECS industry, allowing its players to remain at the forefront in this domain.

0.6. STRATEGY

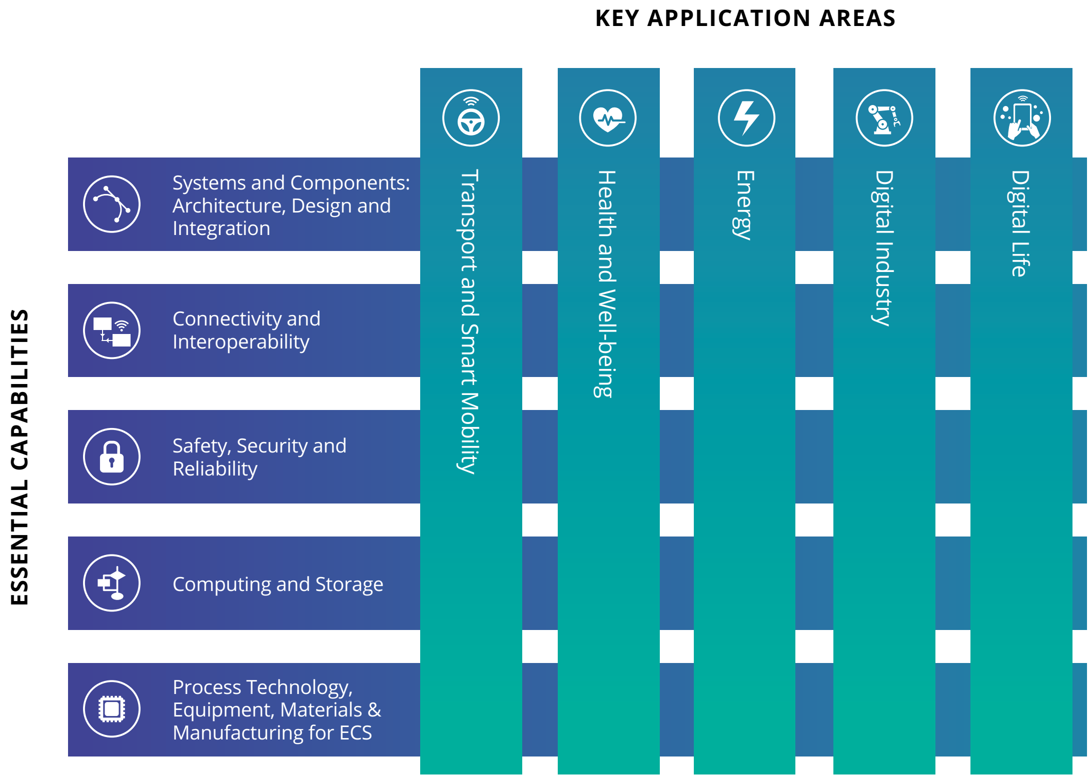
0.6.1. SRA focus areas

To fulfil our vision and ambition, the R&D&I strategy will be based on top-down guidance on the strategic areas for project generation by identifying the game-changers and market drivers to resolve the major challenges (societal or technological). This will have the ultimate purpose of generating the best set of projects that respond to short-term, medium-term and longer-term targets, thus covering the TRL scales from basic to applied and innovative research.

At the risk of stating the obvious, one guideline to select R&D&I priorities for the ECS industry in Europe should be to use our strengths to capture opportunities. Most societal challenges facing us are in domains where Europe hosts world-level champions: health, transportation, energy and the digitalisation of Industry, and where solutions will be built on the essential capabilities mastered by Europe. Focusing on these domains will not only help solve these challenges for Europe, but also allow our industry to develop markets beyond our frontiers, since the issues addressed here are shared by the rest of the world. Significant investment in innovation is needed to maintain our competitive advantage against fierce worldwide competitors – not only from the US, but also from Asia, mainly China.

In addition, the SRA addresses the essential capabilities required to meet the application needs. Europe is well-positioned for many of these, although further R&D&I is required to maintain and develop that leading edge (e.g., all the building blocks for successful deployment of the Internet of Things). However, we cannot limit ourselves to just working on our strengths: there is a real danger in the current situation where most of the leading companies providing computer and network infrastructure and services, and the sub-10 nm silicon technologies using them, are non-European. Nevertheless, this is not a lost battle: as new paradigms emerge (neuromorphic computing, quantum computing, transaction-based ledgers) that will require new technologies, Europe has the opportunity to position itself competitively, leveraging its cooperative capabilities and its great scientific base. However, time is of the essence.

Jointly considering key application areas and essential capabilities allows us to leverage our strengths for the benefit of other sectors. For example, industrial applications (such as Industry 4.0) and automotive (such as the autonomous car) are launch pads for new technologies trying to cope with challenges that are shared by embedded, mobile, server and HPC domains: energy and power dissipation, and complexity management. Overall, this SRA focuses on a set of five key applications areas and five essential capabilities, which can be seen in Figure 16. Together, these market sectors represent over 50% of European GDP.



SRA focus areas **F.16**

In implementing this Strategic Research Agenda, the ECS industry will leverage a strong and enabling position in multiple value chains, and hold a pivotal position in research, development and the deployment of innovative solutions to create a visible impact on society through technology.

0.6.2. R&D&I priorities selection and description

The top-down guidance of the above themes is backed by an open, bottom-up process to detail R&D&I priorities in separate chapters, created and maintained by partners from industry and science. Each chapter follows the same structure, opening with the relevance of the theme in terms of competitive value and societal benefits, and then outlining the major challenges with their connected vision, scope and ambition, and explaining the high-priority R&D&I areas, the competitive situation and the expected achievements. The chapters conclude with high-level timeframes for the relevant roadmaps over the period 2019–28, and the main synergies with other themes.

The roadmaps indicated in the various chapters list, for each high priority R&D&I topic, the expected progress over time. Each timeline is divided into three parts, corresponding to the project results of TRL2–4, 4–6 and 6–8, respectively. The concrete significance of this TRL indication is to envision, in a given year, the start of projects that will produce results at this TRL level or higher (i.e., a project aiming at a higher TRL level than denoted in the table might start that year). However, this does not prevent lower TRL projects also starting that year, to work on the next generation solutions for the research topic related to that timeline.

0.6.3. Deriving work programmes

Defining R&D&I priorities, as this SRA has done, is just the starting point. An essential part of the strategy is to prepare work programmes that generate projects to fulfil the major challenges of each of the chapters. This follows two threads.

Strategy thread 1: Address next-generation digital technologies and potential breakthroughs to build a strong EU-based ECS, positioning Europe at the forefront of the digital economy

- Achieve excellence in priority areas to remain or join the frontrunners of the new era with strong competitive power, while taking into account the European societal requirements of quality of life, safety and security, ethics and sustainability.
- Build on existing European technological strengths to improve their competitiveness and sovereignty, and reinforce them in areas such as low-power consumption, high-performance computing and high-power sensors, smart systems integration, safety and security.
- Develop those technologies to a high TRL (pilot lines) to ensure the innovation will be brought to market.
- Think big and act fast: in new areas such as AI and HPC, speed is of the essence to achieve economies of scale and to act efficiently to bring innovative solutions to the global market (the way US GAFA and Asian competitors act).

Strategy thread 2: Pool research and development efforts on a number of priorities, and to remove barriers between application sectors

- Build better and more efficient European technological solutions for greater combined strength in the context of global competition, and foster proposals where there is real value creation.
- Encourage projects that address the whole value chain and leverage vertical integration, if this is expected to enhance user benefits and experience.
- Adoption of a platform approach as described in the section ‘innovation accelerator’ for a faster ‘go-to-market’.

While the SRA is structured by key application areas and essential capabilities, which in turn are subdivided into five separate chapters, this by no means implies that the resulting work programmes and projects should be developed in silos. As mentioned, applications and technologies are becoming increasingly intertwined. As they work through the document, the reader will realise that many capabilities are required across most, if not all, applications. For example, this is the case for artificial intelligence and security solutions. By identifying generic technologies, this SRA will help the submission of projects that address specific technological areas along with their use in a variety of applications.

Conversely, many applications will come to life only when combining many essential capabilities, as witnessed in the smart sensors of the Internet of Things, requiring the integration of ultra-low power computing and storage, networks, sensing, actuating and power management functionalities. As a complement to these cross-domain projects, low TRL, in-depth research projects in specific capabilities are also required and encouraged.

0.6.4. **Strategy implementation via R&D support programmes**

0.6.4.1. Research funding programmes

To facilitate the implementation of the SRA, research funding programmes should:

- encourage the development of holistic electronic components and systems innovation ecosystems in Europe spanning complementary R&D&I actors, with the goal of converting promising ideas for (disruptive) innovations from universities, RTOs and industry research teams into global sales by SMEs and large enterprises alike;
- allow participants on publicly funded research projects to leverage complementary co-funding opportunities from the EC, national and regional levels through harmonisation of participation rules, funding rates and procedures;
- encourage the combination of R&D efforts across Europe for future proven application domains and technologies, while pooling resources in key areas, and involving the relevant players with the ability to ensure successful valorisation and uptake of the results;
- put in place the appropriate metrics and regular follow-up processes to assess the impact of projects and measure return on investment for the EU member states and industry.

0.6.4.2. Lighthouse initiatives

'Lighthouse Initiatives' is a concept set-up by the ECSEL JU to signpost a specific subject of common European interest that calls for a set of coordinated activities – including, but not limited to, facilitating the cooperation of ECSEL projects with Horizon2020 (e.g., FET Flagships), Eureka projects, and national or regional projects.

Lighthouse Initiatives encourage the joining of forces across projects to increase their impact at the EU level, with a strong emphasis on standardisation and regulatory aspects. Conducting non-technical activities is important to pull together the eco-systems actors in a field, and to investigate issues of social acceptance, regulatory environment and business models to increase the impact of individual project achievements.

Lighthouse Initiatives also materialise in practice through CSA (coordination and support actions) projects. The overall work of the CSA or Lighthouse is monitored and supported by a Lighthouse Initiative Advisory SErvice (LIASE), consisting of senior professionals in the field from industry and academia. Among other activities, the CSAs provide valuable input to the ECS-SRA.

There are currently three Lighthouse initiatives: on mobility, digital industry and health. More are needed, especially in areas where standardisation and regulatory aspects play a crucial role, such as energy.

0.7. INNOVATION ACCELERATORS/ MAKE IT HAPPEN

However successful they may be, research projects do not resolve societal challenges and create economic value for Europe. This will happen only if a number of 'innovation accelerators' are in place that will bring research results to market. Major ECS industry innovation accelerators fostering the implementation of the present SRA are described below.

0.7.1. Education and training

The innovation capabilities of Europe depend hugely on the capabilities of the next generation of engineers. While the EU is boosting the digital single market, taking care to make it secure and trustworthy, companies are currently struggling with what experts call the 'largest human capital shortage in the world'. Effective education and training is crucial to maintaining competitive leadership, and is a precondition for any sustainable innovation ecosystem.

The rapid evolution of the new global digital economy is generating needs and challenges at such a high growth rate that even the human capital market is not able to keep pace. The availability of graduates that meet industry and new job requirements is a major concern, with a shortage of up to 900,000 ICT professionals currently forecasted. Therefore, education and skill-building and 'making education a specific deliverable for all EU projects' are key pillars in the EU strategy towards the digital transformation of society and as part of the digital single market strategy (see, for example, the European Commission initiative on Digital Skills and Jobs Coalition at https://ec.europa.eu/digital-single-market/en/digital-skills-jobs-coalition).

0.7.2. Standardisation and regulation

Standards enable the development of open markets for electronic components and systems. Open markets offer opportunities for new businesses, including SMEs, to bring new products and services to market. In this context, standardisation contributes to increased interoperability, security, privacy and safety of electronic systems and applications, making it essential to build trust with customers and users, and create confidence between stakeholders in the market.

Regulation is needed to allow the deployment of many applications in Europe.

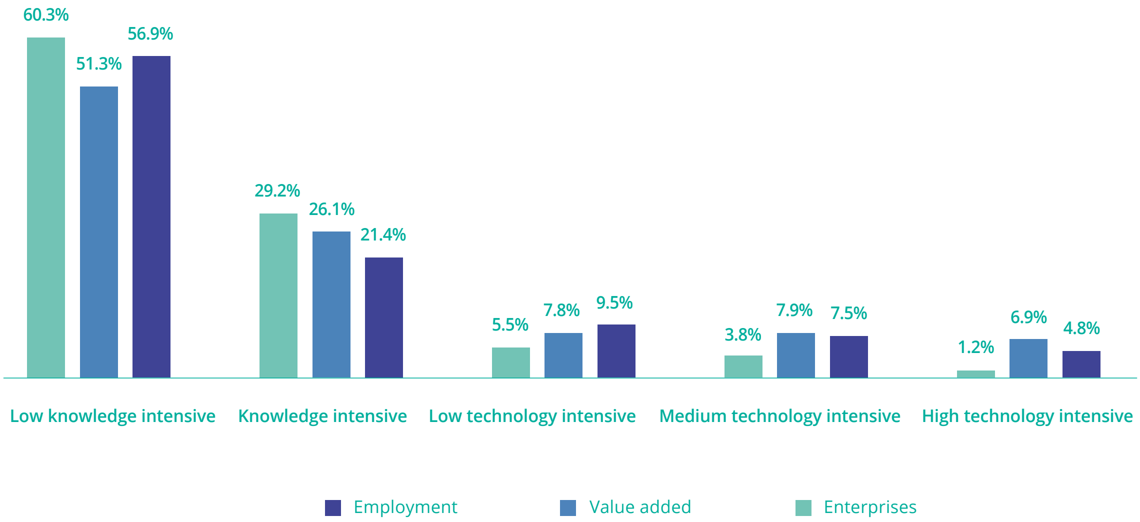
- For instance, a reduction in the number of accidents, fatalities and injuries could contribute strongly to the fulfilment of future EU guidelines, targets and regulations while meeting increasing customer demand for safe and convenient road transport. ADAS technology already provides the necessary sensing capabilities to operate vehicles in a complex and interacting environment (such as with other vehicles, objects and infrastructures).
- For health and wellbeing, non-technological issues need to be addressed, such as ethics, regulation, privacy, accessibility and equality, which are key to increasing the acceptance and adoption of innovation in healthcare.
- For repair and recycling, regulations for the collection, recycling and disposal of technological products at the end of their useful life are well-established in the EU, particularly for electronic goods and cars (although disposal has overtaken repair and routine maintenance in this field).
- Security concerns are one of the main concerns and constraints for the widespread adoption of electronic components and systems. If there is the ability to manipulate physical assets remotely, then there is a danger of privacy violations and safety problems. In turn, such issues can then promulgate worries over trust, security and privacy. It is hoped that regulation will help alleviate some of these concerns, and thus be an enabler of electronic components and systems technologies.

0.7.3. Platform concept and the hyper-scalability business models

The platform concept, common in the Internet economy, is a characteristic of digital transformation. It provides facilities to experiment and test innovative ideas, integrate research results into innovative products and validate service concepts. It also helps organisations to scale up their development activities by sharing efforts and minimising investments to rapidly deliver such products and services to the market. The GAFA and similar business models have demonstrated the unprecedented and tremendous growth potential of such platforms.

0.7.4. Pilot lines

In their report about 'Key Enabling Technologies', the EC stated that despite a leading position of European RTOs in inventing new technologies and applications, Europe is weak in bringing those innovations to market. To bridge this 'valley of death', it is necessary to support the development and installation of pilot lines, which require huge and risky investments – especially for semiconductor technologies and equipment. In former ENIAC and ECSEL projects, pilot lines proved to be essential in transferring the benefit of the ECS projects to society.



F.17 *Distribution of EU-28 SMEs in the non-financial business sector across sectors of different knowledge and technology intensities (2017).*[25]

0.7.5. From start-ups and scale-ups to SMEs

SMEs and start-ups are an essential component of European industry landscape: For instance, for the period 2008 to 2017 gross value-added generated by EU-28 SMEs increased cumulatively by 14.3%, while SME employment increased by 2.5%. EU-28 SMEs made a significant contribution to the recovery and subsequent expansion of the EU-28 economy, accounting for 47% of the total increase in the value-added generated by the non-financial business sector between 2008 and 2017, and for 52% of the cumulative increase in employment in the sector.[26] However, the majority of SMEs in the EU-28 are still active in fields with low knowledge intensity.

In existing European funding programmes the participation of small and medium-sized enterprises remains below the intended threshold. Research Infrastructures. Today in ECSEL, the Joint Undertaking for Electronic Components and Systems for European Leadership, only a small part of funding goes to SMEs (ca. 13% on average). Much better results in terms of SME participation have been achieved in transnational projects supported in the EUREKA clusters. Some requirements for an effective and efficient participation of high-tech SMEs in European programmes have recently been published by EPoSS[27] that could support better participation in all European funding instruments in future European programmes.

One approach to enhance the participation of SMEs in ECS programmes, including start-ups and scale-ups, could involve LEs with an eco-system

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[25] *Reference: https://op.europa.eu/en/publication-detail/-/publication/a435b6ed-e888-11e8-b690-01aa75ed71a1*

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[26] *Reference: https://op.europa.eu/en/publication-detail/-/publication/a435b6ed-e888-11e8-b690-01aa75ed71a1.*

[27] *https://www.smart-systems-integration.org/system/files/document/EPoSS%20%20SMEs%20in%20European%20Programmes_0.pdf)*

in need of new entrants, and cover the complete business creation process: coaching (identifying and optimising value proposal); acceleration (validation of technology as to its business value); and investment (financial support to scale-up and productise). CSAs or other measures could be employed to facilitate ecosystem development and validate such an approach – for example, within Lighthouse Initiatives.

It is expected that increased participation of SMEs in funded cooperative research programmes will allow them to grow and increase their presence and competitiveness in international markets, while the SME subset of start-ups will also benefit from synergetic exposure of their technology and business models to other consortium partners.

There is a need to balance the mainly single science/technology thinking into multidisciplinary thinking. Infrastructures that are focused on cooperation and the sharing of knowledge and expensive equipment or large-scale field experiments should be sustained. Serving the same aim, European governments should sustain the creation of new, and the improvement of existing, research infrastructures such as science parks, fabrication and prototyping facilities, incubators and venture partnering to support the creation of new high-tech SMEs. Setting such infrastructures will reinforce the global competitiveness of European research infrastructures (including e-infrastructure).

0.7.6. Research Infrastructures

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0.7.7. Relationship with other relevant initiatives and PPPs

Fostering the synergies and relationships with the various European, multinational (such as EUREKA), national and regional initiatives, such as European technology platforms (ETPs), public–private partnerships (PPPs), joint undertakings (JUs) or industry associations such as AIoTI, BDVA, EuRobotics, ERTRAC and EFFRA is needed. Each of these initiatives and PPPs shows a high commitment in its respective area. Howeever, they also have the same need to rely on each other's specificities, and share a number of challenges and opportunities. As a key enabler in optimising investments in R&D&I programmes and avoiding duplication of effort, ECS technologies have a major role to play.

0.7.8. International cooperation

Research and innovation have become global, ignoring frontiers and being performed where creative individuals and ecosystems exist. The race is now about being 'best in the world' or the 'world of the best'. International collaboration should fit into a global win–win strategy geared to achieving participants' long-range aims. Defining such a vision and strategy is crucial for guiding international collaboration.

0.8. LONG-TERM VISION

For the 10 focus areas depicted in Section 0.6.1, the ECS-SRA provides timelines spanning the coming 10 years, from 2019 to 2028. It is also essential, however, to look further out to project which embryonic, emerging or disruptive technologies at the lowest TRL today will determine the future of the ECS domain in Europe. Future applications will be enabled by enhanced performance and novel functionalities generated by new technology options, as projected in technology-application roadmaps, but it is also possible that technology evolution leads to disruptive applications that were not projected in the roadmaps. To ensure that these opportunities are recognised and used effectively, cooperation by the academic, institutional and industrial stakeholders that constitute the value chain is a prerequisite.

To that effect, the ECS-SRA includes a dedicated long-term vision chapter that surveys emerging technologies with a significant potential impact on the European ECS landscape 10 years from now, and beyond. Rather than attempting to make specific predictions that could always be disputed, this chapter highlights challenges to be solved, based on probable long-term trends (fossil fuel availability, requirements for personalised medicine, zero-emission environmental norms, to name but a few), and identifies which technology or applications are the most promising, or must be developed, to meet expected societal needs. In particular, it focuses on expected future requirements that cannot be achieved through the predicted evolution of current technology.

By highlighting the key research and innovation topics required to maintain the competitiveness of the European ECS industry in the long run, this chapter on long-term vision is an essential element to achieving the ECS-SRA mission of generating growth, creating value, jobs and prosperity, and safeguarding Europe’s competitiveness and sovereignty.


vehicles
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vehicles

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Transport & Smart Mobility

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[28] *More about the competitive situation of European automotive industry can be found in the appendix in section "Competitive situation of automotive industry in Europe".*

1.1. EXECUTIVE SUMMARY

The Major Challenges in Transport & Smart Mobility are:

- Clean, affordable and sustainable propulsion.
- Secure connected, cooperative and automated mobility and transportation.
- Interaction between humans and vehicles.
- Infrastructure and services for smart personal mobility and logistics.

These four Major Challenges aim to keep Europe in the lead for innovations throughout the automotive value chain and to broaden the Research & Development & Innovation (RDI) horizon so that future research and innovation focuses more on holistic, cross-domain and sustainable mobility solutions for all the main transportation domains (Road, Rail, Aviation (incl. drones) and Maritime).

Currently, the first two challenges are high on the list of priorities. In addition, the strong research focus on battery electrical vehicles and H_2-based electrical vehicles is growing in importance due to their very good environmental performance and the potential ”cradle to grave” impact (see [1]). The development of electronic components, sensors and embedded SW, as well as the validation tools for assisted and automated vehicles, are the second research focus as defined in Major Challenge 2.

Key aspects to cover throughout the four challenges are increasing performance, security, privacy protection features, safety, sustainability, affordability, human interaction and societal acceptance. The defined Transport & Smart Mobility challenges not only address the most urgent Research and Innovation priorities in the sector, but also focus on developments that could be substantially driven by innovations in the European micro-electronics, nano-electronics and embedded systems industry in combination with the European IoT community.

1.2. RELEVANCE

1.2.1. Competitive Value

Mobility is not only a visible expression of Europe’s economic and societal prosperity; it is also an important source of that prosperity. Employing about 3 million people in manufacturing and another 11 million in services, the transportation system is of high socio-economic relevance for Europe. Currently, the transportation sector is undergoing a fundamental and complex transformation across all modes. The European Commission’s Strategic Transport Research and Innovation Agenda (STRIA) describing this transformation distinguishes seven transversal dimensions ranging from low emission, alternative propulsion system to smart mobility systems [28].
Mobility is on the verge of tremendous change, and will increasingly rely on electrification to achieve the environmental goals of the European Union in limiting global warming. The most important factors for this imminent transition arethe need to accelerate efforts to tackle climate change coupled with the widespread

public concern regarding air quality, especially in cities. Therefore, the European Union and other countries have either introduced or are planning to introduce strong regulations in terms of CO_2 and pollutant emissions, as well as having ambitions to reduce the dependence on fossil fuels and accelerate the move to CO_2-free mobility. Further and significant progress in technology for electric motors, power electronics, batteries and the intelligent embedded software that controls those components will be necessary to allow the transition from fossil-based mobility to CO_2-free mobility. As fuel cell electrical vehicles gain greater prominence, especially for long range mobility [1] as well as for trucks and railways, the development of the necessary ECS components and associated software is crucial. The enhanced use of electrified 2/3-wheelers (e.g. pedelecs and scooters) for inner city usage will also require research and development into the requisite controller components. All of above has to be combined with research & development of ECS-based instrumentations, test systems and verification, validation and certification methodology for the components of electrified vehicles.

Looking back on the challenges, transport demand requires the coexistence on networks of passengers and goods in outer- and inner-urban environments with managed throughput to ensure reliable, highly secure, seamless multimodal solutions for both classes. Cities and regions need to have established strategies for managing the shared use of infrastructure by passenger and freight traffic and in parallel for personal autonomous vehicles and public transport. Multimodality in transport will require strong individual modes with an appropriate infrastructure and a network of well-situated nodal points (ports, inland ports, dry ports, logistics platforms, rail freight terminals, urban nodes), with good access to and from their neighbourhood. The individual transport modes will need to be effectively interconnected physically and digitally at the appropriate nodes. Long-haul transport and urban delivery will be better aligned. Interfaces between systems in the different modes will ensure that decisions in one mode consider the effects on other modes and shared information will be used to evaluate the best traffic management action for each single mode.

There will be unmanned vehicles on roads, on rail, on water, through the air and inside freight terminals. Connected cars are the first and important step towards highly automated and autonomous self-driving cars. Even though basic safety functions have to be provided by vehicle-based sensor systems even if connectivity fails, the comfort and efficiency of automated operation will increase if additional information from other vehicles, dynamic maps and traffic management systems is available. Connectivity will be based on multiple protocols and standards, as e.g. camera's, vision systems, radar, lidar, C2X 820.11p (G5), NFC, 5G, etc. In cooperation with the public authority's necessary investments to provide 5G (and probably future generation) telecoms in all but the most remote or rural areas is crucial. Galileo is an essential building block providing standard and enhanced services for positioning, telecoms and remote sensing. The mix of terrestrial and satellite, short- and longer-range, will support continuous and ubiquitous connectivity which in turn will enable continuous vehicle-infrastructure and vehicle-vehicle linking. It will also be of crucial importance towards connecting the car and the vulnerable road user. Security is a crucial issue that needs to be resolved prior to deploying large scale connectivity solutions.

Autonomous trains should take into account current project developments supported by Shift2Rail JU focusing on an adaptable communication system for train control applications in all market segments, using packet switching/IP (GPRS, EDGE, LTE, 5G, Satellite) technologies, enabling easy migration from legacy systems, providing enhanced throughput, safety and security functionalities to support the current and future needs of signaling systems, and resilient to interference and to radio technology evolution. It is important to develop and validate automatic train operation (ATO) for ETCS, where applicable, up to Grade of Automation (GoA) 4 (unattended train operation) for urban and suburban applications, and at least GoA2 (semi-automated train operation) for other market segments, including freight lines. Moreover, developing and validate a high capacity, low cost, highly reliable signaling system based on moving block principles, thereby allowing more trains on a given main line, especially for high density passenger services. The system should be backward compatible with existing ERTMS system specifications and enable evolutions towards CBTC functionalities for Urban applications. Advanced traffic management systems should be automated, interoperable and inter-connected. This should be combined with Driver Advisory Systems (DAS) and automation functionality to allow for predictive and dynamic traffic management in regular and degraded situation, integrating and using real-time status and performance data from the network and from the train, using on-board train integrity solutions and network attached object control functions, supported by wireless network communication.

Autonomous driving, mobility and logistics are high profile applications where the use of AI technologies is growing very rapidly, affecting directly both society and industry. The European transport industry is world leading but it is expected to be revolutionised by the introduction of AI (combined with electric vehicles). AI applications in transport are very challenging, as they typically involve highly complex environments, large number of possible situations, real-time and highly critical as well as reliable decision making, large-scale deployment to edge, etc. Innovative use cases such as reliability in bad weather conditions and other critical situations. A key novel contribution will be the use and validation of digital models (Digital Reality) of sensors and the environment learned from the real world that drive simulations for generating synthetic input data for training and validation of autonomous vehicles. This will improve the reliable handling of rare but critical traffic events (such as a child in the front of a car or driving in bad weather conditions with deteriorating sensor performance).

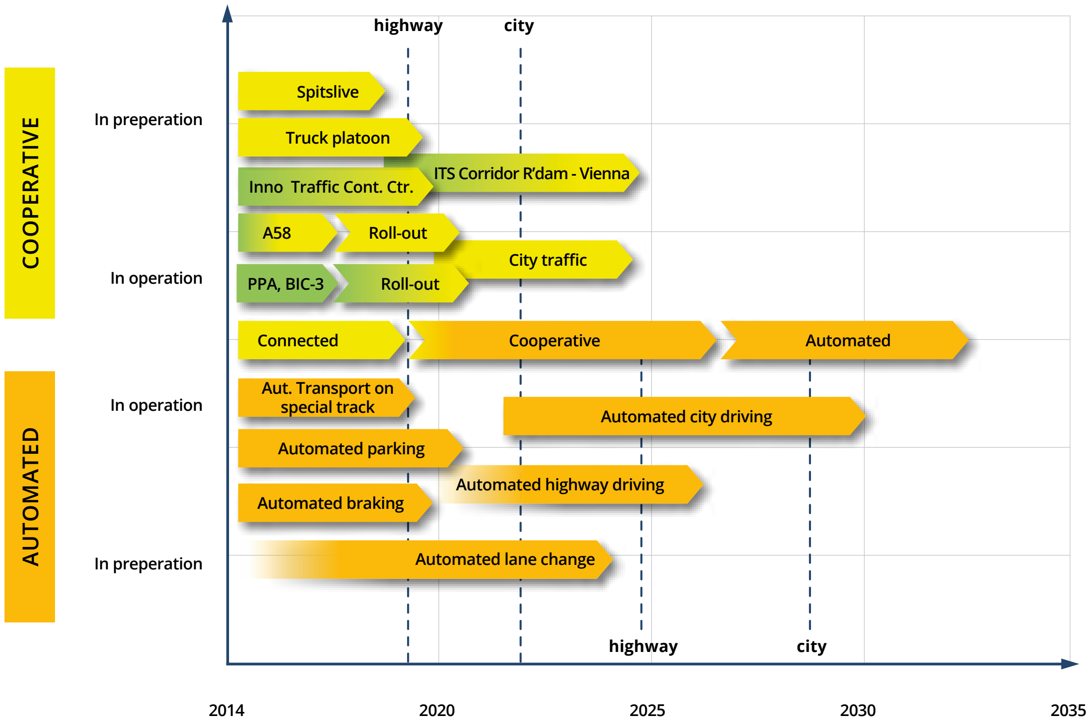
There will be continued pressure for physical infrastructure to be complemented by digital services to support traveller information, the operation of connected and highly automated vehicles, and adaptive area-wide traffic management. Infrastructure will be required to cope with traffic jams, man-made incidents and deliberate attacks as well as exceptional conditions such as drought, flooding and extreme temperatures. ERTICO Traffic Management 2.0 analysis of transport systems makes it clear they will have to be robust, sustainable and resilient to support daily life under all conditions, composed of infrastructure that reduces functionality gracefully and safely when under extreme pressure. There will be seamless integration of services across all modes, with reconfigurable networks so that local incidents can be isolated and traffic re-routed. Many technologies will be routinely deployed to contribute to proactive maintenance tools, before and on-trip traveller information, and the optimisation of operations, in order to ensure continuous everyday mobility.

The expected timeline is the following:

In the area of automated vehicles, the main challenge is the transition from niche market products to mainstream products. Three things must happen to enable a large market penetration of automated vehicles:

- there must be a large reduction in cost of the components, the embedded SW, the system integration as well as the validation effort.
- the problem of homologation and validation of automated vehicles has to be solved.
- A compatible road and traffic infrastructure has to be established.

Therefore, the development of efficient methods and tools for virtual and real-world verification & validation, as well as certification of partial or fully automated vehicles that takes into account (physical and perceived) safety, security and reliability, is an essential challenge and therefore an ECSEL research goal for mobility.
Vehicle automation can play also an important role in the success of electrified vehicles. The management



F.18 *Source: Gear 2030 Discussion Paper – Roadmap on Highly Automated Vehicles (Group E. C., 2016)* [29]

of charging stations and driving to and from the charging stations can increase the societal acceptance as it is than easier to utilise especially expensive super-chargers without tedious waiting time from drivers.

The expert group in the European commission stated in a report that *"that digitisation is currently reshaping the sector* [30]. Additional information about roadmaps on introduction of connected and automated vehicles can be found in [31].

Maritime transport within the EU faces challenges such as significant increases in transport volumes, growing environmental requirements and a shortage of seafarers in the future. The concept of the autonomous ship brings along the potential to overcome these challenges. It allows for more efficient and competitive ship operation and increases in the environmental performance of vessels. Furthermore, the shore-based approach offers "seafaring" the possibility to become more socially sustainable by reducing the time seafarers spend away from their families. The accident statistics of the European Maritime Safety Agency point to human error as the triggering factor in 62 per cent of incidents with EU registered ships from 2011 to 2016. Statistics on fatal accidents have ascertained that work on deck, for example mooring operations, is 5 to 16 times more dangerous than jobs ashore. Autonomous maritime solutions will minimise the number of persons

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[29] *E. C. G. 2. H. L. Group, "GEAR 2030 roadmap on highly automated vehicles," European Commission, Antony Lagrange – DG GROW, Unit C4, Brussels, 2016*

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[30] *E. Commission, "STRIA Roadmap 3 – Smart mobility and Transport Services and Systems," Horizon 2020 Commission expert group to assist the Strategic Research and Innovation Agenda (STRIA) initiative (E03420) , Brussels, 2017*

[31] *ERTRAC, "New Automated Driving Roadmap," ERTRAC, Brussels, 2017*

in dangerous work areas and increasing safety at sea considerably by means of highly automatised/autonomous ship.

The MESA FP7 project on behalf of the European Technology Platform Waterborne[32] stated that the analysis of global trends through to 2030 clearly indicates an increasing demand for shipping of all types, from coastal food and water carriers, through vessels for supplying the growing mega cities, to large and sophisticated cruise ships to provide leisure activities for the new middle classes. This creates significant opportunities for the global maritime industry, its extensive supply chain and the infrastructure which supports it.

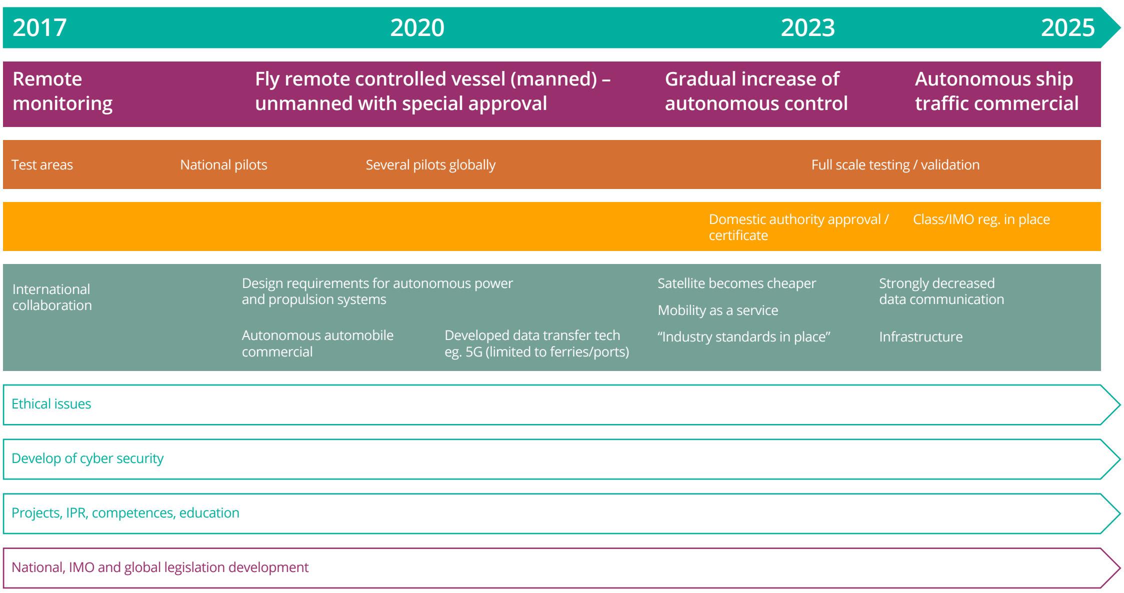
The EU's maritime industry is characterised by high value-added endeavour, rapid innovation, high safety standards, and a leading position on green technologies. A strategy to build on these strengths will ensure that the EU retains its competitive position in the global maritime industry and reaps the rewards in terms of jobs and wealth creation.

A roadmap for autonomous ships has been introduced by One Sea – Autonomous Maritime Ecosystem, and is presented in the following figure:

[32] *See https://www.waterborne.eu/media/20004/global-trends-driving-maritime-innovation-brochure-august-2016.pdf*

[33] *See https://www.wartsila.com/media/news/22-05-2017-one-sea-autonomous-maritime-ecosystem-introduced-roadmaps-to-autonomous-shipping*

TIMELINE FOR AUTONOMOUS SHIPS



Source: ONESEA Autonomous Maritime Ecosystem – Roadmap on Autonomous Shipping [33]

F.19

The roadmaps include a timeline towards 2025 and major themes to be investigated and levels of maritime autonomy – all minimising accidents, decreasing the environmental footprint of marine traffic, and advancing possibilities for efficiency improvement and new commercial venture.

In the past years, ICT applications have substantially contributed to the logistics sector, e.g. tracking and tracing goods, controlling and/or optimising supply chain network, and establishing (inter-)connectivity for logistic actors. Projects such as AEOLIX and SELIS have already developed a pan European Solution for Supply chain visibility, supported by easy access to, and exchange and use of, relevant and abundant logistics-related information, needed to increase efficiency and productivity, and reduce environmental impact. An essential element of the approach is to ensure that, for logistics actors, connecting to and using the AI ecosystem is undemanding and has a low level of complexity. We envision the ecosystem enabling the integration of supply-chain-related transport business processes through logistics software solutions for cloud-based connectivity and interaction, in order to support more efficient collaboration in the logistics supply chain than exists today. Supply Chain Automation is well established, but the increased use of Artificial Intelligence in logistics is rapidly reshaping how companies think and plan. Supply chains, although automated to a degree, still face challenges caused by the amount of slow, manual tasks required and the daily management of a complex web of interdependent parts. AI is seen by many as the key to further automation capability and especially the integration of 5G sensors for goods management. Data-driven and autonomous supply chains provide an opportunity for advanced levels of optimisation in manufacturing, logistics, warehousing and last mile delivery. This will need to be linked to Robotics and other areas of manufacturing systems. ALICE adopted the objective towards **"Zero Emissions Logistics"** for its long-term strategy (2050) and is working towards the goal of Physical Internet Paradigm. The Physical Internet (PI) was defined as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols that are easily transported through all transport means (e.g. planes, trucks, barges, drones and private cars). Modularly sized from small parcels to large maritime containers, the PI containers move through distributed, multimodal transportation networks in which transit sites aggregate containers from diverse origins to optimise the loading on the next segments.

1.2.2. Societal benefits

The EU-project "Action Plan for Future Mobility in Europe" (Mobility4EU) has identified and assessed societal challenges that influence future transport demand and supply. Societal trends, economic and political factors and stakeholder needs have been summarised in a context map [34].

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[34] *Mobility4EU, "ACTION PLAN FOR THE FUTURE OF MOBILITY IN EUROPE," Consortium Mobility4EU, 2017. [Online]. Available: http://www.mobility4eu.eu/wp-content/uploads/2016/10/context-map-deliverable_colours_vectors.pdf. [Accessed 14 08 2017]*

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[35] *Deloitte, "The future of mobility: What's next," 2016. [Online]. Available: http://publications.deloitte.nl/mobility#!/the-future-of-mobility-duplicate*

[36] *See https://www.waterborne.eu/media/20004/global-trends-driving-maritime-innovation-brochure-august-2016.pdf*

Mobility is a subject that concerns everyone. It is a subject that progresses of course rapidly in urban areas, but it also concerns rural areas. Developing the right solutions for mobility across Europe can have a great impact on the overall image of Europe. Today, many people in the rural areas feel disconnected. They feel disconnected from mobility, from progress, from Europe. This feeling is at the origin of fatigue for the European case. The right developments can inverse this trend and bring all populations back on track.

The average age of the European population is growing constantly. In order to provide personal mobility to the elderlies, automation in transportation and smart mobility will play an important part to increase the quality of life. Fewer auto-related accidents and fatalities could reduce costs for emergency medical services and related legal fees. Furthermore, more time available through autonomous drive and shared smart mobility will increase consumption of multimedia and information and generally enhance the time spent in-transit [35].

CO_2 reduction in transportation as agreed in the Paris treaty requires also significant advances in the automotive, maritime, aerospace electronics and embedded cyber-physical software technologies. Consumers and governments have more and more concerns about combustion engines; this forms an impetus to accelerate the exploration of new ways of propulsion, as e.g. hydrogen, electrical and other means.

European Technology Platform Waterborne [36] concluded that civil society, consumers and workers will become less willing to accept negative environmental and social impacts of economic activities in the maritime sector such as, e.g. accidents, water pollution, and unsafe working conditions. The expected increasing scarcity of qualified personnel will also motivate the sector to improve working conditions. Societal expectations will, therefore, lead to the maritime sector becoming more socially and environmentally responsible by complying with stricter regulations and possibly by adopting voluntary standards. The impact of societal expectations related to health, safety, environmental and security on the maritime sector is moderate and will not fundamentally alter the sector’s future prospects.

1.3. MAJOR CHALLENGES

1.3.1. SWOT analysis

The table below presents a SWOT analysis on the current European position in Transport and Smart Mobility. These points are addressed in the individual Major Challenges and expected results.

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU industry	**Strengths:** Presence of strong stakeholders in the automotive value chain in the EU Market leaders in rail & air in EU Many pilot sites for autonomous driving Great design capabilities and experience in semiconductor & embedded systems in EU	**Weaknesses:** High price & slow expansion of electric cars in some countries in EU Limited cross-border cooperation Security & privacy threats could slow down the societal acceptance of autonomous driving
External factors To the EU industry	**Opportunities:** Advent of IoT, 5G and AI/Deep Learning will open new opportunities for future vehicles and other modes of transportation New mobility services and business models Electrification of vehicles Introduction of fuel-cell electric vehicles	**Threats:** Competition from other continents (US: Tesla/Apple/Google & China local industry) Legislative requirements different in different continents

F.20 *SWOT table for Transport and Smart Mobility*

1.3.2. Major Challenge 1: Developing clean, affordable and sustainable propulsion

1.3.2.1. Vision

Road transportation alone accounts for 21% of Europe's fossil fuel consumption and 60% of its oil consumption. The increasing effect of the CO_2 emission as well as health-effecting gases as NO_x emitted by conventional vehicles motivates the global community to introduce new environmentally friendly mobility. The Paris Agreement from 2016[37] is an important international step towards a CO_2 neutral world. Several countries announced to ban the new vehicles based on ICE engines. An example is UK planning to ban them in 2040[38]. Electro-mobility will be based on either plug-in batteries charged or H_2-based fuel cells as energy system. It will come strongly within the next seven years to replace progressively traditional combustion engine driven cars. In parallel, conventional vehicles need more sophisticated sensors and software systems in order to reduce also their emissions and energy consumptions in the interim period. Predictive maintenance and smart service concept shall secure constant stable low emission and energy consumption level over the life time as well as the **availability of the vehicles** at reasonable costs [39, 40].

Considering the maritime sector, the Expert Group on future transport fuels[41] stated that the use of alternative fuels in the context of multi-fuel engines opens up a completely new field. While LNG has been widely adopted in Europe as well as internationally, the next big step will be the adoption of even more alternative fuel concepts to be run in a single engine. This is associated with developments addressing technology as well as logistics with a special focus on lifecycle costs and impact assessment.

Emission reductions, though not strictly in the context of Energy Efficiency or savings, will play an important role in the future. Post-treatment technologies like second-generation scrubbers will receive more attention; modelling and more technical developments will be required. Here again, life-cycle considerations will play an important role.

Furthermore, a complete management of the entire energy household on board ships is one of the main development areas promising substantial gains for the future. While several EU research and other development lines have addressed the issue already in the past five years, a holistic solution is still missing. With "Big Data" being one of the buzz words in present shipping terminology, technological advances (IT) and advanced regulations (e.g. MRV guidelines) allow and require capturing a much larger amount of data relevant for the assessment and management of Energy consumption of a vessel.

1.3.2.2. Scope and ambition

The scope of the development efforts covers all aspects including intelligent vehicles, optimal energy utilisation, increase in energy efficiency (especially larger range for battery electric vehicles), reduction of emissions from conventional combustion engines by embedded intelligence, reduction of costs, increased reliability, ...

This requires advanced embedded software taking advantage of new concepts such as deep learning neural networks or model predictive control algorithms, advanced sensors (e.g sensors for fuel cell systems to detect leakage, pressure, gas concentrations, humidity and flow, as well as the internal state in a fuel cell system) and powerful, fast and energy-optimised actuators (e.g. power electronics in the case of electrified vehicles) to semi-conductor component level, up to full electronic system design and the necessary embedded software. An additional challenge poses the validation of partially or fully electrified vehicles and their infrastructure (e.g. charging devices for battery

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[37] U. Nations, "Paris Agreement C.N.92.2016.TREATIES-XXVII.7.d of 17 March 2016," United Nations, New York, 2015

[38] Z. online, "Autoindustrie: Großbritannien will offenbar Diesel und Benziner verbieten," ZEIT Online, no. 26. Juli 2017, 5:09 Uhr Quelle: ZEIT ONLINE, Reuters, mib , 2017

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[39] E. I. Association, "EPOSS Strategic Resource Agenda," EPoSS, Berlin, 2017

[40] ERTRAC, "Integrated Urban Mobility Roadmap," ERTRAC, ARRAC, ALICE, Brussels, 2017

[41] State of the Art on Alternative Fuels Transport Systems in the European Union – Final Report, DG Move – Expert Group on future transport fuels, July 2015

electrical vehicles (conductive or inductive) for personal mobility or fully electric good transports over short and long distance) or hydrogen fuelling stations).

The smart usage of the additional information from the infrastructure or connected vehicles is another mean to reduce energy consumption and emission dangerous for the health of humans as well as increase safety and comfort for the passengers and vulnerable road users.

1.3.2.3. Competitive situation and game changers

In particular Asia is active in this area with Chinese, South Korean and Japanese car manufacturers and their related suppliers working on integrated solutions for electric and fuel cell-based powertrains. Especially in H_2-based electrical vehicles, the first three commercial vehicles were introduced from far east companies. Furthermore, China has the target to become number one manufacturer of electric vehicles in some years and pushes its industry to accelerate the research on related technologies.

The US companies are more and more teaming up with the very large local IT giants working on electric (and automated) vehicles. This can endanger the current leading position of the automotive industry in the future.

1.3.2.4. High priority R&D&I areas

In order to achieve the above-mentioned ambitions, the following R&D&I topics have priority as they are enabling the efficient development of electronic components and their embedded software, which are the heart of in the clean, energy efficient transportation and smart mobility system.

New energy efficient system architectural concepts (EE as well as embedded SW)

As the automotive industry is in the transition from conventional internal combustion engine to hybrid, battery and fuel cell electric powertrains, energy efficiency has several aspects for electronic components and systems as well as its embedded intelligence, the embedded software. The improvement of conventional powertrain concepts is also needed to already contribute to the CO_2 reduction during the transition period. New faster and more complex control algorithm are essential. The technologies and R&D&I tasks described in Chapter 3 are in close relation to the R&D&I topics listed below.

The following R&D&I topics have to be addressed:

- Architecture for control systems of alternative powertrains
- Energy efficient electric/electronics/embedded-SW architectures (e.g. using energy harvesting, …) for alternative powered vehicles,
- Ultra-low power / high performance control units
- Higher energy efficiency of electrified vehicles (e.g. using higher frequencies of power electronics, better control software and advanced thermal management systems; the use of wide bandgap technologies)
- Improved / new safety concepts for high voltage powertrain systems
- Connected vehicles
- More efficient control algorithms conventional and hybrid powertrains to support the transition period to alternative CO_2 neutral mobility

Filling/charging and energy & power storage, management and generation

The successful adoption of electrification (either battery or fuel cell-based) require the implementation of a charging/refuelling and energy / power management systems. Only if mainly electricity of renewable sources is used, the desired positive impact of the transport sector to the CO_2 reduction will be achieved.

- ECS for efficient electrical or H_2 energy storage.
- Electrical charging infrastructure and their smart control (conductive or inductive) for fully electric good transports over short or long distance, as well as for passenger cars.
- Dynamic charging, charging-on-the-move.
- Fully automatic high power (10x higher than today) and quick charging near highways.
- New efficient systems to convert electricity into hydrogen (hydrolyser).

Control strategies and predictive health management

The electrochemical or thermodynamical components as well as the advanced emission after-treatment systems are controlled by complex control systems. They are optimised to achieve the best energy efficiency while fulfilling other requirements as low emissions or protecting elements from overheating. The ageing effects of those components change their behaviour over time significantly, thus decreasing the energy efficiency or their performance with respect to other requirements. Therefore, predictive maintenance systems are necessary to allow optimal service interventions at lowest costs. Research in smart maintenance concepts will help to achieve those goals.

- Model predictive control algorithms supported by high performance multi-core real-time operating systems providing the necessary intelligence is another research direction.
- Energy efficient power management of electrical
- ECS for next generation of fuel cell electrical vehicles
- Predictive monitoring and diagnostics for electrical, hybrid or fuel-cell electrical vehicles to increase the lifetime
- Predictive maintenance for vehicles to reduce costs for the operation of vehicles

Smart sensors

Reduction in weight is another means of increasing energy efficiency. As the amount of electronics in vehicles has exploded, the weight of sensor and communication cables increased accordingly. Wireless non-safety critical vehicular networks will have to improve significantly and guarantee highly dependable communication for distributed automotive, maritime, aerospace or rail powertrain systems.

- Development of smart sensors for the next generation of FCEV (e.g. sensors for fuel cell systems to detect leakage, pressure, gas concentrations, humidity and flow, as well as the internal state in a fuel cell system), battery electrical vehicles (e.g. SOC or SOH observers), hybrid vehicles.
- Integrated smart sensor systems to increase battery or fuel cell systems by individual control of cells using smart sensors – e.g. embedded sensors in batteries, fuel cells or exhausts after treatment systems.
- Embedded control software for an efficient, environment friendly, safe and user-friendly operation of electrified vehicles.

Smart actuators and motors in transport systems

Similarly, smart actuators and motors will decrease in weight and contribute to the efficiency targets.

- Smart actuators for energy efficient powertrains
- New topology (multi-phase for improved availability) for e-motors with reduced amount of rare earth materials.
- ECS and the necessary performant embedded control software for balance of plant (BOP) components of fuel cell-based powertrain systems.

Maritime sector

Improve ship powering

- Electronic systems and the embedded software to control multi-fuel engines.
- Optimisation of energy distribution, storage and peak smoothing, Short term: Improvement of existing system and architecture for the storage. ECS to optimise the power-load-distribution, in normal and/or peak conditions.

Energy management, ship analytics and decision support

- Analysis and decision making (tools): Short Term: Concepts for optimal energy management; advanced decision support systems; Medium Term: Prototypes for energy management decision support systems.
- Data acquisition governance in ships, secure transfer to shore-based headquarters.

1.3.2.5. Expected achievements

The European supplier industry together with the OEMs and relevant research and development specialists need to get competitive and finally global leader in electrified propulsion.

The deployment of alternative resource efficient vehicles in Europe is expected to follow a series of milestones which link the market penetration to the availability and affordability of key technologies under the assumption of major breakthroughs [42, 43, 44]. Europe will also see progress in bio fuel-based vehicles. Similar roadmaps exist for other domains of mobility as rail, aerospace, off-road vehicles, trucks etc.

Overall, safety, security and transparent mobility services are a prerequisite for successful market penetration.

In parallel to the advancement of electric and plug-in hybrid passenger cars as well as light duty vehicle technologies, electrified trucks and buses or fuel cell vehicles will be developed. However, the ramp-up of their deployment is expected to start later. Furthermore, resource efficiency is the driving force of research and innovation in other transport modes, e.g. air transport [45].

1.3.3. Major Challenge 2: Ensuring secure connected, cooperative and automated mobility and transportation

1.3.3.1. Vision

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,

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[42] *E. I. Association, "EPOSS Strategic Resource Agenda," EPoSS, Berlin, 2017*

[43] *ERTRAC, "Integrated Urban Mobility Roadmap," ERTRAC, ARRAC, ALICE, Brussels, 2017*

[44] *ERTRAC, "New Automated Driving Roadmap," ERTRAC, Brussels, 2017*

[45] *C. S. JTI, "Work Plan 2014-15," Clean Sky JTI, Brussels, 2014*

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[46] *Commission Staff Working Document on the implementation of the EU Maritime Transport Strategy 2009-2018, Brussels 30.9.2016, SWD920160 326 final*

maritime (over water as well as under water transport) and rail). Their competitive asset is a profound expertise in developing complex electronic components, cyber-physical systems, and embedded intelligence. Nevertheless, a bundle of challenges in terms of autonomy, complexity, safety, availability, controllability, economy, and comfort have to be addressed to harvest the opportunities from increasingly higher levels of automation and related capabilities.

To date, we have mastered the first steps in the evolution of automated and autonomously acting machines. This movement is characterised by:

- increasingly autonomous behaviour
- increasingly complex and unpredictable environments that become an integral part of the complex control system of an automated vehicle.
- complex vision systems.
- increasing usage of artificial intelligence especially, but not limited to perception systems.
- fulfilling objectives of increased complexity.
- the ability to collaborate with other machines and humans, and the capability to learn from experiences and adopt the appropriate behaviour.
- exponentially increasing complexity of the verification and validation process, which requires a combination of a real-world proving ground and road testing, as well as increasing the proportion of virtual testing. In particular, scenario-based validation methods will require high performant electronic components for real-time AI software execution. Real-time simulation and the support of complex data types (as object lists or lidar point clouds) have to be supported.
- increasing demand for new standardised interfaces in validation toolchains.

No single organisation will be able to capture these tremendous efforts for research and development. In order to maintain a leading European position, it is therefore necessary to establish collaborations in and across industrial domains, learn from operational field data, and jointly drive the strategic actions.

The overall vision is to realise safe & secure always connected, cooperative, and automated transportation systems based on highly reliable and affordable electronic components and systems of European origin as well as technologies for new ways of interacting between humans and machines.

As for the maritime sector [46], improving competitiveness, safety, and security of European shipping is a major objective of the EU Maritime Transport Strategy, which in turn shapes the requirements for upgraded maritime transport information management. Advances in ICT have created a demand for new forms of surveillance and information management systems; these are increasingly driven by policy and governance addressing safety, security, and sustainability. This is reflected in the emergence of the IMO’s e-navigation concept and the more embracing European Commission’s e-Maritime framework, established for measurable economic, social and environmental benefits.

The rapid development in information and communication technologies will significantly increase digitalisation in all waterborne sectors and lead to data-driven services such as optimising energy use and fuel efficiency, vessel performance and condition monitoring, and weather routing. A higher degree of systems automation, the availability of smart sensors and global networks for data transfer between ship and shore will promote remote controlled, and semi or fully autonomous operation of assets. Interconnectivity between sea-based operations and shore-based operation centres will enable increasing support and control from the shore. This will require secure systems and operations against cyber-attacks.

Furthermore, ships will become fully connected throughout the world. Remote monitoring of vessels is already possible, allowing for condition-based maintenance. Building on the increasing automation on-board, remote operations of vessels will become possible, eventually moving towards full autonomy of vessels. The wider use of Unmanned Autonomous Vessels (UAVs) – either aerial, underwater or on surface – will increase flexibility and energy efficiency of operations.

1.3.3.2. Scope and ambition

Connected, cooperative, and ultimately automated mobility and transportation is seen as one of the key technologies and major technological advancements influencing and shaping our future quality of life. ECS will enable different levels of partial, conditional, highly and fully automated transportation posing new challenges to traffic safety and security in mixed scenarios where vehicles with different automation levels coexist with non-automated vehicles. Both development approaches – evolutionary (stepwise increase of automation level, "conversion design") and revolutionary (SAE level 5, "purpose design", e.g. people mover in structured environment) – should be covered as well as cross-fertilisation with other industrial domains as Industry 4.0.

As the proportion of electronics and software as a percentage of the total construction cost of a vehicle[47] increases, so does the demand for the safe, secure, reliable and un-hackable operation of these systems. In addition, privacy protection is a key element for car owners and drivers/operators. These requirements ask for fail-operational technologies that deliver intrinsically safe operation and fail-safe fall-back from component to subsystem and provides a fall-back for problems in interaction with the cloud. This demands new developments in terms of multicore-/many-core-based platforms and sensing devices, combining advanced sensing in harsh conditions, novel micro- and nano-electronics sensors, filtering, advanced sensor fusion, noise reduction, fault detection, low power operation, self-testing and reliable predictable actuation.

Research, development, and innovation will focus on capabilities in the fields of sensing, communication, navigation/positioning, computing and decision-making, control and actuation based on smart systems for mobility and the necessary tools, methods, and processed for development and validation. Along with deterministic control strategies, data-driven algorithms based on artificial intelligence (AI) are covered in both ECS development phase and in-vehicle operation. It will be necessary to find new ways to perform fast and repeatable validation and non-regression tests independent from real-world tests.

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[47] *The term "vehicle" includes cars, aircrafts, trucks, vessels, trains, off-road vehicles, satellites, drones.*

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[48] *https://www.acea.be/automobile-industry/facts-about-the-industry*

1.3.3.3. Competitive situation and game changers

Especially in European countries, the mobility and transportation industry plays a central role for the internal market as well as for export markets. In the automotive sector – according to ACEA (European Automobile Manufacturers Association) – around 13.3 million people are employed (out of which 3.4 million jobs in manufacturing), contributing 6.8 percent of the European Union's GDP [48].

However, competition is getting fiercer. Since 2013, China has overtaken Europe in number of cars produced. European car manufacturers are competing in a worldwide race toward vehicle automation and connectivity with newcomers from the IT sector. The value is being reshuffled across the value chains. According to several studies, 30 to 40 per cent of the value in the automotive value chain will pass through digital platforms, in the near future. Dependence on a reliable low latency IT infrastructure and its maintenance adds complexity to the value chain, and is an important issue to consider in order to realise the expected benefits of automation. If Europe safeguards its well-established market position by developing innovative and effective safety features, many jobs in the automotive, aeronautics and railway industries will be preserved as well as newly created.

1.3.3.4. High-priority R&D&I areas

The following research, development and innovations areas and their subtopics are identified (more details can be found in the Appendix to Chapter 1, section "Details to high priority R&D&I topics for Grand Challenge 2 in Application Chapter Transport & Smart Mobility":

Automated road transport:

- Environment recognition (sensors and sensor fusion) and AI methods for robust and flexible identification of object classes.
- New cost-efficient sensors and perception systems for precise perception and use in severe weather conditions (mainly using AI software).
- Localisation, maps and positioning (also for urban applications where GPS is not working accurately enough).
- Control strategies (sensor input, object detection, sensor fusion on raw date level and/or object level), environment modelling, trajectory planning, actuator control, monitoring, v2x communication; energy-optimal, performance optimised model predictive control (MPC) systems for highly automated vehicles, as well as validation tools for these control systems.
- Customer-friendly safe handover strategies when leaving the operation design domain (ODD) of an automated vehicle or encountering safety-critical situations for (highly) automated systems; co-existence concepts and systems for automated and manual operation of vehicles.
- HW and SW platforms for control units for automated mobility and transportation (including support for artificial intelligence), e.g. IoT integration platforms for automated and connected environmentally friendly vehicles.
- Communication inside and outside vehicle.
- Validation methodology and the necessary toolchains for safety, security and reliability (including answering the question, when is enough tested) as well as reference architectures for validation toolchains for automated vehicles; accelerated lifetime testing tools of degradation of AI-based control HW and SW components for (highly) automated systems.
- Cost and time efficient regression tests for continuous integration in vehicle controllers (tools and methods).
- Real-time co-simulation supporting complex data types (such as object lists, video stream, lidar point clouds).
- Environment simulation for workstation and cloud usage.

- Vehicle in the loop test systems for testing of safety critical scenarios and/or sensor degradation in a safe environment.
- Models of all relevant components of automated vehicles, including methods and tools to validate these models (vehicle model, sensor models, environment model, V2x communication model, localisation models, human driver models, traffic participant agent models); holistic design and verification methods for digital twins for generic or specialised use (e.g. for safety validation, security validation, HMI testing).
- Extraction of relevant scenarios from road test data and conversion into scenarios for virtual testing.
- Create and maintain scenario databases.
- Creation of KPIs to evaluate the results of road testing, as well as virtual testing.
- Analytics platforms to manage data from virtual and road testing (peta byte of complex data).
- Data acquisition system for road testing.
- Data labelling and scenario tagging tools, as well as creation of open source labelled data for research usage.
- Automation systems for tests on proving grounds using ultraflat overrunable objects (UFOs).
- Stimulators for sensors (used in vehicle in the loop testbeds or sensor testbeds).
- Swarm data collection and continuous updating.
- (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.
- Increase of automation across boundaries in and between companies to significantly reduce logistics overhead along the DEVOPS cycle of automation systems in vehicles (including the necessary complex perception system and their sensors).
- Functional safety and fail-operational architecture and functions (sensors, electronics, embedded software and system integration).

Connected maritime systems and automated transport [49]

- Improved port and logistics infrastructure and operations.
- Improved ship security systems/Improved protection against hacking.
- Greater shore-based monitoring, predictive maintenance and surveillance.
- Continuing drive for greater energy efficiency/Better design codes and modelling.
- Flexible and adaptive ship operations/Improved ship handling and survivability/improved vessel routing.
- Greater ship autonomy/more autonomous ship operation.
- Greater integration of the logistics chain/displacement of paper systems.

Smart and autonomous ships

- Open and integrated maritime data networks protected from cybersecurity risks enabling new innovative ship functions and easy integration with shore services; Long term: Smart and automated functions are developed that can be integrated from third parties into existing ship systems and can be type approved by software and functionality. System approval automatically from the configuration of individual function and infrastructure approval.
- Improved integration with shore support centres for technical operation and remote maintenance. Improved maintenance systems and processes for zero defects during voyage; Long term: Development of new shore control centres for navigation as well as technical maintenance and operations. This should support remote monitoring and control of ships.

- Development of decision support for safer and more automated nautical operation of ships at sea and in port, including fully or periodically remote control from shore; Long term: Automated navigation functions, integrated with VTS and shore control for autonomous voyages combined with remote control and periodically unmanned bridge.

1.3.3.5. Expected achievements

The impact of automated and connected vehicles could be huge. It could help to drastically reduce road fatalities and road accidents. New transport services could also be provided especially when the vehicle is provided with connectivity in addition to automation, e.g. traffic safety related warnings, traffic management, car sharing, new possibilities for elderly people or impaired people. Automation will also enable user's freedom for other activities when automated systems are active. Drivers/operators can expect more individual comfort and convenience which is likely to be the major motivation for upcoming automated driving. In the long term, automation could have a revolutionary impact on travel behaviour and urban development. It could also result in new business models, such as shared and seamless intermodal mobility which could have an impact on the number of vehicles on our roads.

Connected, cooperative, and automated mobility also brings new challenges for regulators concerning road safety, security, traffic law, access to data, protection of personal data, financing, etc. which have to be addressed.

Multiple innovative components and systems are expected for making highly secured automated and connected vehicles, including:

- Interacting information systems for safe and secure connection between vehicles and between vehicles and infrastructure, also enabling intelligent traffic/logistics management systems
- Intelligent on-board traffic management and navigation systems to achieve maximum efficiency and range/mileage
- Energy harvesting sensor & actuator systems in harsh conditions
- Next generation multi-core/many-core-based architectures
- Industrialisation of AI-based systems
- Safe fall back vehicle sensing and actuation systems
- High precision low cost localisation platform for civil use
- Fail-operational and 24/7 available ECS at low cost
- Methods and tools to virtually validate and approve connected, cooperative, automated vehicles
- Certification procedures

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[49] *Commission Staff Working Document on the implementation of the EU Maritime Transport Strategy 2009-2018, Brussels 30.9.2016, SWD920160 326 final*

- Over-the-air update services combined with tools for the cost-efficient validation of updates
- Monitoring systems and software that check the health of the safety critical components (as perception system and its sensors), as well as to identify unknown scenarios that are reported back to the development teams (DevOps cycle)

Development of such systems will be accomplished through the use of innovative new components and systems, methods and tools, and standards (e.g. sensors, embedded mixed criticality systems, actuators, communication protocols, etc.), new system-on-chip and system-in-package technologies, and new design/validation/verification methodologies on component and system level.

1.3.4. **Major Challenge 3: Managing interaction between humans and vehicles**

1.3.4.1. Vision

Vehicles are being more and more equipped with massive computing power, artificial intelligence, numerous assistance/ infotainment/ communication systems and partially autonomous functions. Individual transport has never been so distracting, easy and safe at the same time. One clear and shared vision of all industry branches related to transportation is that in the future there will be a broad variety of partially and fully autonomous operating vehicles, ships, drones, aircraft, trains, etc. In this world, the exchange of information between humans, either in the technical system (vehicles/railway/ship/airplane) or outside (such as pedestrians or cyclists) and the technical systems is essential.

1.3.4.2. Scope and ambition

The great challenge in this future coexistence of humans, “traditionally” operated vehicles and (partially) autonomous systems is the dynamic interaction between them: How does the human know what the machine is going to do? How does the human tell the machine what to do and what not to do?

There is a clear demand for interfaces between humans inside and outside of such transportation systems and the technical systems which have to be: easy to understand, intuitive, easily adaptable, safe, secure, unobtrusive and reliable.

1.3.4.3. Competitive situation and game changers

With the rising number of capabilities of electronic systems also the number of possible use cases is rising. One example is the hype of speech recognition and home assistance systems, being pushed by Google, Amazon, Microsoft, Samsung etc. Adapting these solutions to the transportation sector is one of the next tasks to perform.

1.3.4.4. High priority R&D&I areas

The following research, development and innovations areas and their subtopics are identified:

- **Driver activities and vital signs monitoring:** (Partially) Autonomous vehicles have to know, in a non-invasive manner, the current status of the “driver” in order to notify adequately if any manual driving action needs to be done. This starts from e.g. the exact seating position and extends to monitoring the vital signs in order to be able to do emergency driving maneuvers in case of e.g. a sudden sleep attack (ref. Commission Directive 2014/85/EU regarding OSAS as a risk factor for driving), or a heart attack. Here the new generation of wearable sensing devices can play a role, being interconnected with the vehicle network.

- **Future human interaction technologies and concepts:** More and more functions in today's and even tomorrow's vehicles mean that an easy usage will be a great challenge. We need concepts and technologies to tell the technical systems what to do and what not to do. In addition to this we need ways for the systems to clearly tell/ show the humans what is happening right now, what will be happening next and which options there are. This is not restricted to persons e.g. sitting in an autonomous car but also includes all other road actors, e.g. pedestrians in the "world out there". This will need new components to interact between driver and automobiles, ships, airplanes etc. (haptic, optical, acoustic, … sensors).
- **"Online" Personalisation of vehicles:** With "Shareconomy" and on-demand services getting more and more popular in the transportation sector there is a clear need for quick and easy individualisation/ personalisation of vehicles. We need concepts, technologies and systems which allow to adapt all functions and services of such a vehicle to the user/ passenger instantaneously.
- **Smart mobility for elderly, very young or non-technical-affin people:** With an ageing society there is a clear demand for smart concepts which allow elderly people unlimited mobility. Seniority needs have to be considered for interaction concepts and systems.
- **Smart mobility for digital natives:** Digital Natives are used to always-on connectivity, digital interaction and fast information exchange. Concerning mobility there is the expectation of a seamless and instantaneous experience which can be fully managed by digital devices. Mobility clearly is a service.
- **Smart mobility for handicapped people:** Mobility for handicapped people needs special concepts which allow to adapt to various types of physical and mental disabilities and ideally allowing these people to travel individually in a safe and secure way.

1.3.4.5. Expected achievements

The expected outputs are described in Section 1.3.4.4.

1.3.5. Major Challenge 4: Implementing infrastructure and services for smart personal mobility and logistics

1.3.5.1. Vision

An important future trend in transportation and mobility is the shift away from the paradigm of either exclusively personally owned or publicly operated modes towards integrated mobility solutions that are consumed as a service. Smart mobility services will establish more seamless, economic and sustainable mobility across all transportation modes in the smart cities of the future. This is enabled by combining transportation services from public and private providers through a unified IT platform and supported by jointly used physical and digital infrastructures. Both the transport of people and goods could be organised more efficiently in response to demand this way. The challenges to create smart multimodal spaces are covered in the chapter "Digital life – Major Challenge 4: Ensuring sustainable spaces", the challenge to offer multimodal transport means is covered in this chapter.

1.3.5.2. Scope and ambition

The solutions to be considered under this Major Challenge are manifold but highly depend on electronic components and systems; e.g. advanced V2X technology, traffic management systems, 2-/3-D navigation and guidance solutions in combination with mobility-as-a-service concepts will be fundamental to providing the optimal utilisation of new vehicle concepts for personal mobility and transportation in congested urban areas. These services will also be the basis for radically new mobility models – including robot taxis, shared self-driving shuttles and cooperative fleets of drones for last-mile delivery.

1.3.5.3. Competitive situation and game changers

Countries such as Japan already have a communication infrastructure deployed that allows the development and full-scale testing of systems under real conditions. ECSEL needs such an environment to be able to develop competitive solutions. Regulations on V2X have e.g. pushed the development in the US to an acceleration.

V2X communication technology (ETSI ITS-G5 in Europe and US DSRC based on 802.11p) offers low latency short range communication in highly dynamic mobile environments, and is the basis for large scale deployments in several European countries. While the access layer technology has matured through extensive testing in the last decade, the main challenges in connected driving are vertical to the access layer: Safety-critical functions need to be ensured under security and privacy constraints. Services offered among infrastructure and vehicles need to discover in an ad-hoc fashion and made available in a seamless and transparent way. Automation functions such as platooning require very robust short-range wireless links with low latency. The same holds for guidance of vehicles by the traffic management and sharing of sensor perception between infrastructure and vehicles.

While the access technology is already available, communication protocols ensuring robustness and synchronisation with other services using shared communication channels need to be developed, along with the methodology. Especially the mobility domain is characterised by highly dynamic, open and interconnected systems of systems, which requires design methodologies to develop protocols for such open environments, which require appropriate design methodology to ensure safety and security.

Single vehicle data enables the traffic management to obtain the traffic status on a very fine granularity, but also gather information about environment (local weather conditions, slippery road etc.). This can be seen as an evolutionary path from today's probe-vehicle data to comprehensive data allowing collaborative environment perception. Real-time data from infrastructure sensors will augment the vehicles perception capabilities.

Above technologies together with increasing difficulties to provide enough space for the increasing traffic especially in mega cities leads to radically new mobility concepts as mobility as a service. The paradigm shifts from owning the devices providing mobility to purchase only the services to move oneself or goods from one place to another. This requires new digital platforms and business systems to manage the mobility services with secure communication to the vehicles providing the mobility service.

The traffic management of the future needs to provide an optimal combination of different transport modes in response and anticipation of user demands. Traffic management will guide automated and non-automated vehicles. Road conditions, traffic situation, transport demands, weather conditions etc. need to be monitored in a fine-grained way using new infrastructure and distributed smart sensor technology including complex local pre-processing (e.g. machine learning).

New traffic sensor technology is required to support robust fine-grained mobility detection. Combinations of several technologies such as high-resolution short-range radars, time-of-flight cameras might be a way forward. Guidance systems for truck platoons and automated vehicles require robust wireless links in real-time, fast and reliable detection by on-board and infrastructure sensors and reliable connection of this data, such that the central traffic management or a lead vehicle of a platoon can be sure to communicate and interact with the vehicles which are perceived by its sensors.

1.3.5.4. High priority R&D&I areas

The following research, development and innovations areas and their subtopics are identified:

- V2x communication
- Privacy by design
- Traffic management for single-modes (multi-modal traffic management is covered in the WG "Digital Life")
- Management systems for multimodal transport means including necessary distributed smart sensors, interfaces, privacy protection, data management, traffic prediction, route optimisation
- Guidance systems (remotely operated drones, trucks, ships, etc. …)
- Mobility platforms for mobility as a service with seamless billing and payment systems (incl. e.g. personalised cards for users, usage of mobility services)
- Mobility as a (smart) service communication, security and privacy systems
- Predictive and remote maintenance
- Efficient logistics in freight and goods
- Vehicles offering services (also during parking) (e.g. WiFi extender, monitoring traffic density, airplanes acting as communication repeaters, etc. …)
- Security and reliable availability of V2x communication

1.3.5.5. Expected achievements

Development of further solutions for connectivity going from the individual car to the full system including infrastructure. This shall prepare the ground for the development of new services.

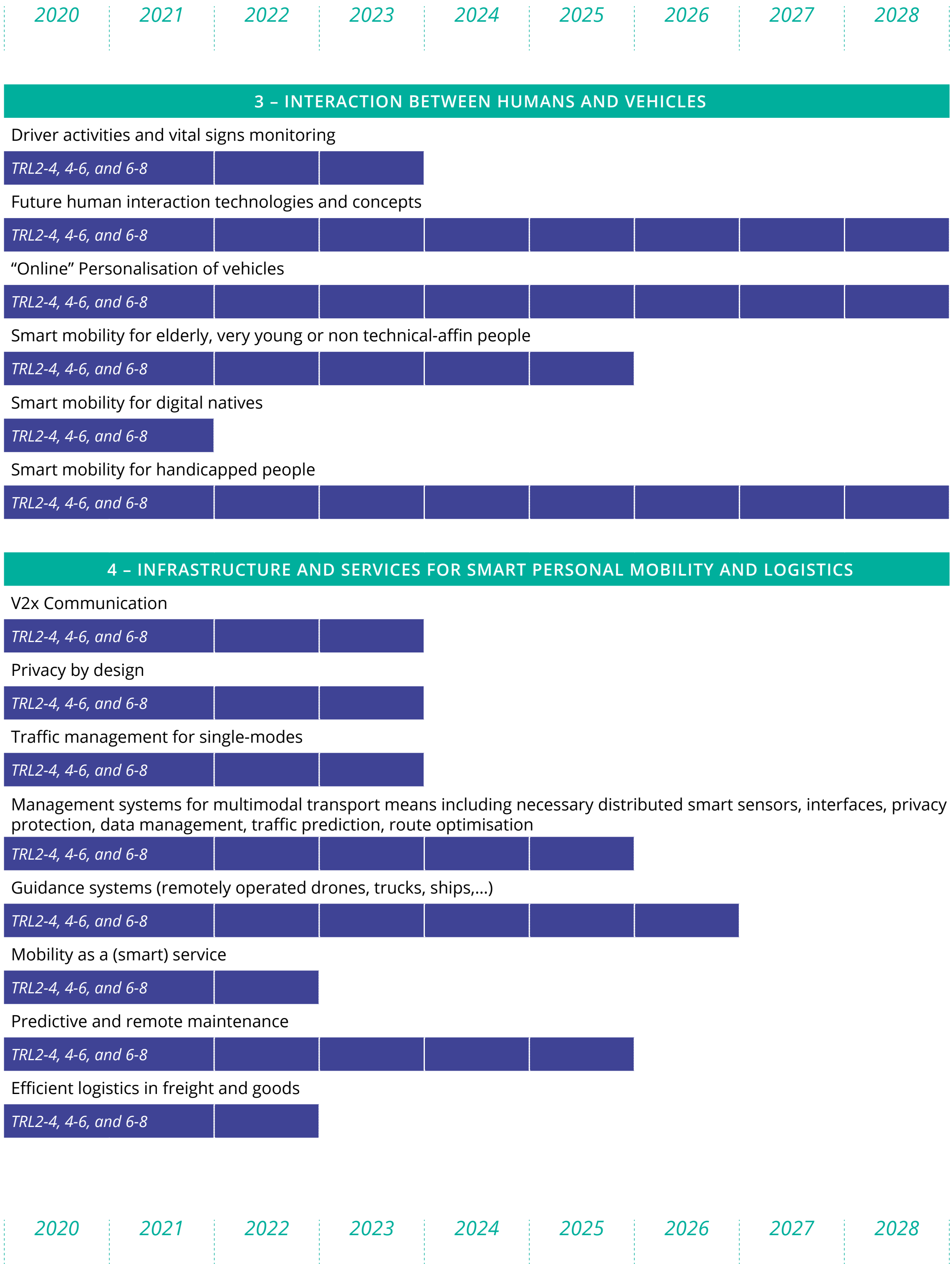
1.4.
MAKE IT HAPPEN

Achieving the aforementioned goals requires the adoption of a focused strategic approach that combines R&D competencies from across Europe and involves all stakeholders in the value chain. Most of the mentioned research topics will require several innovation steps in order to solve technological barriers and establish adequate price levels of the semiconductor, sensor and system components and necessary embedded cyber-physical software base. Therefore, the cooperative research in at different TRL levels will be necessary in order to achieve the necessary innovation speed required to keep the European industry in the field of transportation and smart mobility at the forefront in the world. The TLR level of RDI work depends always on the position of the research partner working on a task in the supply chain. Low level components typically have higher TRL levels than the application systems, into which they are integrated. Therefore, all task in the roadmap can be addressed by RIA or IAs.

Special attention will have to be paid to the interaction with legislative actions in this domain and societal acceptance of highly automated vehicles and new business models of future mobility. Furthermore, standardisation will be crucial for future automated and autonomous cars, including the embedding of enhanced safety, security, and privacy protection features.

Finally, governments will need to increase the amount of pilot test sites on both private as well as public grounds.

1.5.
TIMEFRAMES



Timeframe 2019–2028 **F.21**

1.6. SYNERGIES WITH OTHER THEMES

The widespread expectation of modern information and communication societies is that individuals take advantage of all existing services regardless of where those individuals are located – in the office, at home or on the move. Therefore, there is a synergy with the theme of **"Digital Lifestyle"**. Whereas "Digital Lifestyle" will focus on the future life from a static point of view, meaning the citizen on a specific location or in a specific environment, the theme "Transportation and Smart Mobility" will focus on the dynamics and moving of the citizen in the society.

When moving to autonomous vehicles, the driver behaviour and monitoring will become more and more important. For that purpose, there is a synergy with the theme **"Health and Well-Being".** Within "Transportation and Smart Mobility", seamless connectivity, interoperability and privacy protection become more and more important. This should be supported by cross-domain use of the themes of **"Connectivity & Interoperability"** and **"Dependability and Trustablity"**.

In contrast to other domains, Automotive & Transport applications are characterised by stringent real-time requirements and severely limited energy resources. To meet these requirements, robust technologies, components, simulation modelling & tools and domain-specific implementations of the same functionality are needed. Therefore, there is a synergy with the theme of **"From Systems to Components".**

The vehicles used for "Transport and Smart Mobility" are themselves products of long and complex supply chains, produced in increasingly digital factories. This could form a twofold synergy with the **"Digital Industry"**, as the infrastructure and logistics of "Transport and Smart Mobility" influences the "Digital Industry", while simultaneously "Digital Industry" provides more digitised vehicles, possibly integrating production data into e.g. smart motors, and facilitating predictive maintenance aspects of "Transport and Smart Mobility".

The research topics of challenge 1 are also related to the activities in Chapter 3 "**Energy**". The activities in the chapter "Transport & Smart mobility" concentrate more on the specific energy saving measures in the technical systems specific for transport whereas chapter 3 has the focus on energy production, transmission, conversion and energy savings measures across different domains.

2

Health and Wellbeing

2.1.
EXECUTIVE SUMMARY

Healthcare systems face a huge challenge in providing the same level of care, in an appropriate, efficient and cost-effective way, to a rapidly growing and aging population. By 2030, the world population will have risen by 1.3 billion to 8.5 billion people; due to ageing, the world's population in the age bracket 65+ is projected to increase by 436 million to 1.3 billion people and the urban population by 1.5 billion to 5 billion, who all will require increased access to healthcare facilities and services.

Innovative technologies in health have long been integrated into devices that treat acute or chronic diseases, and which affect vital prognoses or alter drastically the quality of life of numerous patients. However, tremendous progress in research fields such as image-guided interventions, smart catheters, genomics, bionics, bioelectronic medicines, bio-sensing, regenerative medicine, energy harvesting and low-power electronics for secure communication and extending processing and memory capacities now offer completely new approaches based on artificial intelligence, deep learning and the understanding of biological mechanisms at the origins of diseases that will radically change the way diseases are diagnosed, treated and followed-up. This is true for both professional healthcare as well as vitality, wellbeing and prevention.

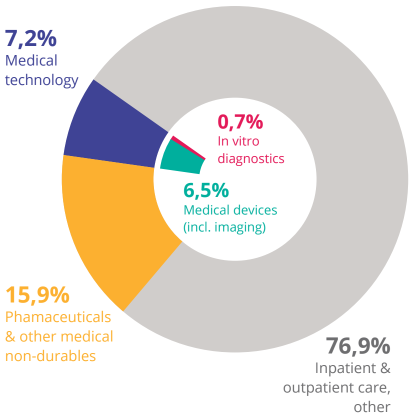
The way healthcare is provided is changing substantially, as medical care and interventions in the future are no longer confined to hospitals, clinics or medical offices, but will be provided anywhere in people's life, especially in their homes. Ambulatory, "point-of-care" and "home care" are terms that will gain significance in the future.

This trend of a "decentralised" healthcare will not only have an impact on how medicine reaches the patient, but will require a redefinition of the role and positioning of healthcare providers. ECS have the potential to provide suitable systems solutions, both to support the rising importance of personalised delivery of healthcare and to smarten existing healthcare providers and to assist the population in changing behaviours to improve their health.

2.2. RELEVANCE

2.2.1. Competitive value

BREAKDOWN OF TOTAL HEALTHCARE EXPENDITURE IN EUROPE



WORLDWIDE MEDTECH SALES BY EVALUATEMEDTECH® DEVICE AREA: TOP 15 CATEGORIES & TOTAL MARKET (2017 & 2024)

Rank	Device Area	WW Sales ($bn) 2017	WW Sales ($bn) 2024	CAGR % Growth	WW Market Share 2017	WW Market Share 2024	WW Market Share Chg. (+/-)	Rank Chg. (+/-)
1.	In Vitro Diagnostics (IVD)	52.6	79.6	+6.1%	13.0%	13.4%	+0.4pp	-
2.	Cardiology	46.9	72.6	+6.4%	11.6%	12.2%	+0.6pp	-
3.	Diagnostic Imaging	39.5	51.0	+3.7%	9.8%	8.6%	-1.2pp	-
4.	Orthopedics	36.5	47.1	+3.7%	9.0%	7.9%	-1.1pp	-
5.	Ophthalmics	27.7	42.2	+6.2%	6.8%	7.1%	+0.3pp	-
6.	General & Plastic Surgery	22.1	34.3	+6.5%	5.5%	5.8%	+0.3pp	-
7.	Endoscopy	18.5	28.3	+6.3%	4.6%	4.8%	+0.2pp	+1
8.	Drug Delivery	18.5	25.3	+4.6%	4.6%	4.3%	-0.3pp	-1
9.	Dental	13.9	21.6	+6.5%	3.4%	3.6%	+0.2pp	-
10.	Diabetic Care	11.7	19.8	+7.8%	2.9%	3.3%	+0.4pp	+3
11.	Wound Management	13.0	17.8	+4.6%	3.2%	3.0%	-0.2pp	-1
12.	Healthcare IT	11.8	17.6	+5.9%	2.9%	3.0%	+0.1pp	-1
13.	Neurology	8.6	15.8	+9.1%	2.1%	2.7%	+0.5pp	+3
14.	Nephrology	11.7	15.6	+4.2%	2.9%	2.6%	-0.3pp	-2
15.	Ear, Nose & Throat (ENT)	8.9	13.1	+5.7%	2.2%	2.2%	+0.0pp	-
	Top 15	342.0	501.7	+5.6%	84.4%	84.4%	-0.0pp	
	Other	63.1	92.9	+5.7%	15.6%	15.6%	+0.0pp	
	Total WW Medtech Sales	405.0	594.5	+5.6%	100.0%	100.0%		

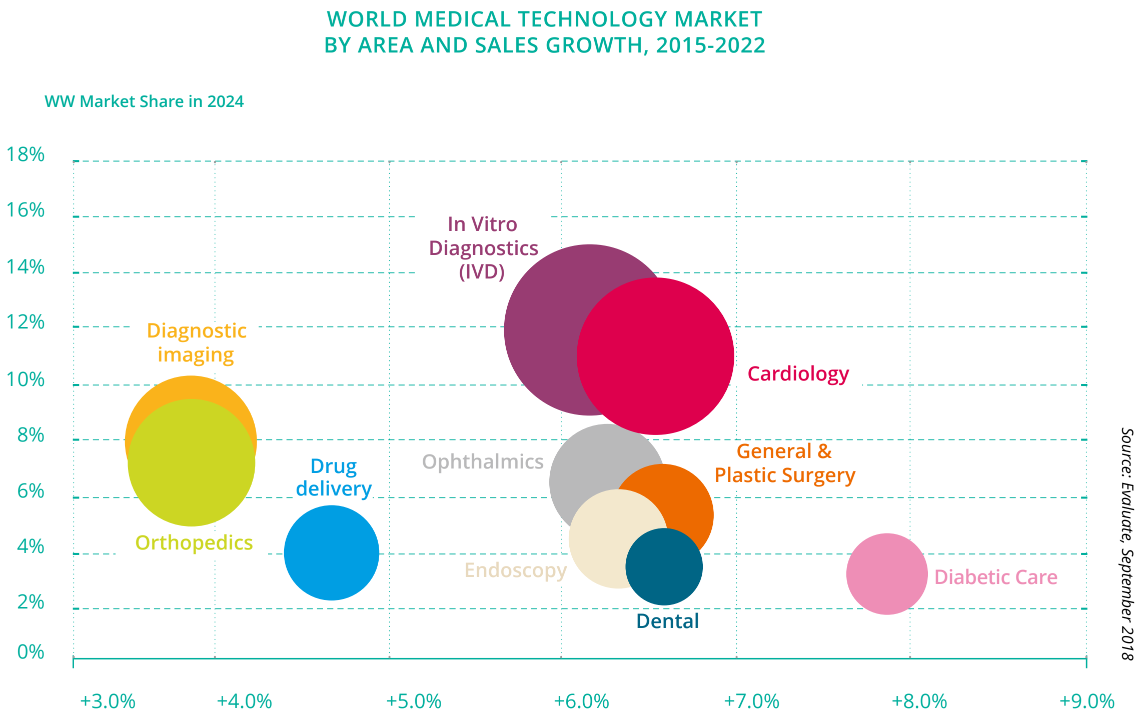
Note: Analysis is based on the top 300 medtech companies. Sales in 2017 based on company reported data. Sales forecasts to 2024 based on a consensus of leading equity analysts' estimates for segmental sales.

F.22 *Breakdown of total healthcare expenditure in Europe, Global Market Share of Medical Devices. There are 26,000 medical technology companies in Europe, 95% SMEs (Source: MedTech Europe 2019, Evaluate, September 2018)*

In Europe, an average of 10% of gross domestic product (GDP) is spent on healthcare. Of this amount, around 1% of GDP is attributed to medical technologies. Expenditure on medical technology per capita in Europe is at around EUR197 (weighted average).

The European medical technology market has been growing on average by 4.6% per annum over the past eight years.

EvaluateMedTech® consensus forecasts that the Medtech world market will achieve sales of $595 billion by 2024 (CAGR of 5.6%). Neurology is set to be the fastest-growing device area, with a CAGR of 9.1% between 2017 and 2024. In vitro diagnostics will remain the number one device area in 2024 with sales of $79.6 billion; Roche is forecast to have 18% of the market. Medtronic will remain the top group in cardiology in 2024 with sales of $14.2 billion, a 20% market share. Diagnostic imaging sales are forecast to reach $51 billion in 2024; Siemens Healthineers, General Electric and Philips will continue to dominate the market. Essilor will continue to dominate the ophthalmics market in 2024, with forecast sales of $11.6 billion.

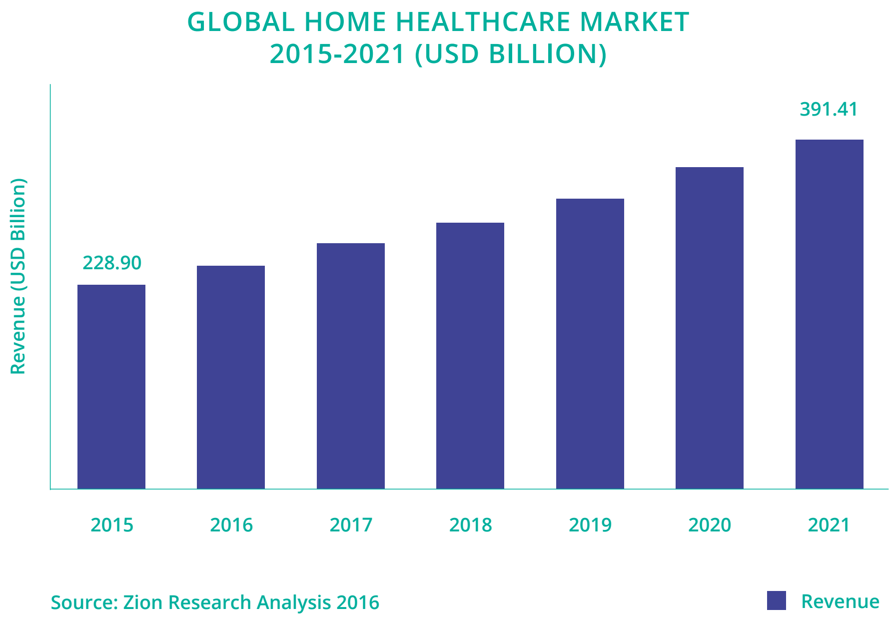


World medical technology market by area and sales growth, 2017–2024

F.23

The market for image-guided intervention and decision support will grow substantially. A completely new area is connected care and hospital informatics, which will focus on workflow and digital solutions both in the hospital and other care facilities. The area of personal health will also grow considerably.

The global home healthcare market is mainly driven by an increasingly geriatric population, rising healthcare costs and technological advancements in healthcare devices. With increasing health awareness among people, growing numbers of people diagnosed with chronic diseases such as diabetes, cardiac disorders and respiratory diseases, the demand for home healthcare market is expected to grow in the near future. The population of geriatric people is growing rapidly across the world, a population that is more vulnerable to non-communicable diseases such as diabetes. This, in turn, is expected to fuel the growth of home healthcare market. However, changing reimbursement policies and limited insurance coverage may pose a challenge to the home healthcare market growth in the near future. Rapid decentralised job growth, especially in-home healthcare services, is expected to open alluring avenues for the market to grow over the next few years.



F.24 *Global home healthcare market 2015–2021*

2.2.2. Societal benefits

Healthcare provision is in the process of "industrialisation" in that it is undergoing changes in the organisation of work, mirroring those that began in other industries a century ago. This process is characterised by an increasing division of labour, standardisation of roles and tasks, the rise of a managerial superstructure, and the degradation (or de-skilling) of work. The consolidation of the healthcare industry, the fragmentation of physician roles, and the increasing numbers of non-physician clinicians is likely to accelerate this process. Although these changes hold the promise of more efficient and effective healthcare, physicians should be concerned about the resultant loss of autonomy, disruption of continuity of care and the potential erosion of professional values. On the other hand, physician roles will become more complex because patients will be multi-morbid and can only be treated by an integral approach to all disorders simultaneously.

Healthcare will also become more personalised. Besides age, blood pressure and cholesterol levels, personalised healthcare also looks at biological information, biomarkers, social and environmental information to gauge the risk of disease in individuals. Furthermore, it means providing individuals with tools like digital health and fitness apps, telemedicine providers and at-home testing kits. These on-demand health solutions enable people to understand their health on their own terms, while receiving doctor input. Personalised health also applies to patient-specific optimisation of diagnostic imaging and image-guided therapy and tailored settings of smart implantable medical devices (bioelectronics medicines) based on an individual's personal data.

In many cases, poor nutrition is a primary source of ill health and significantly impacts health expenditure. For this reason, health policy-makers are now investing more resources in the early detection of causes of ill health related to food, rather than simply focusing on diagnosis and treatment. In this way, policy makers can potentially reduce the burden of food-related disease on the health services and improve the health of the population at large.

The ambition is to mobilise all stakeholders in the entire health continuum. The stakeholders are individual patients, healthcare professionals, industry, payers and the economy as a whole.

For patients, benefits should include shorter hospital stays; safer and more secure access to healthcare information; relevant, correct and without information overload; better personalised prevention, information about environmental factors, diagnoses, management and treatment; improved quality of life and productivity; and reduced risk to further complications that could result from hospital treatment.

For healthcare professionals, benefits are directed towards improving decision support; providing safer and more secure access to healthcare information, precise and without information overload; unlocking entirely new clinical applications; and enabling better training programmes leading to better trained professionals.

The impact on European industry is targeted at maintaining and extending leadership positions of European Industry; creating new market opportunities in the digital world for European large industry and SMEs; opening up a new world of cloud-based collaborative care; and increasing efficiency of disease prevention, diagnoses and treatment.

Benefits for the European society at large include the creation of a European ecosystem around digital healthcare; contributing to the reduction of growth of healthcare cost; increasing people's years of healthy life; improving quality of life, wellbeing and productivity of the workforce; and decreasing or considerably slowing down morbidity among society.

Benefits for healthcare payers (such as insurance companies, national authorities and citizens themselves) target health prevention, a reduction of cost and a leaner approach to healthcare provision coupled with an improved quality of treatment.

2.2.3. Game changers

To realise the abovementioned benefits, we should focus on innovations and technologies that have the potential to become game changers in the health industry. The most important technologies are listed below:

- **Wearable and remote sensing technologies:** These will allow patients and the elderly to remain for longer in their home environments and will take costly clinical trials out of the hospital.
- **Bioelectronic medicines:** Small intelligent implantable devices to modulate the function of organs without the side effects of traditional chemical medicines to treat immune diseases, spinal cord disorders and even lifestyle disorders such as obesity, depression and hypertension.
- **Smart minimal invasive instruments:** Replacing traditional surgery with less burden and risk for the patient and strongly reduced hospitalisation. New X-ray-free guidance technologies will guide these instruments, relieving the burden on physicians and clinical staff.
- **e-Health devices and applications:** Technical solutions, apps and AI appliances will replace standard physician consultations and guidance at a fraction of the cost. They will monitor people's lifestyle and help them to live healthier.
- **Affordable point-of-care diagnostic tools:** Based on MEMS (ultra-sound) imaging, devices and sensors assisted by AI interpretation will allow point-of-care workers to diagnose patients without the need for a hospital visit. Besides, it will bring advanced healthcare to remote and rural areas in developing countries.
- **Organ-on-chip:** New technologies on the interface between microfluidics, microfabrication and biology will result in improved models of organs and diseases that will help pharma develop safer and more effective medicines, and also shorten the pharma innovation cycle.

2.3. MAJOR CHALLENGES

2.3.1. SWOT analysis

Below a SWOT analysis of the current European position in healthcare is presented. These points are addressed in the individual Major challenges and expected results

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU ECS industry [50]	**Strengths:** Presence of strong industrial players in EU (e.g., Philips, Elektra, Siemens, B Braun) Much creativity in EU Great design capabilities in EU Strong entire value chain Strong presence of small Medtech companies Good cooperation between universities, RTO, companies and hospitals Experience from past EU projects – pilot tests Leading position of Europe in MtM/sensor domain Strong, well developed mobile telecom with good territory coverage Health insurance systems in Europe are in general very elaborate	**Weaknesses:** Fragmented market across countries Limited start-up / VC culture Personalised cloud providers from US Fragmented solutions, no integrated solutions at hand Limited cross-border cooperation Necessity of multi-lingual solutions
External factors To the EU ECS industry	**Opportunities:** Move from hospitals to homes and care centres will enable high volumes Ubiquitous availability of smartphones will enable new eHealth services Low-cost availability of accurate health sensors will enable remote health monitoring Formulation of unified requirements concerning semantic interoperability and process interoperability will enable flexible modular solutions Availability of personal data enables new services and solutions European market is the largest in number of treated patients Faster market introduction due to EU directive on medical devices Similar cultural background in Europe might help in user acceptance Increasing demand of medical devices (prediction until 2022) Predicted growth of R&D expenses Ageing population results in growing market	**Threats:** Ageing population results in growing needs for integrated care Not all legislation uniform in EU Reimbursement schedules vary per EU member state Increasing competition from less fragmented markets Lack of widely accepted, advanced privacy and security technical standards

F.25 *SWOT analysis on current European position in healthcare*

2.3.2. Moving healthcare from hospitals into our homes and daily life requiring preventive and patient centric care

2.3.2.1. Vision

Increasingly present-day patient care is moving out of the hospital. In the end, only treatments and diagnoses that need large equipment and/or the near presence of specialised medical personnel will remain in hospitals that will transform into treatment and/or diagnosis centres. Enabling mobile diagnoses and treatment systems means that specific procedures can move out of the hospital towards general practitioners or patient homes. In the meantime, the focus of healthcare (time spent and cost) is on embedding diagnosis and treatment in the hospital with home-based prevention, monitoring and chronic disease management.

Patients are becoming healthcare customers. They and their relatives are engaged in the prevention and care, and they are empowered to participate. This is supported by widespread connected care, integrating home-based systems, and professional healthcare systems and information repositories.

Monitoring and alert systems are widely used to support prevention, diagnosis and aftercare. They are sensors and actuators to ensure precise and timely analysis and medical decision support.

Healthcare providers need to be proactive and address care customers, intervening before they notice their health condition is affected. Diagnosis and treatment are not bound to fixed places, but can occur near any place where the care customer is. Many chronic disorders will be treated at home with active implantable medical devices (bioelectronic medicines), which may be enhanced by body sensor networks. In addition to electronics, advanced biocompatible materials may be used as stimulators.

2.3.2.2. Scope and ambition

Just products, or point solutions, are not sufficient anymore. Care solutions need to be holistic and integrated services, combining information across all phases of the continuum of care from many sources, preventing, preparing and providing care based on the person specific characteristics, taking co-morbidities into account. Predictive and preventive care is based on information originating from massive and continuous data collection and analysis of individuals and populations.

Given the ageing of the population, the incidence of co-morbidity is growing rapidly. To make electronic treatment with Active Implantable Medical Devices (AIMDs) viable, these AIMDs will have to coexist with each other within a single patient. Furthermore, there will be a coexistence between mainstream diagnostic and therapy systems in hospitals and implantable devices.

←

[50] *EU industry here means the full Large Industry + SME + RTO + University eco-system*

An important aspect is to deal with the many different formats in which data are and will be collected. Because of the large variety in bandwidth and information range, and also the differences in age of the equipment, it is unrealistic to assume that all devices and sensors will use the same protocol. Therefore, analysis and decision support will be based on incoming information in many protocols.

2.3.2.3. High priority R&D&I areas

- From products to integrated solutions and services
- Improved biomedical models of the health situation of healthcare customers, taking heterogeneous, longitudinal (image) data, context and population information into account
- Use large heterogeneous data from many sources to obtain precise information
- Ensure low-latency analysis and reasoning involving 2D, 3D and 4D images, and prompt delivery of precise results, also in situations with partial and imperfect data
- Longitudinal monitoring and data analysis of many patients applying AI techniques, leading to precise alarms only when needed
- Remote diagnosis and treatment delivery based on advanced user interaction models and collaboration models involving the healthcare customer and the healthcare practitioners
- Development of smart catheters used in (image-guided) treatment and specialised operating theatres (e.g. Cathlabs)
- Development of active or passive implantable medical devices for chronic disorders currently not treated or treated by life-long pharmacy (e.g. stimulators for spinal cord disorders, depression, obesity, hypertension and immunomodulation)
- Development of surgical robots
- Development of novel regenerative medicine solutions
- Development of technologies such as smart body patches and monitoring implants for continuous monitoring, e.g. bringing clinical trials to the home
- Mutual coexistence between implants and mainstream diagnostic systems is a high priority research area stretching from basic electromagnetic compatibility aspects to communication protocols and harmonised cloud analysis interfacing
- Diagnostic imaging equipment with sufficient accuracy for active/passive implantable medical devices placement, preventing trial-and-error approach
- Development and industrialisation of radiation-free imaging and guidance technologies based on e.g. ultra-sound, optical shape sensing, or electromagnetic sensing

2.3.2.4. Competitive situation

The current AIMD market is mainly governed by US companies Medtronic, Abbot and Boston Scientific. Nevertheless, in Europe a variety of start-ups, SMEs, large enterprises and the presence of two major healthcare diagnostic players, Siemens and Philips, are leading to promising market expectations.

For regenerative medicine, there are no big players yet, but there is a large number of start-up companies active that are being closely watched by the established industry.

Start-ups, SMEs are the most active players for introducing disruptive innovations in healthcare and wellbeing. Their innovation is industrialised and commercialised worldwide by large companies. The close collaboration between start-ups, SMEs and large companies is essential to strengthening the ecosystem.

2.3.2.5. Expected achievements

- Integrated solutions and services for specific disease groups, for customer groups, and for populations, covering parts of the care cycle
- Applicable biomedical models for specific disease groups, for customer groups, and for populations, covering parts of the care cycle, taking heterogeneous data involving history, context or population information into account
- Low-latency (large image) data analysis and reasoning and dependable delivery of results
- Long-term monitoring and data analysis of patients with chronic diseases, leading to decision support with a low level of false alarms
- Effective remote diagnosis and (image-guided) treatment delivery involving collaboration between the healthcare customer and the healthcare practitioners
- High quality of life for patients with damaged of dysfunctional body parts, reducing lifetime costs
- More accurate (higher precision) diagnostic imaging
- Faster and less costly drug development

2.3.3. Restructuring healthcare delivery systems, from supply-driven to patient-oriented

2.3.3.1. Vision

Today healthcare costs are mainly based on demanding fixed prices for fixed, predefined, treatments at moments when the health problem unavoidably disturbs the life of the patient. Large amounts of images will be combined with other sensor data and biomedical models to get precise, quantified information about the person's health condition. 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. Additionally, imaging will be improved to become less harmful and less expensive.

For chronic patients, the costs are determined by long-term pharmaceutical prescriptions and irregular treatments, when the disease gets severe. However, patient centric healthcare demands prevention, early diagnosis before suffering, and continuous care in the case of (multiple) chronic diseases. Outcome based healthcare will predict the outcome of a disorder and its treatment for a patient much faster. At its core is maximising value for patients: that is, achieving the best outcomes at the lowest cost [51]. Not the number of treatments but the optimal value for the patients will become the driver of care. In addition, care centres will not be organised according to general hospitals that serve any disease. Instead, they will specialise to

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[51] https://hbr.org/2013/10/the-strategy-that-will-fix-health-care

specified disease types, to improve the total outcome. These centres will act not only for visiting patients but, increasingly, through remote access, for patients anywhere in the world.

2.3.3.2. Scope and ambition

The goal of outcome based healthcare is to improve value for patients, without increasing the costs, and preferably lowering the costs. This demands that reimbursement schemes have to be changed, allowing more cost-effective care involving prevention, early detection and treatment, and continuous monitoring of chronically ill patients. Outcome based healthcare will learn and adopt optimisation practices common in industry. The ambition is that outcome based healthcare will improve the predictability of diagnosis and treatment.

2.3.3.3. High priority R&D&I areas

- Holistic healthcare involving all imbalanced health situations of the patient
- Use of the (growing) whole body of medical knowledge during diagnosis, (image-guided) treatment and monitoring
- EHR involving patient health models supporting precise communication between different care givers
- EHR involving health models that exactly describe the outcome heath values for the patients, both short and long term
- Transform large healthcare systems to optimise hospital workflow, automatically optimise diagnostic imaging and tracking of therapy results, enable preventive maintenance and generation of requirements and test cases for new generations of systems
- Predictable and repeatable outcome of diagnostic imaging. Current diagnostic imaging is often of a qualitative nature, meaning that comparison over time or with other patient cases is impossible
- Apply generic standards (e.g. industry 4.0) to diagnostic and therapy systems and use of big data principles to reduce cost of ownership
- Create and apply biomedical models for AI based automation, visualisation and decision support, to get precise, quantified information of the person’s health condition. This needs large amounts of images and other sensor data at many levels: from molecular imaging up to whole body imaging
- Less harmful and less expensive imaging modalities at several levels: from molecular imaging up to whole body imaging, in the prevention, diagnosis, therapy and monitoring phases
- Humanoid robots applying interpreted human body language and emotion in care delivery
- Robotics to improve treatments either in the operating room, minimal invasively inside the body, at general practitioners or at home
- 3D Printing and CNC (Computerised Numerical Control machining): printing implants and prosthetics for individuals, create patient-specific anatomical models, e.g. create powered exoskeleton to help paraplegics to walk again

2.3.3.4. Competitive situation

Two of the three major diagnostic imaging and image-guided intervention companies (Philips and Siemens) are based in Europe. Competition from China (e.g. United Imaging) and Korea (Samsung) is emerging, driving the need for faster innovation at lower cost in Europe.

2.3.3.5. Expected achievements

- Healthcare delivery for patients with co-morbidities
- Preventive and early warnings for (combine) diseases
- Image analysis and decision support for diagnosis, treatment and monitoring, using large medical knowledge bases

- Quantitative, less harmful and less expensive imaging for diagnosis and therapy
- Patient health models on complex heath conditions
- Outcome based treatment, diagnosis and monitoring health models
- Healthcare systems, IoT with big data learning for optimising workflow, usage, capabilities and maintenance
- Repeatable and quantifiable outcome of diagnosis (including the use of biomarkers) and treatment

2.3.4. Engaging individuals more actively in their own health and wellbeing

2.3.4.1. Vision

In 2030, digitalisation will be common in our society, and will bring healthcare from clinical centres into the everyday life of the citizen, in health and vitality promotion as much as for healthcare and disease prevention. Highly motivated individuals will improve their vitality by using wearables and connected software, thus enabling adjustment of personalised models that make them increasingly aware about the impact of body movement, food and nutrition on their health. The development of digital health ecosystems (comprising digital health platforms, health monitoring wearables and devices, mobile applications and online services) will empower individuals to monitor against a norm, manage, track and improve their own health. This will open new markets of solutions and services directly targeted at both healthy and patient individuals, and positively impact the effect of preventive practices as well as on the application of treatments earlier.

2.3.4.2. Scope and ambition

A motivated and educated population will take preventive measures. Collection of long-term data will contribute to early capture of a disease or disorder, which will increase probability of fast and successful treatment.

The ecosystem of healthcare solutions targeted at individuals is growing fast. The competition is pushing the improvement of features provided and quality of service as well as the specialisation. Smart algorithms for different purposes will be developed and specialised marketplaces will emerge; the demand and supply of data analytics will push the creation and sharing of data sources; precision medicine will follow the two previous building blocks.

2.3.4.3. High priority R&D&I areas

- Wearables or minimally invasive implants, Internet of Things, simple analysers for home use; reliable data collection and analysis – focus on input data quality assessment (we need to know whether we evaluate useful data or noise and artefacts); standardisation of calibration, process interoperability
- Devices or systems for utilising/extracting/sharing new knowledge in the most informative and efficient manner (e.g. vitality data, molecular profiling, biotechnology, diagnostics, ICT tools) in the most appropriate personalised setting (e.g. healthcare system, at home)
- Devices or systems for protecting and enforcing individual health-related information: ownership and secure storage of health data, data sharing with healthcare providers, and rendering real-time anonymity for wider data analytics
- Devices or systems improving security for executing transactions in healthcare and wellbeing, like blockchains to improve health or personal records exchanges and interact with stakeholders
- Devices or systems for integration of health and prevention ICT solutions in national health systems.

2.3.4.4. Competitive situation

A major development is the rapid development in the wearable technology and devices market. According to a research report conducted by Transparency Market Research, the wearable devices market, or the remote patient monitoring devices market, is anticipated to reach USD 0.98 billion by the end of 2020. This represents 14.2% CAGR. Top players are Biotricity Inc., Abbott Laboratories, Apple, Alphabet, Business Machines Corp.

Three groups are fighting a war for control of the "healthcare value chain":

- One group comprises "traditional innovators" – pharmaceutical firms, hospitals and medical-technology companies such as GE Healthcare, Siemens, Medtronic and Philips.
- A second category is made up of "incumbent players", which include health insurers, pharmacy-benefit managers (which buy drugs in bulk), and single-payer healthcare systems such as UK NHS.
- The third group are the technology "insurgents", including Google, Apple, Amazon and a host of hungry entrepreneurs that are creating apps, predictive-diagnostics systems and new devices. These firms may well profit most handsomely from the shift to digital.

2.3.4.5. Expected achievements

- Repeatable and quantifiable outcome of vitality and prevention.
- Early diagnostics based on assessment of longitudinal patient data.
- New models of person-centred health delivery, also integrating health and social care and considering the environment and community setting of the individual. Transition to a decentralised model, from traditional healthcare venues like hospitals to integrated care models (e.g. transfer of records to patients);
- Empowerment of the individual to manage his data: individuals taking greater ownership of his/her state of health, especially for those with chronic conditions.

2.3.5. Ensuring affordable healthcare for the growing amount of chronic, lifestyle related diseases and an ageing population

2.3.5.1. Vision

Most of the chronic and lifestyle related diseases and elderly diseases need long-term monitoring of the patient's state and rehabilitation support. Current rehabilitation and physiotherapy are labour-intensive, thus the machine supported rehabilitation and physiotherapy could contribute to higher efficiency of the work.

According to several foresight studies[52], in 2030 priorities will lie with promoting healthy lifestyles, preventing illness and prompt cure while supporting vulnerable people and enabling social participation.

2.3.5.2. Scope and ambition

Modular rehabilitation devices with intelligent real-time feedback to the user can enhance the efficiency of treatment. Gamification of the interaction may contribute to motivation of the user. Modularity of the devices allows for personalisation of the treatment. Basic components will be built on Industry 4.0 principles.

2.3.5.3. High priority R&D&I areas

- Wearables or minimally invasive implants, including new sensor systems for easier and more efficient measurement of physiological parameters, incl. posture, sitting position, physical activity, dynamics of walking, etc

- Devices or systems using biomedical models for better diagnostics, therapy and feedback to the patient for several chronic diseases e.g. musculoskeletal system and simulation of activity of muscle groups, joints, etc.
- Devices or systems using predictive models to anticipate the appearance of co-morbidities because of the evolution of chronic diseases
- Real-time location services with badges that can track patients, staff and medical devices, Environmental monitoring — for example, checking hand hygiene compliance. Mobile apps will replace traditional physician visits
- Devices and systems that improve drug adherence especially for expensive biological drug therapies

2.3.5.4. Competitive situation

Few companies exist that focus on development of precise models, e.g. Dassault systems. In the area of rehabilitation there are companies producing exoskeletons, e.g. ReWalk, Cyberdyne, Ekso Bionics Holdings.

2.3.5.5. Expected achievements

- Focus on wellbeing and prevention to identify trends towards ill health and so strive to keep people away from unnecessary care and to encourage them to be proactive
- Person-oriented approaches for the treatment of patients with multiple chronic diseases, situations of frailty and/or of loss of functionalities in a multi-cultural context
- Individuals taking greater ownership of his/her state of health, especially for those with chronic conditions
- Modular systems adjustable to individuals' needs. Gamification will increase motivation of the patients

2.3.6. Developing platforms for wearables/implants, data analytics, artificial intelligence for precision medicine and personalised healthcare and wellbeing

2.3.6.1. Vision

In 2030, technologies such as wearable devices, remote diagnostics, tele-medicine and personalised medicine will be successfully developed to reduce inefficiencies and improve access to healthcare, with apps providing innovative platforms. These devices will generate enormous volumes of data. The role of digital health platforms, wearables or minimally invasive implants and mobile devices will evolve beyond remote health monitoring and reporting towards smarter tools able to make early decisions, both for medical professionals and the customer and his/her relatives, especially in cases where quick action is needed (e.g. brain stroke prevention). This will enable new approaches to early disease detection, prevention and treatment, paving the way for personalised treatments.

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[52] *National Institute for Public Health and the Environment (2014) A healthier Netherlands: Key findings from the Dutch 2014 Public Health Status and Foresight Report. RIVM, Netherlands.*

Furthermore, professional data, data originating from a person's wearables or minimally invasive implants, and environmental sensors will be integrated into relevant information about that person's health condition. This information will become the main source of decision support that alerts caregivers and the persons themselves about situations that endanger heath. Health measurements will combine both cheap retail products, sensors and certified healthcare measuring devices. Dependent on the person's condition, more or fewer certified products will be used.

2.3.6.2. Scope and ambition

Mobile devices and wearables will leverage advances in diagnostics, integrating sensor scanning, data recording and data analysis. New pharmaceuticals and treatments will be developed for personalised medicine settings by embedding connected devices and exploiting the potential of IoT and AI. AI (machine-learning, deep learning and related) will be the key differentiator for any smart health device. Smart algorithms and specialised predictive models will be developed, with specialised marketplaces emerging. Data analytics demand will push the creation and sharing of data sources, as well as the development of mechanisms (e.g. distributed ledgers) to protect the transmission of health data records across the healthcare value chain.

The aim is to deliver preventive and early care to everybody, wherever they may be, based on personalised models. Care is provided by combining many sensor inputs, personal historical information and analysing it according to their healthcare merits.

2.3.6.3. High priority R&D&I areas

- Smart, robust, secure and easy to use devices or systems (wearable or implantable and autonomous) for detection, diagnostic, therapy, through big data, artificial intelligence, machine learning, deep learning person-centred
- Multi-modal data fusion devices or systems: the generation of enormous amounts of data from different sources (e.g. vital signs from mobile apps, home monitoring, real-time sensors, imaging, genomic data, pharmaceutical data, and behavioural markers) brings valuable information to improve clinical decisions and to reveal entirely new approaches to treating diseases. But the fusion of multi-modal data poses several technical challenges related to modelling, data mining, interoperability, data share keeping privacy
- Scalable platforms able to support the automatic deployment and maintenance of applications for digital health, guaranteeing Service Level Agreements and Security for data
- Energy efficiency for medical wearables/implants: Improvement of energy consumption and battery life at device levels. Ability to deliver connected devices (wearable/implants) that are self-sustainable from an energy point of view for the full duration of a medical treatment (weeks, months or years)
- Sustainable, renewable or harvested long-term highly integrated energy sources or devices
- Upgradability of medical wearables/implants: A wearable/implant must be able to adapt to several configurations in the function of the evolution of a disease and improvements in its treatment. The upgrade/downgrade must not imply obsolescence of the wearable/implant. Therefore, a supporting wearable infrastructure should support the possibility of running virtual devices that complement the processing power and storage embedded in wearables/implants
- Highly dependable (reliable, secure, safe, privacy supporting, easy to use, …) IoT platforms
- Devices or systems data with low-latency analysis performed with deterministic algorithms or deep learning that are able to deal with known levels of trust (both high and low) for precise presentation of the results to medical professionals and non-professionals
- Devices or systems based on cognitive computers providing support to professionals or non-professionals for healthcare or wellbeing

2.3.6.4. Competitive situation

The digital health market is fragmented geographically, with large companies, local small players and start-ups competing together in different regions. Globally, North America is expected to retain the highest market share (the US being the dominant market in this region), followed by Western Europe (Germany) and Asia (China)[53]. Major global players include European companies (Philips, Siemens, Lifewatch, Bosch Healthcare, SAP), although US companies dominate the global landscape (GE Healthcare, Qualcomm, McKesson Corporation, AT&T, IBM, Cerner Corp., Cisco, eClinicalWorks, athenahealth), followed by emerging competitors from China (iHealthLabs, Alibaba Health Information Technology, Tencent, Baidu). Major IT technology players are also positioning in the market, with solutions leveraging data analytics: IBM, Microsoft, Google, Apple and Amazon.

2.3.6.5. Expected achievements

- Better understanding of treatment response and prognostic heterogeneity. More refined, patient tailored approaches to disease detection, prevention and treatment
- Better integration and analysis of multi-modal data, providing new tools for clinical decision-making and precision medicine. Development of dynamic healthcare systems that learn in real-time from every result
- New technologies for early diagnostics, personalised medicine and potential curative technologies (e.g. regenerative medicine, immunotherapy for cancer). Development of a wider European market offer of wearable and mobile devices for healthcare
- Repeatable and quantifiable outcome of diagnosis and treatment. Adjustment of treatment based on intermediate/ continuous data evaluation.
- Dependable IoT platforms
- Models for levels of trust of sensor data and data quality
- Low latency analysis algorithms that are able to deal with known levels of trust (both high and low) of sensor data
- Presentation of analysis results to medical professionals and healthcare customers

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[53] *Global Market Insights: Digital Health Market forecasts 2016-2024. November 2016.*

2.4. **TIMEFRAMES**

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Major challenge 1: MOVING HEALTHCARE FROM HOSPITALS INTO OUR HOMES AND DAILY LIFE REQUIRING PREVENTIVE AND PATIENT CENTRIC CARE

1.a From products to integrated solutions and services

1.b Improved biomedical models of the health situation of healthcare customers, taking history, context and population information into account

1.c Use large heterogeneous data from many sources to obtain precise information

1.d Ensure low-latency analysis and reasoning involving 2D, 3D and 4D images, and prompt delivery of precise results, also in situations with partial and imperfect data

1.e Longitudinal monitoring and data analysis of many patients applying AI techniques, leading to precise alarms only when needed

1.f Remote diagnosis and treatment delivery based on advanced user interaction models and collaboration models involving the healthcare customer and the healthcare practitioners

1.g Development of smart catheters used in (image guided) treatment and specialised operating theatres (e.g. Cathlabs)

1.h Development of active or passive implantable medical devices for chronic disorders currently not treated or treated by life-long pharmacy (e.g. stimulators for spinal cord disorders, depression, obesity, hypertension and immunomodulation)

1.i Development of surgical robots

1.j Development of novel regenerative medicine solutions

1.k Development of technologies such as smart body patches and monitoring implants for continuous monitoring, e.g. bringing clinical trials to the home

1.l Mutual coexistence between implants and mainstream diagnostic systems is a high priority research area stretching from basic electromagnetic compatibility aspects to communication protocols and harmonised cloud analysis interfacing

1.m Diagnostic imaging equipment with sufficient accuracy for active/passive implantable medical devices placement, preventing trial-and-error approach

1.n Development and industrialisation of radiation-free imaging and guidance technologies based on e.g. ultra-sound, optical shape sensing, or electromagnetic sensing

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Major challenge 2: RESTRUCTURING HEALTHCARE DELIVERY SYSTEMS, FROM SUPPLY-DRIVEN TO PATIENT-ORIENTED

2.a	Holistic health care involving all imbalanced health situations of the patient
2.b	Use of the (growing) whole body of medical knowledge during diagnosis, treatment and monitoring
2.c	EHR involving patient health models supporting precise communication between different care givers
2.d	EHR involving health models that exactly describe the outcome heath values for the patients, both short term and long term
2.e	Transform large healthcare systems to optimize hospital workflow, automatically optimize diagnostic imaging and tracking of therapy results, enable preventive maintenance and generation of requirements and test cases for new generations of systems
2.f	Predictable and repeatable outcome of diagnostic imaging. Current diagnostic imaging is often of qualitative nature, meaning that comparison over time or with other patient cases is impossible
2.g	Apply generic standards (e.g. industry 4.0) to diagnostic and therapy systems and use of big data principles to reduce cost of ownership
2.h	Create and apply biomedical models for AI based automation, visualisation and decision support, to get precise, quantified information of the person's health condition. This needs large amounts of images and other sensor data at many levels: from molecular imaging up to whole body imaging
2.i	Less harmful and less expensive imaging modalities at several levels: from molecular imaging up to whole body imaging, in the prevention, diagnosis, therapy and monitoring phases
2.j	Robotics to improve treatments either in the operating room, minimal invasively inside the body, at general practitioners or at home. Robotics can also be used to improve treatments either in the operating room or inside the body or at home.
2.k	3D Printing and CNC (Computerised Numerical Control machining): printing implants and prosthetics for individuals, create patient-specific anatomical models, e.g. create powered exoskeleton to help paraplegics to walk again.

Major challenge 3: ENGAGING INDIVIDUALS MORE ACTIVELY IN THEIR OWN HEALTH AND WELLBEING

3.a	Wearables or minimal invasive implants, Internet of Things, simple analyzers for home use; reliable data collection and analysis – focus on input data quality assessment (we need to know whether we evaluate useful data or noise and artifacts); standardization of calibration, process interoperability
3.b	Devices or systems for utilizing/extracting/sharing new knowledge in the most informative and efficient manner (e.g. vitality data, molecular profiling, biotechnology, diagnostics, ICT tools) in the most appropriate personalized setting (e.g. health care system, at home).
3.c	Devices or systems for protecting and enforcing individual health-related information: ownership and secure storage of health data, data sharing with healthcare providers, and real-time anonymization for wider data analytics
3.d	Devices or systems for integration of health and prevention ICT solutions in national health systems.

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Major challenge 4: ENSURING AFFORDABLE HEALTHCARE FOR THE GROWING AMOUNT OF CHRONIC, LIFESTYLE RELATED DISEASES AND AN AGEING POPULATION

4.a Wearables or minimally invasive implants, including new sensor systems for easier and more efficient measurement of physiological parameters, incl. posture, sitting position, physical activity, dynamics of walking, etc

4.b Devices or systems using biomedical models for better diagnostics, therapy and feedback to the patient for several chronic diseases e.g. musculoskeletal system and simulation of activity of muscle groups, joints, etc.

4.c Devices or systems using predictive models to anticipate the appearance of co-morbidities because of the evolution of chronic diseases

4.d Real-time location services with badges that can track patients, staff and medical devices, Environmental monitoring – for example, checking hand hygiene compliance. Mobile apps will replace traditional physician visits

4.e Devices and systems that improve drug adherence especially for expensive biological drug therapies

Major challenge 5: DEVELOPING PLATFORMS FOR WEARABLES/IMPLANTS, DATA ANALYTICS, ARTIFICIAL INTELLIGENCE FOR PRECISION MEDICINE AND PERSONALISED HEALTHCARE AND WELLBEING

5.a Smart, robust, secure and easy to use devices or systems (wearable or implantable and autonomous) for detection, diagnostic, therapy, through big data, artificial intelligence, machine learning, deep learning person-centered

5.b Multi-modal data fusion devices or systems: the generation of enormous amounts of data from different sources (e.g. vital signs from mobile apps, home monitoring, real-time sensors, imaging, genomic data, pharmaceutical data, behavioral markers) brings valuable information to improve clinical decisions and to reveal entirely new approaches to treating diseases. But the fusion of multi-modal data poses several technical challenges related to modelling, data mining, interoperability , data share keeping privacy

5.c Scalable platforms able to support automatic deployment and maintenance of applications for digital health/wellbeing, guaranteeing Service Level Agreements and Security for data.

5.d Energy efficiency for medical wearables/implants: Improvement of energy consumption and battery life at device levels. Ability to deliver connected devices (wearable/implants) that are self-sustainable from an energy point of view for the full duration of a medical treatment (weeks, months or years)

5.e Sustainable, renewable or harvested long term highly integrated energy sources or devices

5.f Upgradability of medical wearables/implants: A wearable/implant must be able to adapt to several configurations in the function of the evolution of a disease and improvements in its treatment. The upgrade/downgrade must not imply obsolescence of the wearable/implant. Therefore, a supporting wearable infrastructure should support the possibility of running virtual devices that complement the processing power and storage embedded in wearables/implants

5.g Highly dependable (reliable, secure, safe, privacy supporting, easy to use, ...) IoT platforms.

5.h Devices or systems data with low-latency analysis performed with deterministic algorithms or deep learning that are able to deal with known levels of trust (both high and low) for precise presentation of the results to medical professionals and non-professionals

5.i Devices or systems based on cognitive computers providing support to professionals or non-professionals for healthcare or wellbeing

research or TRL 2-4; *development or TRL 4-6;* *pilot test or TRL 6-8*

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

F.26 *Timeframe 2020–2030*

2.5.
SYNERGIES WITH OTHER THEMES

In the chapters **Transport & Smart Mobility** and **Digital Industry** new industrial processes are explored to optimise industrial processes, a cooperation between these domains and the Health and Wellbeing domain can be useful to support the major challenge “Restructuring Healthcare Delivery Systems”.

Digitisation is a main driver in **Transport & Smart Mobility** and **Digital Life** and challenges related to the use of data, trust, safety and security are shared with the other domains.

Challenges on **Connectivity and Interoperability** and **Safety, Security and Reliability** are shared with most of the application domains especially relevant for the Health and Wellbeing chapter with the emerging Internet of Things (IoT) entering the hospital.

3

Energy

3.1. EXECUTIVE SUMMARY

The energy world is in transition: different energy sources are linked to achieve high efficiency, reliability and affordability. Renewable energy sources, such as solar and wind power, are changing the nature of the world's power grids. The centralised power generation model is gradually turning into a distributed one, causing today's unidirectional power flows to become bidirectional. This situation requires intelligence and security features at each level of the grid and interfaces. Micro- and nano-electronics, integrated into power electronic modules and systems, are essential for an efficient, reliable and secure management of power generation, transmission, storage and consumption through smart grids, safe and secure system applications and devices.

All stakeholders of the European ECS industry, including nano-electronics, electronic device manufacturers and systems integrators (OEMs), together with the research institutes, contribute with innovative solutions, based on long-term continuous research on all Technology Readiness Levels (TRLs), to achieve the targets jointly agreed by the Industry and the European Commission.

Significant reduction of the primary energy consumption, along with reduced carbon dioxide emissions, is the key objective of the Energy chapter. ECS are key enablers for higher efficiency and intelligent use of energy along the whole energy value chain, from generation to distribution and consumption. Enhancing efficiency in the generation and distribution as well as reducing energy consumption and carbon footprint are the driving forces for the research in nano-/micro-electronics, and in embedded and integrated systems, to secure the balance between sustainability, cost efficiency and reliability of supply in all energy applications.

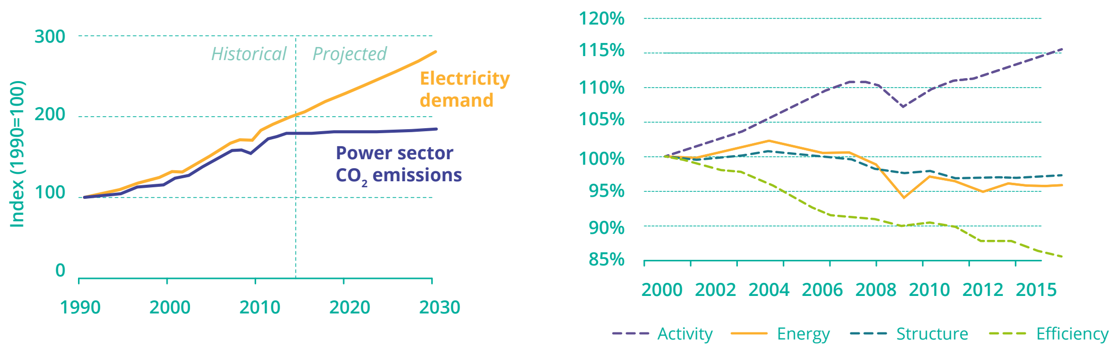
3.2. RELEVANCE

3.2.1. Competitive Value

In recent years, it has become apparent that semiconductor-based innovative technologies have enabled more electrical energy savings than the growth in demand in the same period. The core of the European competitive advantage is in system knowledge and the provision of holistic system solutions. Saving energy is equivalent to reducing the costs and being more competitive. Energy efficiency levels in the IEA member countries improved, on average, by 14% between 2000 and 2015. This generated energy savings of 19 exajoules (EJ) or 450 million tonnes of oil equivalent (Mtoe) in 2015. These savings also reduced total energy expenditure by USD 540 billion in 2015, mostly in buildings and industry. While GDP grew by 2% in IEA countries, the efficiency gains led to flattening of the growth in primary energy demand. In parallel, global CO_2 emissions have risen at a rate of 1,5% per year in the last decade, stabilizing only briefly between 2014 and 2016. Fossil CO_2 emissions from energy use and industry, which dominate total GHG emissions, grew 2.0 per cent in 2018, reaching a record 37.5 Gt CO_2 per year (source: United Nations Environment Programme, Emissions Gap Report 2019). The stabilization and the slower increase is a result of lower coal consumption, higher energy efficiency and increased renewable power generation, particularly wind and solar power[54].

Energy saving is also an opportunity. In fact, by reducing power dissipation and corresponding heat production, energy is available for other uses and equipment.

GROWTH IN WORLD ELECTRICITY DEMAND AND RELATED CO_2 EMISSIONS



Source: World Energy Outlook Special Briefing for COP21 (2015)

Source: adapted from IEA Energy efficiency market report, 2016, based on IEA energy efficiency indicators database

F.27 *Growth in world electricity demand and related CO_2 emissions 2018-2030*

According to IEA, the analysis of factors driving energy consumption trends in IEA member countries indicates that the decoupling was mainly due to efficiency improvements (figure upper right). Structural changes (mostly a shift to less-intensive industries and services) also assisted in efficiency improvements by reducing total energy consumption. Cumulative savings over the period 2000 – 2015 were 159 EJ, equivalent to more than one year of final energy consumption in Europe, China and India combined.[55]

Examples of the most important ECS applications having high impact on the efficient use and generation of energy are power inverters – a steadily growing market (USD 65 billion forecasted for inverters in 2020[56]).

Another example of ECS market contributing to the efficient use of energy is the wireless infrastructure RF power device market, with around USD 1 billion TAM. The share of GaN based devices is expected to increase from 10% in 2015 to 40% in 2022 (source ABIresearch, 2017), which demonstrates how fast new techniques can be deployed if the added business value is achieved. Driven by new developments, such

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54 *Trends in global CO_2 and total greenhouse gas emissions: 2017 Report; © PBL Netherlands Environmental Assessment Agency; The Hague, 2017; PBL publication number: 2674*

55 *Energy efficiency indicators by OECD/IEA – Highlights 2016*

56 *Power Integrated Circuit 2017 – Quarterly Update – Yole Développement*

Industrial 4.0 example (Source Hannover Messe conferences)

F.28

as the electro mobility and Industry 4.0, new energy supply chains and consumption patterns are emerging. Powering the electro mobility is a major challenge in the coming years with the implementation of a reliable and sustainable charging infrastructure.

The potential of the emerging industrial era 4.0 is based on the combination of novel technologies: Cyber-Physical Systems (CPS), Internet of Things (IoT) and Artificial Intelligence (AI). Higher efficiency at all levels in power usage is one enabler for Smart Industry: Power conversion & energy harvesting, Power Management, Power storage & Motor Control (see figure above).

European ECS companies are among the leaders in smart energy related markets, which is largely driven by political decisions as well as by the move to renewing energies and to added costs on carbon dioxide emissions. Leading market positions are achieved in electrical drives, grid technology and decentralised renewable energy sources. This position will be strengthened and further employment secured by innovative research at the European level. Competitive advantages can be gained by research in the following areas:

1. Significant reduction and recovery of losses (application and SoA-related);
2. Increase of power density and a decrease of system size by miniaturisation and integration, on the system and power electronics level;
3. Increased functionality, reliability and lifetime (incl. sensors & actuators, ECS HW/SW, artificial intelligence and machine learning, monitoring systems …);
4. Manufacturing and supply of energy relevant components, modules and systems;
5. The game changer to renewable energy sources and decentralised networks, including intermediate storage;
6. Energy supply infrastructure for e-mobility, digital live and industry 4.0;
7. “Plug and play integration” of ECS into self-organised grids and multi-modal systems;
8. Safety and security issues of self-organised grids and multi-modal systems;
9. Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.
10. ECS for storage solutions.

3.2.2. Societal benefits

The ECS for energy (incl. components, modules, CPS, application software), which supports the EU and national energy targets, will have a huge impact on job generation and education if based on the complete supply chain and fully developed in Europe. Key will be the capability to maintain complete systems understanding and competence from small-scale solutions up to balanced regional energy supply solutions. It is mandatory to have plug-and-play components enabled by broad research contributions from SMEs and service providers, including EU champions in the energy domain. Thanks to the expected wider proliferation of energy storage devices in the smart city context, new distributed forms of energy storage will become available, to be exploited by smart control systems, based as well on artificial intelligence enabled solutions.

Societal benefits include access to knowledge, development of modern lifestyle and the availability of energy all the time and everywhere – with a minimum of wasted energy and a minimum of greenhouse gas emissions. Applications having a huge energy demand and therefore a large saving potential are in the areas of High Performance Data centres serving the mobile connected world, the implementation of Smart Cities and the future implementation of e-mobility with widely distributed charging stations, demanding a higher density of energy distribution points with, as a key feature, local intermediate storage systems.

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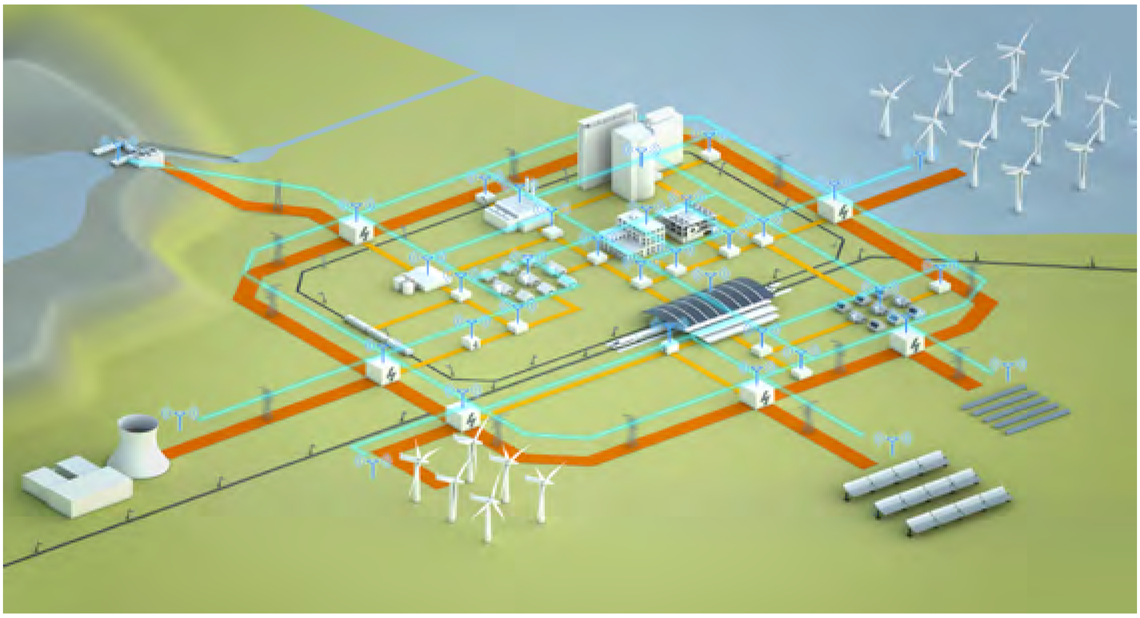
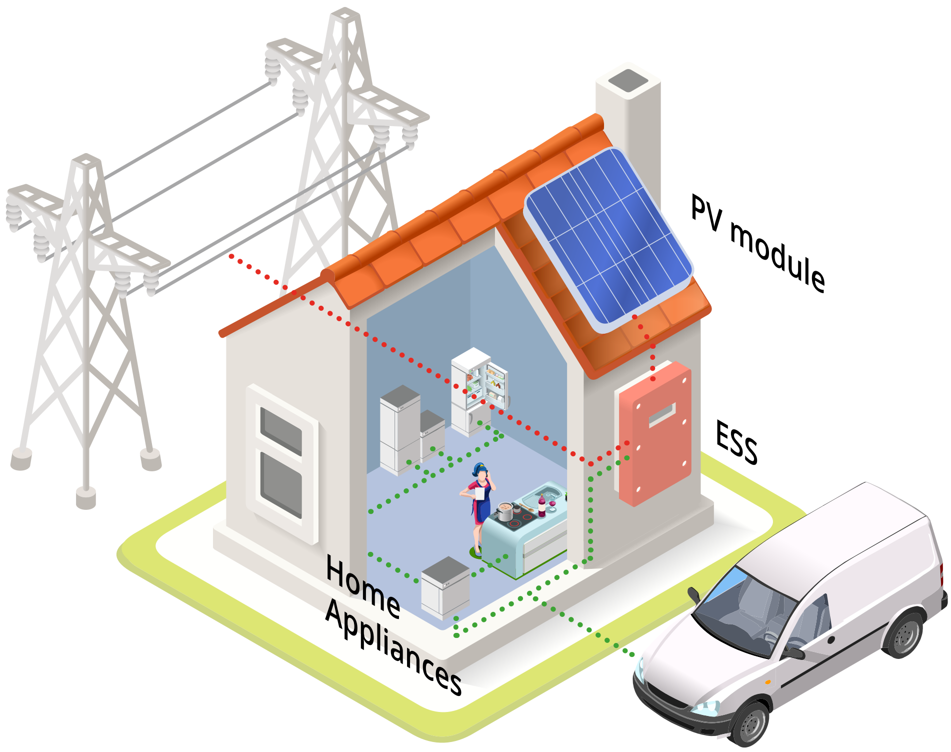
[57] *http://www.ecsel-ju.eu/web/downloads/documents/ecsel_gb_2015_46_-_masp_2016.pdf*



F.29 *Smart Energy landscape – from centralised to distributed (PV, wind, biogas, ...) generation and conversion, consisting of High/Medium Voltage grid (orange), Low Voltage grid (yellow) including Communication Network (aquamarine) linking producers and consumers down to regional and community level (source ECSEL MASP 2016[57]).*

Digitalisation in the smart grid will be one element for delivering smart energy from providers to consumers, and to control appliances at consumer homes to save energy, reduce cost and increase reliability and transparency.



The Prosumer concept. The Power transmission goes from one-way to two-way lines. F.30

Highly innovative technologies guarantee high-value employment. With more than one million jobs in the field of renewable energies and indirectly involved technologies, this is a visible and significant factor for economic and societal stability.

3.3. MAJOR CHALLENGES

3.3.1. SWOT analysis

The following table presents SWOT analysis of the current European position on Energy. The table addresses the potential strengths, weaknesses, opportunities and threats in the energy sector for Europe.

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU ECS industry[58]	**Strengths:** Europe has a leading position. Four European-based power semiconductor suppliers among the top 13, having a combined market share of over 21% in 2018. Three power modules suppliers in the top 10 with a market share of over 35%. The overall share of European suppliers is increasing in this growing market, underlining their competitiveness.	**Weaknesses:** Ability to follow very fast changing environment. Speed of introduction of regulations. "100 years old" established infrastructure to be converted into a highly flexible and dynamic energy supply infrastructure. Technological gap of EU to US and China in development of AI technologies. Market size gap of EU vs Asia (far larger).
External factors To the EU ECS industry	**Opportunities:** Affordable energy conversion efficiencies (93% – 99% or more) allowing better use of renewable energy resources, exploiting new materials, new device architectures, innovative new circuit topologies, architectures and algorithms lowering the total system cost. New infrastructure for EV charging is required. Energy highway through Europe has to be implemented. Emission-free cities require electric approaches. Decentralised smart storage. Distributed DC network & grid technology Efficient management of data and data storage. Introduction and implementation of AI as a key enabler for smart power grids. AI approaches and ECS supply chain for integrated applications in Energy (IoT, wireless for domestic use to optimise energy usage, etc).	**Threats:** Availability of renewable energies in sufficient amount. Oversupply and peak supply challenges for variable energy sources. Availability of batteries and their installation. Distribution grid – complexity of current setup and missing acceptance of new HV and DC grid connection. Missing investments into DC voltage infrastructure since very long-lasting decisions have to be taken in a fast-changing environment. Environmental changes. Fragmented legislation. Legislation not prepared for widespread application of AI technologies.

F.31 *SWOT analysis of the position of the European ECS industry for energy*

3.3.2. Digitalisation & Energy – new approaches including artificial intelligence

Artificial Intelligence and Machine Learning (AI/ML) will have an effect on future energy production, distribution and consumption. A lot of data is already being collected from the production sites, distribution networks and consumers. This data will be used by AI/ML solutions/applications, e.g. to estimate energy demand, optimise energy production, manage energy storages and control the grid performance, based on the consumption patterns and status data of grid devices. AI/ML applications can also control grid-connected devices to minimise the energy consumption and usage cost.

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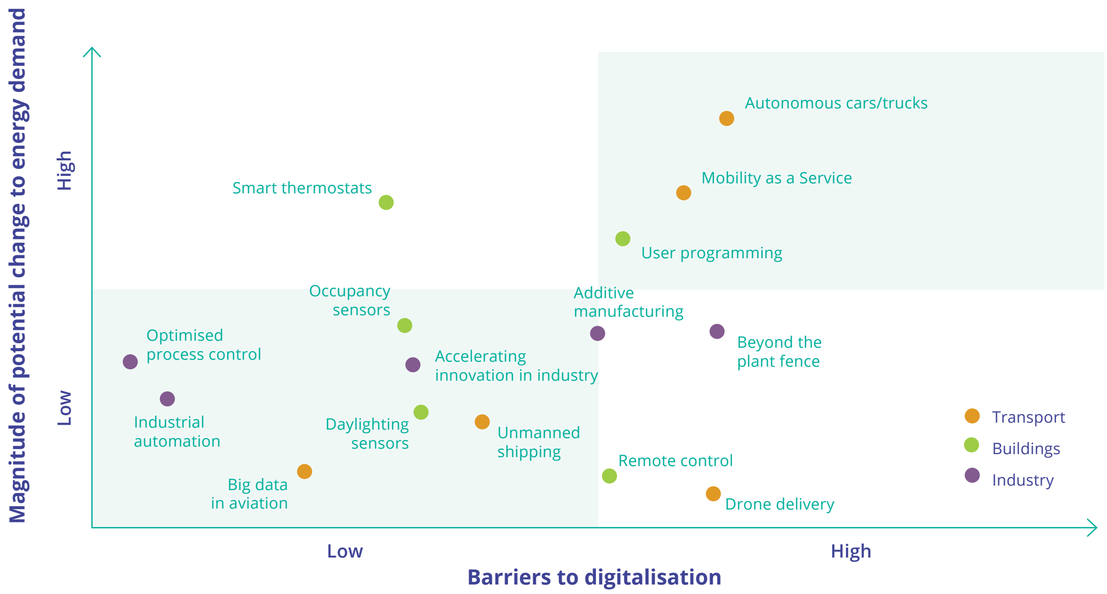
[58] *EU industry here means the full Large Industry + SME + RTO + University eco-system*

→

[59] *http://www.iea.org/publications/freepublications/publication/DigitalisationandEnergy3.pdf*

Having a high potential impact on energy savings, digital technologies and applications face a variety of barriers to adoption and use, and their impact on energy use differ across demand sectors, as shown in the following diagram[59]:



Digitalisation's potential impact on energy demand in transport, buildings and industry (source IEA) F.32

One challenging application for future energy networks is autonomous vehicles – the topic covered more in depth in the transport chapter. The impact of electric autonomous vehicles on energy consumption in the transportation sector is still highly unclear. It has recently been estimated that the adoption of autonomous vehicles could decrease LDV energy usage in the U.S. by around 60% or could increase it by

200% (source EIA[60]). In order to obtain the potential benefits of the digitalisation on transportation, a system-based approach and the use of all advantages of digitalisation and ECS have to be considered.

3.3.3. Major Challenge 1: Ensuring sustainable power generation and energy conversion

3.3.3.1. Vision

The ultimate vision is and will be loss-free energy conversion and generation. A feasible vision is to reach ~99% efficiency by 2020.

3.3.3.2. Scope and ambition

Historically, the topic of Energy Generation can be divided into two main fields: traditional energy generation (e.g. fossil or nuclear power plants) and energy generation based on renewable sources (e.g. wind, solar, hydropower, geo-thermal). In both cases, "raw energy" is produced in a form that cannot be transmitted or used without conversion. A new emerging application in the field of EV is the need for new batteries for energy storage to manage overcapacities and undersupply. Examples are non-continuous energy sources like windmills and solar cells. Using old-fashioned electronics for rectifying, transforming or converting (AC/DC or DC/AC) the currents, only about half of the energy can be used. New, much more dedicated and efficient components have to be developed, partially based on new materials. In general, everything must be done to reduce the lifetime capital and operational expenses (CAPEX and OPEX) of renewable energy generation below those of the traditional energy generation.

3.3.3.3. Competitive situation and game changers

The need for energy is a fact in modern society. The question is how to provide the energy in a resource efficient way and at a cost accepted by the society. Nano-electronics is playing an important role in the generation of renewable energies. Highly efficient conversion leads to fewer investments and therefore lower cost for the renewable energies. CAPEX and OPEX reduction per generated power unit is the only way to compete with traditional energy sources.

In terms of power semiconductors, which are the fuel for energy efficient systems, Europe has a leading position. In 2018, four European-based companies among the top 12 power semiconductor suppliers had a combined market share of over 21%, while three companies among the top 10 power modules suppliers had a market share of over 35%. Overall, the increasing share of European suppliers in this growing market underlines their competitiveness.

←

60 *https://www.eia.gov/outlooks/aeo/pdf/AV.pdf*

3.3.3.4. High priority R&D&I areas

- Affordable energy conversion efficiencies of 93% to 99% or more allowing better use of renewable energy resources, exploiting new materials, new devices architectures, innovative new circuit topologies, architectures and algorithms lowering the total system cost.
- Enhanced device and system lifetime and reliability with effective thermal management ensuring life expectancy for renewable energy systems of 20 to 30 years.
- Developing semiconductor-based solar energy technologies including photovoltaic technologies and integrating them with solid-state lighting applications.
- Reduced physical size and weight of individual transformer stations with equivalent power ratings by the development of solid-state transformers. These actuators will provide new functions for the operation of power systems and avoid infrastructure extensions caused by increasing share of distributed generation.
- Innovative devices exploiting new materials to dramatically increase their power density capabilities to be used in efficient converters, supported by passive elements, new interconnect technologies and packaging techniques to achieve further miniaturisation and further reduce losses.
- New nanomaterials, devices and systems for improving energy efficiency of the growing worldwide renewable energy technologies, such as photovoltaic, wind and hydropower.
- System EMI research to cope with higher switching frequencies and further miniaturisation.
- System reliability enhancement with focus on thermo-mechanical and thermo-electro-mechanical reliability.
- Resilient control strategies and self-healing systems technologies, involving machine-learning capabilities, that enable better use of renewable energy sources, their real-time monitoring, performance prediction, proactive coordination and integration with smart urban systems.
- Smart sensor networks able to measure all internal and external physical parameters that influence energy conversion efficiency and thus help to enable an efficient smart energy landscape. This also includes sensors and AI/ML solutions that support intelligent predictive maintenance concepts resulting in reduced maintenance costs and increased lifetime for equipment and infrastructure.
- Self-powering systems for small IoT nodes have to be developed. The target is that local energy harvesting will substitute battery powered devices and eliminate the high demand of energy for the battery manufacturing and distribution logistics.

3.3.3.5. Expected achievements

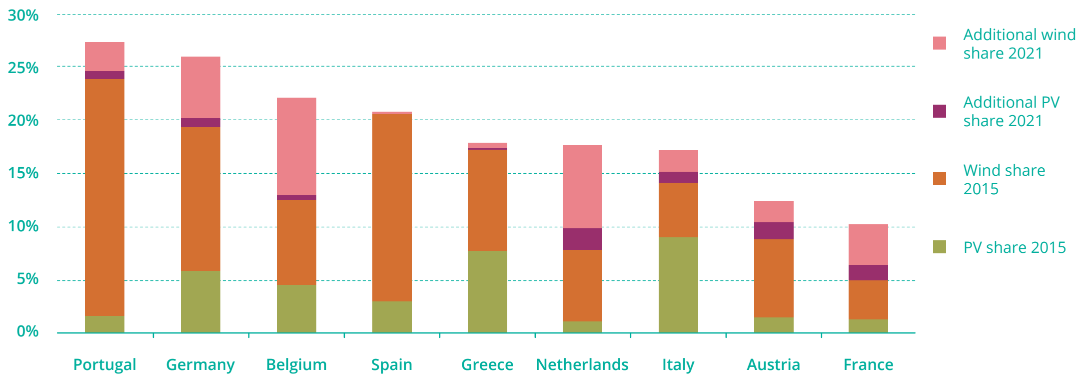
It can be expected that new highly efficient technologies (e.g. wide band gap materials, disruptive innovations based on new processing approaches and architectures) will be introduced and new competitive solutions will lead to a larger share of the power semiconductor market. On the system level, European suppliers are expected to establish their position in the field of resilient control strategies that enable better use of renewable energy sources, their real-time monitoring, performance prediction, proactive coordination and integration with smart urban systems. For the energy supply of the IoT nodes, harvesters and intermediate storages have to be developed to substitute and minimise batteries.

3.3.4. Major Challenge 2: Achieving efficient community energy management

3.3.4.1. Vision

The decentralisation of energy production, opportunities with networked systems, limitations in peak electricity supply, oversupply times, new demand for electric energy supply for the urban mobility and the introduction of storage systems will lead to new challenges in the energy management and distribution for communities and cities.

PV and wind energy are examples that illustrate the change and challenges in energy distribution. Over the last six years, electricity demand in the UCTE countries' grids have slowly decreased, from 2,600 to 2,500 TWh. In the same period, wind and solar PV production has increased by 79% and 338% respectively, reaching 226 TWh and 94 TWh in 2015. This development has led to variable renewable energy (VRE) accounting for 12.8% of total electricity production in 2015. The share of VRE for 2015 and projected for 2021 is shown in the following figure of selected **UCTE countries**[61]:



F.33 *Share of VRE generation in 2015 and 2021 for selected UCTE countries*
Source: Adapted from IEA (2016a), Medium Term Renewable Energy Market Report

3.3.4.2. Scope and ambition

Through the supported technologies highest efficiency and most economic energy supply, distribution and management solutions for communities and smart cities will be reached.

3.3.4.3. Competitive situation and game changers

Advanced control and monitoring systems are already deployed at the transmission network level (high DC voltage). Broad inclusion of small and medium-sized renewable energy sources into the grid and their coordination requires the adoption of control and monitoring systems

61 *Large Scale Electricity Interconnection 2016, IEA*

at the medium voltage level as well. In the medium voltage grids, where small and medium-sized energy sources represent a significant part of the installed energy production potential, real-time monitoring and control of energy flows is needed to enable demand/response management (DRM).

3.3.4.4. High priority R&D&I areas

- Smart Grid applications that exploit demand/response technology in a robust and secure way, negotiating the trade-off between different levels of urgency in energy need with a varying energy price at any given time and accommodating variable renewable electricity;
- Self-organising grids and multi-modal energy systems;
- Improved grid transparency through advanced grid monitoring, including medium and low voltage (MV and LV) levels;
- A highly resilient power grid through the introduction of proactive control algorithms (that go beyond demand/response), significantly improving the grid's self-healing and self-protection capabilities;
- Full implementation of Smart Grid technologies, resulting in the massive deployment of the necessary control options for the complete realisation of the Agile Fractal Grid also including smart agriculture (e.g. greenhouse energy efficiency);
- Smart E-Mobility grid for optimised charging, storage and distribution of electric power for light, medium and heavy vehicle transportation;
- Technological solutions for efficient and smart buildings (indoor) and outdoor subsystems including heating, ventilation, air conditioning and lighting, as well as traffic access, to achieve optimal energy-efficient performance, connectivity and adaptive intelligent management while ensuring scalability and security;
- Fog/cloud computing to offer sufficient and cost-effective processing power and to ease maintenance and update of control software with edge computing to support low-latency applications, such as real-time grid control;
- AI/ML methods and solutions to enable efficient and reliable demand-response driven smart grid control.

3.3.4.5. Expected achievements

Medium voltage level management (utilising DRM) helps to adjust consumption to the production (presently the production is adjusted to match the consumption), promotes the dynamic pricing tariffs that are needed to increase market share of small energy producers and, at the same time, enables the reduction of energy losses by better matching of production and consumption. Improved energy management at the MV level enables risk-free integration of additional renewable energy sources into the grid without any negative impacts on grid stability of the MV an LV micro-grids. Real-time monitoring at the MV level enables the deployment of self-healing MV grid strategies.

The growing impact of e-mobility on the energy infrastructure and management will help to create market success for demand technologies such as the decentralisation of energy & energy storage and fast-charging infrastructure with >150 kW power supply. Future developments will have to consider the infrastructure, as the first 350kW charging stations have already been introduced (Smarte E Fair Munich, 2019) and deliberations about truck charging stations begin.

3.3.5. Major Challenge 3: Reducing energy consumption

3.3.5.1. Vision

The vision for 2030 is to achieve the current EU policy targeted of 30% savings potential by utilising innovative nano-electronics based solutions.

3.3.5.2. Scope and ambition

Three prominent and fast-growing areas are addressed:

- the reduction of power consumption by the electronic components and systems themselves;
- the systems built upon them; and
- the application level in several areas.

Electronic components examples:

- One of the most challenging issues in High-Performance Computing is energy consumption. It is a well-known fact that the energy consumption of HPC data centres will grow by a significant factor in the next four to five years. Hence the costs of associated cooling infrastructures (with 50%–70% of the overall power dedicated to the cooling task of the current generation data centres) already exceed the costs of the HPC systems themselves. Therefore, reduction of energy consumption is becoming mandatory. Otherwise the consumption of exaflop systems will reach up to the 100 mega-watt range.
- The demand for mobile electronic equipment: the scaling is tremendous since billions of mobile electronic devices are deployed and connected to the grid each year. Even low-percentage improvements have a high impact on energy consumption.
- Power consumption of communications networks is going to increase significantly. In the coming 5G networks, the number of connected terminals is estimated to increase by 100–1,000-fold. In IoT type applications, the network should serve up to 1,000,000 devices per km^2. Access rates in the radio interface go to the Gbp level, with peak rates up to 10 Gbps enabling very high data rate services to run in portable devices, such as HD/UHD video gaming, surveillance and monitoring. Data volumes supported by the network are estimated to grow by 1,000–10,000-fold. For the network to serve all customers and expected services, higher frequency bands need to be introduced to obtain the required high data rates. All of this leads to an ultra-dense network infrastructure, implying that the number of base stations increases substantially. To avoid an explosion in energy consumption of the communication networks, energy per transmitted data unit must to be cut radically. In the 5G development, the target is set to limit the energy per transmitted bit to 1/10th of today's level. To reach this target, several measures need be taken – e.g. intelligent beam-forming techniques to transmit radio signals to only the user terminals, efficient communication protocols and network management algorithms, as well as the most efficient electronic components.

System configurations:

The energy efficiency of the system is achieved by using sensors, actuators, drives, controls and innovative components where the loss of energy can be reduced by innovative or even disruptive approaches. The ambition is to reach a wider implementation of adaptive and controlled systems to meet the needs through monitoring and the ability to reduce energy losses. For example, intelligent building management systems can guarantee minimal energy use for heating and lighting (also providing safety and security).

Application level:

MEPS (Minimum Energy Performance Standards[62]): Under the EU Ecodesign Directive, the European Commission sets MEPS for 23 categories of products sold in Europe. The Commission is currently considering revising or developing standards for the following product groups: air heating products, cooling products and process chillers, enterprise servers and data storage products, machine tools and welding equipment, smart appliances, taps and showers, lighting products, household refrigeration, household washing machines and dishwashers, computers, standby power consumption, water heaters, pumps and vacuum cleaners. Furthermore, under the Energy Performance of Building Directive, there is a continuous tightening of national minimum energy performance requirements in line with the optimum cost methodology.

The growing number of computing components within the hardware architecture of both HPC and embedded systems requires greater efforts for the parallelisation of algorithms. In fact, the optimisation of parallel applications still lags far behind the possibilities offered by today's HPC hardware, resulting in sub-optimal system exploitation and hence a significant waste of energy.

3.3.5.3. Competitive situation and game changers

Having the whole value chain represented and with leading positions worldwide, Europe has a rather good chance to build up a healthy "green industry" around tools and goods to reduce energy consumption. European companies have acknowledged strengths in power electronics and in nearly every related application. Market studies show leading positions of Europe in the field of power electronics and advanced LED lighting and even dominance in power semiconductor modules for renewable energies. At the system level, this situation is changing – in the global market for PV inverters former leaders have a decreased market share and Asian suppliers are dominating the market.[63]

Activities inspired, founded and led by European stakeholders such as the GreenTouch® initiative or a number of ETSI and ITU standardisation initiatives and focus groups exert worldwide influence. By employing the latest micro-/nano-electronic technologies and most advanced system concepts, European companies have defined and set new standards, raising the bars in performance and energy efficiency. Related R&D is also very active in all of those domains.

→

62 *ENERGY EFFICIENCY Market Report 2016 – International Energy Agency*

63 *https://www.greentechmedia.com/articles/read/top-five-inverter-players-lose-market-share#gs.jrxxmn*

3.3.5.4. High priority R&D&I areas

- Intelligent drive control: technology, components and miniaturised (sub) systems, new system architectures and circuit designs, innovative modules, interconnect and assembly techniques addressing the challenges at system, sub-system and device level for efficiently controlled engines and electrical actuation in industrial applications;
- Technologies and control systems to improve energy performance of lighting systems;
- Highly efficient and controlled power trains for e-mobility and transportation;
- Efficient (in-situ) power supplies and power management solutions supported by efficient voltage conversion and ultra-low power standby, based on new system architectures, innovative circuit and packaging concepts, specific power components for lighting and industrial equipment serving portable computers and mobile phones, and standby switches for TVs, recorders and computers. Power management solutions in industrial, municipal and private facilities;
- Low-weight/low-power electronics, with advanced thermal management solutions, based on novel materials and innovative devices particularly benefiting, among other areas, medical applications, where improved energy management is one of the keys to cost-effective solutions (for example, medical imaging equipment);
- Immediate issue to be solved on the way towards exascale computing is power consumption. The root cause of this impending crisis is that the needs for ever increasing performances require larger amount of devices (and associated memory) while the chip power efficiency is no longer improving at previous rates. Therefore, improvements in system architecture (e.g. clock switching, etc.) and computing technologies (i.e. usage of low-power processors and accelerators like GPU, FPGA, etc.) are mandatory to progress further;
- Related issue of heat dissipation in computing system requires sophisticated air or liquid cooling units (e.g. chilled water doors, refrigerated racks, heat exchangers, etc.) further adding to the costs;
- Together with computing technologies (CPU, GPU, DSP, etc.) interconnect technologies add their own energy consumption, thus requiring further efforts to optimise routing strategies and switching policies in order to minimise the traffic. Usage of 3D nano-electronics based integrated devices and photonics can be envisioned for such improvement;
- Energy-efficient sensor networks, including hardware and software application layers;
- Optimal parallelisation of traditional sequential algorithms and efficient mapping on parallel and heterogeneous architectures will not only provide necessary performance but help to reduce energy consumption;
- Energy-efficient communication networks with highest efficient ECS, beam-forming and embedded algorithms;
- Efficient adaptive power management for 5G wireless network.

3.3.5.5. Expected achievements

The expected achievements are directly linked to the R&D priorities. It is worth highlighting that in several applications a huge price pressure, neglecting the benefits via reduced operational costs over the lifetime, demands significant achievements in reducing the cost of technologies. The achievement of exascale high-performance computing capability by 2020 requires a reduction by at least a factor of 5 of the current consumption level in order to stay in the domain of technical and economic feasibility.

The following list of potential implementations supports the objective of energy consumption reduction: added increased share of intelligent drive control, electrical actuators for robotics, enterprise servers and data storage products, lighting products, household refrigeration, washing machines and dishwashers, computers, standby power consumption overall, water heaters, pumps and vacuum cleaners. Further potential is seen in highly efficient Industry 4.0 improvements based on sensor data and new control for actuators.

3.4. MAKE IT HAPPEN

The conditions for success are threefold: regulation and standards; technology availability, reliability and seamless integration; acceptance by the users. Standard interfaces and policies for the use and implementation of renewables, grids, farming approaches and others will anchor successful implementations.

Closing the gap in the development of AI technologies and energy-related applications is also seen as an important factor on the way to significantly less energy consumption without compromising on its use.

Decarbonisation is possible — and can be less costly than current policies in the long run. The scenarios show that decarbonisation of the energy system is possible. Moreover, the costs of transforming the energy system do not differ substantially from the current policy initiatives (CPI) scenario. The total energy system cost (including fuel, electricity and capital costs, investment in equipment, energy-efficient products, etc.) could represent slightly less than the 14.6% of European GDP in 2050 for CPI compared to a level of 10.5% in 2005. This reflects a significant shift in the role energy plays in society. Exposure to fossil fuel price volatility would be reduced in decarbonisation scenarios as import dependency falls to 35–45% by 2050, as compared to 58% under current policies

3.5.
TIMEFRAMES

ENERGY:	SHORT TERM TO MEDIUM TERM (2030)	LONG TERM (2050)
Overall – Embedded in EU strategy	Continuation of the research beyond the EU2020 targets to achieve the EU targets for 2030 through continuous improvements. EU Targets 2020 reduced by 20% for greenhouse gas emissions, share of renewables and improvement of energy efficiency. EU Targets 2030[64]: ▸ At least 40% cut in greenhouse gas emissions (from 1990 levels); ▸ At least 32% share for renewable energy; ▸ At least 32.5% improvement in energy efficiency. ▸ Specific: EU Targets 2030 supported by ECS from European suppliers: share of renewable energy in the electricity sector would increase from 21% today to at least 45% by 2030[65].	The EU goal to cut greenhouse gas emissions by 80–95 % by 2050 has serious implications for our energy system. We need to be far more energy efficient. About two-thirds of our energy should come from renewable sources. Electricity production needs to be almost emission-free, despite higher demand. Our energy system has not yet been designed to deal with such challenges. By 2050, it must be transformed.

F.34 *Energy roadmap*

[64] *Energy objectives also depend on external conditions, and will have to be updated for cases of adverse climatic variations. Reference: IPCC PRESS RELEASE 8 October 2018 Summary for Policymakers of IPCC Special Report on Global Warming of 1.5ºC approved by governments.*

[65] *COM (2014) 15 final – A policy framework for climate and energy in the period from 2020 to 2030, Brussels January 2014 – The so called 20-20-20 targets- page 6*

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

1 – ENSURING SUSTAINABLE POWER GENERATION AND ENERGY CONVERSION

1.1 – ENERGY SUPPLY LANDSCAPE

1.1.a 1st order decentralized high efficient simple connected local systems – first integration including power system services

1.1.b 2nd order decentralized – regional area balanced energy supply (villages and cities up to 100.000 users))

1.1.c ECS capable for efficient fast reaction oversupply and peak load management (e.g. low latency, real time, connected, secure)

1.1.d 3rd order decentralized – on country level balanced energy supply

1.2 GENERATION & CONVERSION

1.2.a Highest efficient and reliable ECS for all kind of electrical energy generation – from decentralized to large power plants.

1.2.b Smart and micro inverter reference architecture with integrated control

1.2.c New power electronic actuators for DC and AC grids

1.2.d Inverter on a chip or integrated modules

2 – ACHIEVING EFFICIENT COMMUNITY ENERGY MANAGEMENT

2.1 – ENERGY MANAGEMENT IN COMMUNITIES

2.1.a Monitoring of energy infrastructure and cross domain services; decreased integration costs in self-organizing grids; AI

2.1.b Smart systems enabling optimized heat / cold and el. power supply. **Artificial Intelligence**

2.1.c ECS support for standalone grids and therefore decreasing demand for "big" power plants.

2.1.d New energy market design. E.g. self-coordinated energy supply in local grids

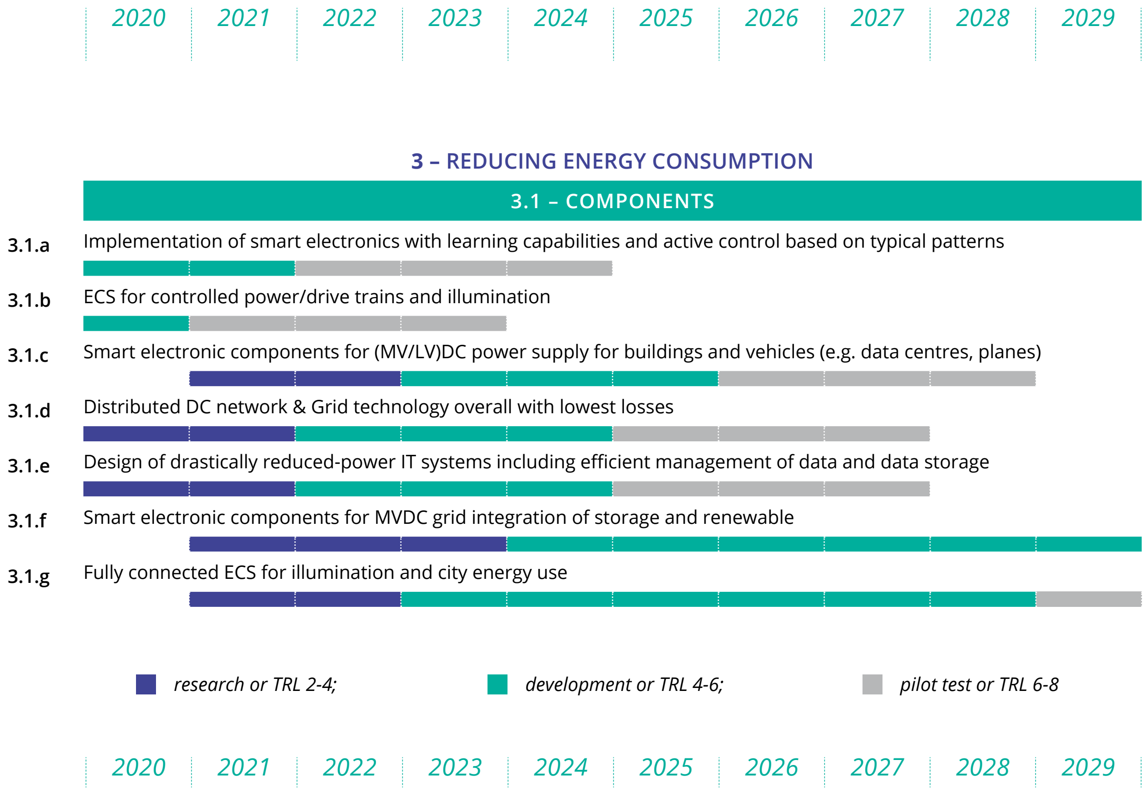
2.1.e Black Out safe energy distribution

2.1.f Management of distribution - new capabilities and high variability of sources and consumers (connected, prediction, secure)

2.1.g Microgrid installations with local decentralized smart storage & redistribution including demand prediction capabilities

2.1.h Sharing of assets (sensors, consumption, demand, ...) with other application areas (transport, industry, digital life, ...)

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029



F.35 *Energy summary roadmap*

SYNERGIES WITH OTHER THEMES

Synergies can be found with all other chapters in terms of energy efficiency that enables new approaches in automotive, society or production. The bases are the technologies: power semiconductors, efficient microcontrollers, secure software, and all sensors and actuators for energy-efficient measurements. On the other hand, the physical and functional integration technologies to realise the systems should be built with components in accordance with the criteria of durability and reliability.

Security aspects related to Energy are considered in chapters Transport and Smart Mobility, Connectivity and Interoperability, Dependability and Trustability, Computing & Storage.

With reference to the Transport and Smart Mobility chapter, as the new concepts of automotive powertrain will be battery powered vehicles, fuel cell vehicles and hybrid engines, there is a need for new technologies with greater efficiency and robustness, so there is a strong connection with high priority R & D & I areas defined in Chapter 3 Energy.

4

Digital Industry

[66] *https://ec.europa.eu/eurostat/statistics-explained/index.php/Manufacturing_statistics_-_NACE_Rev._2*

4.1. EXECUTIVE SUMMARY

Digital Industry will require new applications and methods to make current factories and farms work at the maximum flexibility and efficiency, and to optimise production level. As there will be fewer workers, they will have to handle more complex information. The only way to support that information flow is to use new innovations and integrate them in the normalised work flows. This means that the user should have access to information as he/she needs it in order to take the more adequate decision. This kind of easy access still requires security and a lot of back-end server with data analytics capabilities to process information ready to be used. An optimal system will set itself up according to the designed and installed system. This means we should have self-organising intelligence at the factory and farm level.

Disruption can happen as wireless sensors/actuators and new field connectivity solutions are needed with the industrial Internet. Edge and Cloud-based computing and integration will change the value chain. One challenge is to use these computing facilities in a fast, efficient and dynamic way.

4.2. RELEVANCE

4.2.1. Competitive Value

The manufacturing industry can be classified into two main categories: the process industry and discrete product manufacturing. The process industry transforms material resources (raw materials, feedstock) during continuous or semi-continuous (batch) conversions into new materials that have different physical and chemical performance. Discrete manufacturing, on the other hand, involves the production of distinct items. Automobiles, whitegoods, furniture, toys, smartphones and airplanes are all examples of discrete manufacturing products, whereas in process manufacturing the products are undifferentiated – for example, oil, natural gas and salt.

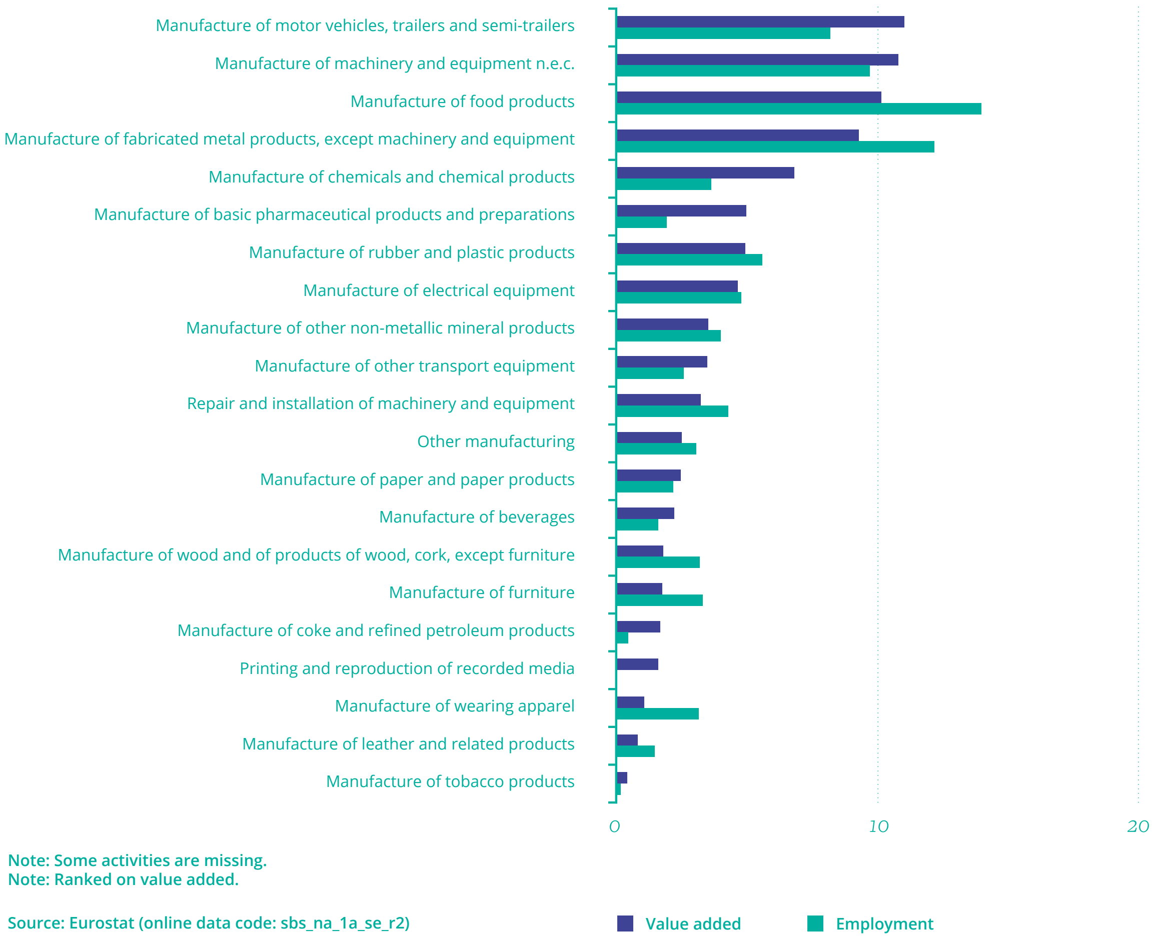
Another oft-used grouping is by end-product, examples of which are the energy industry, chemical industry, petrochemical (oil & gas), food industry, pharmaceutical industry, pulp & paper industry, and steel industry (process industries), as well as automobile manufacturing, the machine industry, robotics and the semiconductor industry. These subdomains are significant for Europe. What is important from an ECSEL point of view is that these industries are increasingly demanding and voluminous consumers of all the technologies that ECSEL represents – e.g. sensors, big data, AI, real-time systems, digital twins, safety & security, computing systems, life-cycle engineering, human–system integration, etc. ECSEL technologies are major drivers of change in these domains.

Manufacturing is the backbone of the European economy. According to Eurostat[66], 9.0% of all enterprises in the EU-28's non-financial business economy were considered manufacturing companies in 2014, a total of 2.1 million enterprises employing nearly 30 million people and generating EUR 1 710 billion of value-added.

This represents 22.1% of employment (14.2% of the total European workforce) and 26% of the value-added of the EU-28's non-financial business economy. A further division of the volumes of the subsectors is shown in the graph below taken from Eurostat documentation. The manufacturing of 1) motor vehicles, etc., 2) machinery and equipment, 3) food products, and 4) metal products constitute a clear top four, followed by other significant subdomains such as chemicals, pharmaceuticals, rubber and plastics, and electrical equipment.

SECTORAL ANALYSIS OF MANUFACTURING (NACE SECTION C), EU-28, 2016

(% share of sectoral total)



Note: Some activities are missing.
Note: Ranked on value added.

Source: Eurostat (online data code: sbs_na_1a_se_r2)

F.36 *Sectoral analysis of Manufacturing (NACE Section C), EU-28, 2016*

Digitisation of industries has already advanced to a high international level, and European factories, as well as, factories globally built by European companies, have 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 who have drawn their competitive edges from automation and digitisation. The business environment has also been changing, i.e., we tend to specialise by new or niche end products, production is becoming more demand-driven or agile, production is more and more geographically distributed, outsourcing of auxiliary business functions, such as condition monitoring and maintenance, is gaining 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 are only realised by having a significantly more extensive digitisation in place.

The process of digitisation as such is again changing and advancing. Internet has become a backbone for many kinds of global and local, near process and enterprise level, open and confidential – process and business management functions. Internet offers, in principle, integration, interoperability, remote operations that are offered today as so-called cloud services. Data analytics, or big data, has become an asset for many kinds of situational awareness, predictive analytics, deep learning, wide optimisation and, in general, new artificial intelligence applications. Modelling and simulation, virtualisation offer versatile opportunities for both factory design and operative factory management. European industrial policies now emphasise building a digital single market for European industries. To achieve this, industrial applications need much more capable Internet than what traditional Internet alone can offer. On top of Internet, we need a so-called industrial Internet whose functionality and form are now developing under the title Industry 4.0. Industry 4.0 is expected to contain all the elements that are needed to realise the complex set of software and automation managed global, distributed and flexible businesses, across value chains, across company and geographical borders, from process to business function levels. A new 'digitalisation' is being emphasised as we now enter an era of novel products calling for new processes, new business models, etc.

As in all digitalisation, cybersecurity becomes a necessity that has to be solved. New generation of digitalisation systems need secure exchange of data ensuring confidentiality, integrity and availability. If not solved properly, cybersecurity issues may become showstoppers. In networked businesses hesitations about trust exist: how can companies in an open-like digital environment trust each other in a constructive way. The whole world is now poised to create the needs of new business culture, contract bases, legislations, market places, business models, i.e., new conditions for growth and success.

Sustainable production must be optimised and accurate. It must be energy-efficient and use raw materials in an effective and even clever way. Raw materials can and must be reused or circulated to maximum effect, and minimise the amount of waste or discharge. Industrial Internet solutions can monitor and report these, and also provide the basis for many kinds of decision-making, both operative and design or building time.

As in the case of Amazon, which sells a lot of consumer goods, this kind of trading needs far more efficient logistics, which may have tremendous effects on production at the same time. The whole value chain is becoming more end-customer driven, agile and faster. 3D printing could be one solution for faster delivery and requires lighter logistics.

Consumer electronics for AR/VR/MR emerging from gaming industry are very attractive for industrial use. These devices are becoming technically more viable, cheaper and providing new possibilities for users at the factories. At the same time, cognitive services using speech interfaces are becoming "intelligent" or applicable. Several such devices are about to become available. In the same way, there are reasonably priced AR/VR/MR kits from the gaming industry with good frameworks. They will enable fast prototyping. The recent commercial release of, e.g., Google Glass 2.0 for business use reflects the current trend as well as Microsoft HoloLens version 2 is targeted more to enterprises than individual consumers.

There should be industrial grade devices attached, e.g., to safety helmets that meet other environmental requirements. Machine learning, AI and chatbots are providing new effective assistants to workers in the field. As digital twin and simulation-based models are built, they can provide effective ways to get real benefits.

Actual chip designs that will support this provide deep neural network acceleration inside central processing units (CPUs). Intel has developed the HPU (Holographic Processing Unit) and its new Nervana processor contains the deep neural network (DNN). In the same way, Nvidia is providing new graphics processing units (GPUs) such as its Titan V for deep machine learning. Google is also providing deep machine learning processors such as tensor processing units (TPUs) and the Edge TPU for different kinds of applications.

Wireless sensors and Ethernet-based field connectivity will change the cost of measurements. Different kinds of low-cost and versatile chips will differentiate and move connectivity towards the Industrial Internet. This is one clear value that European industry should note.

In this chapter, digital farming is also addressed by considering its close resemblance to the needs and solutions of the digital industry. They are based on components and devices that act as sensors and actuators, providing data that allows for the collection of information, monitoring of variables, and then to analyse them and extract knowledge to support decision making for the operation of farming processes. In this sense, it can be seen as a special application environment within the digital industry area. One specificity is the need to integrate data from very diverse sources to deliver relevant decision support information: embedded sensors from industrial hardware (e.g. yield sensor in combine harvesters), standalone IoT sensors, often manufactured by specialised start-ups and SMEs (weather stations or soil monitoring sensors), and large-scale environmental data (gridded weather data, satellite and drone imageries, etc). Other specificities of the farming sector include considerations about its environmental impact and its strong relation to the sustainable development goals defined by the United Nations, along with the need to ensure food security for the population.

4.2.2. **Societal benefits**

Digital industry deals to a large extent with existing production facilities. There are thousands of systems in use that could be more effective and reduce maintenance costs and shorten downtimes. The hardest part of the work is to make it dynamic and self-learning. In this way, it will be cost-efficient to set up and maintain.

The actual value chain will come from the existing installations, whereas new factories are built seldom. As new, fast and secure communication protocols will provide easy connectivity and interoperability across systems, this will enable all integration possibilities. Easy access to a secure internal network will provide all the existing information to users at anytime and anywhere in the plant. Moreover, more interesting features could be provided with cloud or edge-based computing systems. However, this requires new hardware infrastructure to be added to the plant (and farms) with more processing power that can handle large amounts of data.

As for building, these kinds of systems on top of existing installations, there should be reasonable ways to integrate existing legacy systems at the design and communication level. There are existing protocols and architectures to implement this but it should be more effective. New gateways and frameworks should be experimented with and then productised so that a new Industry 4.0-based or a precision agriculture can be built that makes it possible to integrate new services.

New services should be attractive to customers so that they will create value. A service can provide predictive maintenance information or help in troubleshooting. Value comes to the end customer from the savings in the maintenance and fewer downtimes / more production. In the same way, a service can optimise energy or material usage resulting in more profitable production.

Digital farming practices are gaining ground globally across the agricultural sector. The adoption of digital technology in European farms sees an unstoppable trend supported by the benefits it entails: enhanced monitoring of crops/cattle and their production, optimisation of inputs for better productivity, reduced environmental footprint, improved animal and farmer's welfare, enhanced food traceability, to name a few. Apart from the immediate benefit to farmers (digital farming as a "predictive maintenance" for crops and cattle), it becomes a major tool to ensure that societal expectations (reduction of the environmental impact of agriculture) are consistent with farming's economic constraints.

Given the vast economic scale of agricultural industry and current deployment of IoT devices for precision farming, the potential of deploying billions of systems for environmental monitoring is at the horizon. While the expected population growth (more than 9.8 Billion people in 2050, World Population Prospects: The 2017 Revision, UNDESA, 2017) will demand intensification of agricultural production to feed the world, the industry must reduce environmental impact (deforestation and desertification, pollutants, soil degradation, waste). High resolution environmental monitoring (plant growth conditions, status of irrigation and fertilisation), data management and systems that recommend actions for farmers could increase the output per hectare of land.

Knowledge from machine learning and artificial intelligence can be used by service personnel. Users are more valuable and they must learn little bit more about analysis. The use of intelligent services will become more practical and usable for engineers and farmers.

The carbon footprint can be minimised with new industrial Internet-based solutions. Service people and other personnel may avoid travelling in many cases. New solutions can provide dashboards and remote support though connections over Internet. Experts can work from home instead of flying (this can even account for 70% of time), i.e. decision-making will be performed anytime and anywhere. In the case of digital farming, there is a strong focus on the optimisation of farming processes to significantly reduce the environmental footprint – for instance, through the reduction of inputs (e.g. water), pesticides and fertilisers used in agricultural activity.

Servitisation, business models based on machine data

Digital infrastructure and micro services will change business models more towards selling added value as a service. Investment in projects creates network and connections between vendors and providers that the end user (mill, factory or farms) wants to use. For example, maintenance or some other service and condition monitoring needs to get real data from the factory and devices. This kind of value chain contains heterogeneous systems that should be a single channel for the end customer. One dashboard view with background systems will perhaps be integrated to whole factory information and the value of the data will become a key element for the new business; a value chain that integrates multiple sources to one single interface. The next steps are to create actual event notification between other factory systems like Enterprise Resource Planning (ERP), Farm Management Information Systems (FMIS), etc.

In modern machine or system vendor to end-customer or B2B relationships, recent and ongoing R&D or industrial pilots are aiming at delivering many kinds of after-sales services to the end customers. Most typically, such services include condition monitoring, operations support, spare parts and maintenance services, help desks, troubleshooting and operator guidance, performance reporting as well as increasingly required advanced big data analytics, prognostics-based decision support, and management information systems. The actual market for this service is still in its infancy. Many end customers are still hesitant to outsource their condition monitoring business processes but, at the same time, significant joint benefits have been demonstrated by organising such business processes as commercial services and allowing the end users to pay more attention to their core businesses.

Industrial services often represent 50% or more of the industrial business volume, and the 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 evident as service businesses enable continued revenue also after the traditional product sales and, more importantly, the service business is typically many times more profitable than the product sale itself. The service business market is becoming more and more challenging, while the high-income countries are focusing on high-skilled pre-production and after sales life-cycle stages. Fortunately, in the global service business market, Europe can differentiate itself by using its strengths: highly skilled workforce, deep technology knowledge and proven ICT capabilities, but the success needs new innovations and industry level changes.

4.2.3. SWOT analysis

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU ECS industry[67]	**Strengths:** Presence of strong industrial players in EU (Bosch, Schneider, Siemens, ABB, Beckhoff etc.) Much creativity in EU Great design capabilities in EU	**Weaknesses:** Fragmented market across countries Limited start-up / VC culture Few social media companies in EU Personalised cloud providers from US
External factors To the EU ECS industry	**Opportunities:** Ubiquitous availability of smart phones Low-cost availability of accurate sensors Advent of IoT, 5G and AI/Deep Learning Advent of VR, AR, BCI, Robotics, ... Disruption: collaborative business models	**Threats:** Big non-European players Providing platforms & Machine learning

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- Collaboration between industry and research is one key activator to combine research and practical implementations.
- More advanced SOC for Edge computing (Intel and Nvidia). Study level where this can be used.
- AR/VR/MR display technologies and camera use cases.
- Edge computing and chatbot / ML / AI use cases locally (inside factory). How to use cloud-based intelligent services without Internet connection?
- ERP / MESH system API to get benefits from ML/AI results. Uncertain / KPI data from fleet. How to use this data in upper level?

↑
[67] *EU industry here means the full Large Industry + SME + RTO + University eco-system*

4.3. MAJOR CHALLENGES

ECSEL started a special initiative called Industry4.E Lighthouse to boost strategies, community building and impacts of its sector. Moreover, a specific CSA-Industry4.E project started in autumn 2018, to continue for two years. The initiated extensive analyses suggest the following five major challenges.

MC1: Developing digital twins, simulation models for the evaluation of industrial assets at all factory levels, and over system or product life-cycles

In major challenge 1, the digital twin is comprehensively described and specifically elaborated on for 'virtual commissioning'. Moreover 'machining process simulation' is described and the wider context for modelling and simulation, digital design and documentation discussed. (Other) priority areas include multi-simulation, tracking mode simulation, model adaption and simulator-based design. There is a link here to major challenge 4, as digital platforms can provide the infrastructure to automate background processes. Interoperability is a barrier to be overcome, possibly by a standard that allows digital twins to 'communicate'. As indicated in the headline, digital twins are to be developed for the evaluation of industrial assets at all factory levels, and over the system or product life-cycle.

The analysis of different roadmaps (and discussions with experts) revealed that the 'digital twins' referred to within the ECS SRA could be extended toward 'other twins', that the methods for modelling and simulation could be extended and detailed, and the scope of applying the digital twin/methods for modelling and simulation could be widened to include the human-in-the-loop, and the product life-cycle towards a circular economy approach (from cradle-to-cradle). Moreover, the digital twin can support new business models.
Gaps in regard to other roadmaps include the following topics, which should be discussed in relation to how electronic components and systems can play a role (to formulate D1.3 recommendations):

- Further methods for modelling and simulation;
- Human-in-the-loop;
- Circular economy;
- Standardisation;
- Business models;
- Skills.

MC2: AI-enabled cognitive, resilient, adaptable manufacturing

Major challenge 2 focuses on deep learning and involves CPS/Industrial Internet, big data, machine learning and AI, which are not yet transparent nor practical to use. Local edge-based intelligence is seen as an opportunity for Europe. MC2 refers to advanced condition monitoring (towards 5G condition monitoring), which can be supported by AI and is also closely linked to MC1, modelling and simulation/digital twins, as the key priority areas include (automated) modelling and analytics tools and multi-variant and multi objective-simulation and optimisation. Increased efficiency, flexibility and robustness of the production process is expected.

This new major challenge is extended towards AI-enabled, adaptable, resilient factories, including the human as a part of the '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 support human decision making (considering uncertainties) as well as enable resilient manufacturing ecosystems based on new business models.

Gaps in regard to other roadmaps include the following topics, which should be discussed in relation to how electronic components and systems can play a role (to formulate D1.3 recommendations):

- (Big) data analytics, AI / machine learning;
- AI/condition monitoring for high-quality outcomes;
- Cognitive, resilient factories, supply chains, value-creation networks;
- AI and human-in-the-loop, human as part of the resilient factory;
- AI, condition monitoring for the circular economy;
- AI and business;
- AI and skills.

MC3: Developing digital platforms, application development frameworks that integrate sensors/actuators and systems

Major challenge 3 focuses on digital platforms providing computing, storage and networking services between (edge) devices and data centres with AI capabilities. The platform landscape is still very heterogeneous on the supply and demand side. To support interoperability, the IICF and RAMI is mentioned as standardisation will be key. Questions about meta-platforms, integrating AI, performance, security and impact on the environment are raised. The priorities are future industrial and engineering applications, preparing for 5G, low-power consumption, (semi-)autonomy, and trusted (safe and secure by design) platforms.

The analysis of different roadmaps confirms that the platform landscape is still very fragmented, with open and closed, vertical and horizontal platforms, in different developments 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 usable by SMEs) and more decentralised, dynamic platforms supporting AI at the edge. Future (ledger-based) technologies could provide common services on trusted multisided markets / ecosystems.

Gaps in regard to other roadmaps include the following topics, which should be discussed in relation to how electronic components and systems can play a role (to formulate D1.3 recommendations):

- Digital platforms technology;
- Digital platforms standardisation;
- Digital platforms economy / business / society.

MC4: Human-centred manufacturing

- Human–machine relations, interaction, collaboration, complementarity;
- Human-in-the-loop, human-as-part-of-the-system and HMI, including intuitive systems, wearable and implantable systems, and virtual and augmented reality, as well as human–machine collaboration and collaborative decision making;
- New engineering tools that consider humans as part of the systems;
- Human–machine / human–robot collaboration, with enhanced role of workers and customers in manufacturing;
- Manufacturing as networked, dynamic socio-technical systems, HUMANufacturing as a new era of automation and human interaction, customer-centric value-creation networks;
- Human-driven innovation, co-creation through manufacturing ecosystems, customer-driven manufacturing value networks, social innovation;
- Hyper-personalised manufacturing, human-in-the-loop, inclusive manufacturing.

MC5: Sustainable manufacturing in a circular economy

Electronic Components and Systems (ECSs) could have a great bearing in reducing environmental impact through sustainable manufacturing, including energy and resource efficiency and applying circular economy strategies: eco-design, repair, reuse, refurbishment, remanufacture, recycle, waste prevention and waste recycling, etc. This impact can be assessed from two perspectives: the ECS as the product itself to repair, reuse, recycle, etc, on the one side, and the ECS as enablers to improve sustainability and support a circular economy in manufacturing on the other side.

- Responsible value creation in a circular economy, sustainable manufacturing;
- Sustainable manufacturing: innovative processes and systems for sustainability in terms of energy and resource consumption, and impact on the environment.

4.3.1. Major Challenge 1: Developing digital twins, simulation models for the evaluation of industrial assets at all factory levels and over system or product life-cycles

A **digital twin** is a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance of their machines and to find new revenue streams, and to change the way their business behave. Nowadays, machine intelligence and connectivity to cloud allow us an unprecedented potential for large-scale implementation of digital twin technology for companies of various industries. A physical asset can have a virtual copy running in the cloud, getting richer along with every second of operational data. In the area of precision farming, mechanistic crop models are a good example of “digital twins” applied to vegetal production. European agronomic research (both public and private) is at the cutting edge of this technology and its application at the farm level. However, there are currently no equivalent techniques available for livestock monitoring.

Simulation capability is currently a key element to European machine tool industry to increase competitiveness. In the Industry 4.0 paradigm, modelling plays a key role in managing the increasing complexity of technological systems. A holistic engineering approach is required to span the different technical disciplines and prove end-to-end engineering across the entire value chain.

The manufacturing industry can take advantage of digital twin and simulations from different perspectives. Focusing on virtual commissioning with the digital twin, manufacturers and their suppliers can efficiently tackle the pressures of competition: changing customer demands, ever shorter product life-cycles, the increasing number of product variants, the reduced product launch times and the increasing pressure of earnings. At the same time, and to address these pressures, ever more flexible production machines and production systems are introduced, with sophisticated tooling, mechanised automation, robots, transfer lines and safety equipment.

Commissioning is the phase when deliveries from mechanical, electrical and control engineering come together for the first time to form the production machine or system. Until now, such integration had only been possible on the shop floor, which meant that every realised change or revision at that stage generated delays, increased costs, threatened loss of reputation, and potentially reduced market share, undoubtedly if such changes adversely affected machine delivery or production launch. Virtual commissioning allows engineers to connect the digital twin to the PLC to test, refine and optimise mechanical, electrical and logical designs, and the integration between them, well before hardware is assembled on the shop floor, without the need to delay delivery or stop production.

Virtual commissioning provides:

- A common virtual space for mechanical, electrical, control and systems engineers to collaborate and develop simultaneously, rather than serially, at an early stage.
- An environment to perform early testing of control-driven mechanical behaviour, early testing of control logic through observation of machine or system reaction to PLC output, and PLC reaction to machine or system input.
- In-depth simulation of the entire production plant with all its components, allowing ramp up or reconfiguration with minimal production stoppages.
- Shifting of commissioning off the production floor, reducing on-site personnel during the final commissioning phase from several weeks to a few days, cutting costs significantly.
- A realistic validation of a machine or system allowing for identification and resolution of errors, as well as optimisation of the logic programmed into the PLC, by visualising such things as improper material flow or an incorrect sequence of events.

Virtual commissioning scenarios can be composed of virtual **robotic assembly systems** (assembly lines, material handling systems, and machines with integrated robotics), virtual **conveyance-centric material flow systems** (conveyors and devices, whereby the devices are attached to or perform in concert with the conveyors) and virtual **machine tools** (PLC and CNC controls whereby the behavioural physics of parts, such as gravity, force, torque, and load profiles used for sizing drives, becomes increasingly important).

Moreover, in a complementary approach, a digital twin can be employed in **machining process simulation**. Machining process performance is related to the combination of the different phenomena (machine tool kinematic and dynamic behaviour, machining process, tool path, work item dynamics, etc.), and it is necessary to integrate the most important effects in a common simulation environment in which the machine tool, the process and other aspects are simultaneously analysed. A holistic approach based on improved simulation models of energy efficiency or maintenance optimisation can provide more accurate estimations. It is also important to remark that machine monitoring data combined with the model-based estimations will allow an improved performance of the manufacturing process by controlling component degradation and optimising maintenance actions, increasing energy efficiency, modifying process parameters to increase efficiency or even easing operations to protect a degraded component from failure until the next planned maintenance stop, etc.

All indications seem to predict we are on the cusp of a digital twin technology explosion that enhances the necessary collaboration between machine tool builders and part manufacturers in order to improve the productivity of the manufacturing processes.

Besides virtual commissioning, modelling and simulation responds, to a wider extent, to many kinds of digitalisation challenges:

- Understanding, explaining, and visualisation of 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, ascertaining safety, providing a test-bench for automation and IoT solutions.
- The effects of changes can be safely and more comprehensively experimented in advance in a virtual domain than using real plants, equipment or even mock-ups.
- Simulators offer versatile environments for user or operator training
- It is evident that former CAD driven digitalisation is moving the focus towards simulation-based design.

Simulators may be used online and parallel with its real counterpart to predict future behaviour and performance, to give early warnings, to outline alternative scenarios for decision-making, etc. In spite of years of research, such tracking simulators are still in their infancy, at least in industrial use.

4.3.1.1. Scope and ambition

The digital twin does not only mean simulation and modelling but also documentation and design exist as digital. They are constantly updated as there are changes in production and/or process. There is need to have digital platforms that will provide an infrastructure that can be used to automate the required background processes.

4.3.1.2. Competitive situation and game changers

Siemens has already adopted the term "digital twin" though the term has been in popular use generally and earlier, too. Siemens is providing the Comos platform that enables application life-cycle management. MindSphere brings IoT platform as a commercial solution. GE has similar products and initiatives.

There are multiple digital platforms of this kind that are focused on a digital single market. Commercial providers are becoming dominant in the market, whereas, research solutions provide only practical examples and proof-of-concept studies.

4.3.1.3. High priority R&D&I areas

- Virtual commissioning.
- Interoperability is one major challenge. Applications cannot yet be used across platforms. Heterogeneous systems are and remain a challenge.
- Having all relevant engineering disciplines (processes, assembly, electronics and electrical, information systems, etc.) evolving together and properly connected over the life-cycle phases. Multisimulation.
- Tracking mode simulation. Model adaption based on measurements.
- Generating simulators automatically from other design documentation, measurements, etc.
- Simulator-based design.

4.3.1.4. Expected achievements

In an ideal world, interoperability runs on a communication level, but in terms of applications, there are ontological and semantic challenges. There is a possibility to create a standard to define applications and digital twins that could communicate together.

4.3.2. Major Challenge 2: Implementing AI and machine learning to detect anomalies or similarities and to optimise parameters

There are several machine learning systems provided by major Internet players like Google, Microsoft Azure IBM Watson, Nvidia, Intel, etc. These are using different kinds of implementation from the deep learning or other algorithms. Deep learning usually needs a large amount of carefully selected training data to be accurate. There is a need for time series data handling to detect similarity or anomaly with an easy set up. This is one basic principle that is required to get successful implementation to industry. As there are not so many data scientists for every company or domain, a solution suitable for normal automation engineers should be developed.

Due to the lack of mechanistic models ('digital twins') in cattle monitoring, deep learning is becoming the major tool for detection and prevention of health and reproduction problems.

Even though we have large libraries using a variety of programming languages, this is not enough since engineers with a common PLC/DCS background cannot use them. This will require software or framework that can be configured and connected easily to system. Existing runtime systems are not even capable of running algorithms fast enough. Again, this will require an edge computing device (perhaps with GPU) to run analysis to provide result in reasonable time.

Another interesting aspect is cognitive services. As some high-end systems will understand speech and run actions or use background services, they are providing new natural language understanding (NLU). One problem with these services is how to integrate them into the production unit without access to Internet. It will require some security and DMZ set-up to use it in safe way. Or another implementation could be a private hybrid cloud solution. Nevertheless, this new AR/MR application can be a real game changer for user interfaces. Maintenance people can talk and walk and get instant information from the devices and systems nearby.

Condition monitoring techniques can be applied to many types of industrial components and systems, although often at an additional cost. To determine which level of condition monitoring machinery warrants, a criticality index method can be utilised – categorising machinery into critical, essential and general purpose – that takes into account factors such as downtime cost, spares proximity, redundancy, environmental impact and safety. Commonly, the business value required from condition monitoring depends on higher availability of equipment and, for production processes, information provision to be able to plan and act on maintenance proactively instead of reactively, decreased cost and improved on-time delivery. Other business values that may be of interest are safety, and optimal dimensioning/distribution of spare parts and maintenance staff. Thus, serious breakdowns and unplanned stops in production processes can largely be avoided using condition monitoring.

It is possible to combine quantitative approaches and methods (e.g. using machine learning, historical data/big data) with qualitative approaches and methods to achieve a higher level of prediction accuracy and identify more types of problems/issues. Regarding qualitative approaches and methods, these require a deeper understanding of the equipment or process and the application/area to be able to model the data and find relationships based on sometimes more than 3–5 parameters that together may characterise the issues. Furthermore, (on-line) condition monitoring can be combined with other aspects to reveal additional issues/problems that otherwise would not have been indicated or discovered based on condition monitoring alone. An example of this is continuous quality control that firstly checks that the input is within accepted ranges, secondly that the process parameters are fine, and thirdly that the output produced meets the expected requirements, etc. Thus, if output problems are detected and all the others look acceptable, it is an indication that the equipment needs maintenance or the process should be adjusted.

To achieve advanced condition monitoring, it is important that it has already been considered during the design stage so that the necessary sensors are included, data can be extracted at the rates needed, and that it is possible to add additional sensors later if required. Otherwise, it will be hard to successfully and economically perform condition monitoring that results in the required business value. In addition, using the results of the condition monitoring in re-designs or designs of new models/versions is encouraged as many future problems can then be avoided (as well as achieving greater reliability and potentially also improved maintainability if components or sub-systems that are error-prone are made easy to service and change parts).

4.3.2.1. Scope and ambition

How to use and get applications for domain users defines the scope. Intelligent services will provide knowledge and information to the user in a normal and transparent way. Digital industry results should be used by a normal engineer. He/she does not have to be a skilled specialist in programming or data science.

Since industry has been digital in many ways for decades and in growing proportions, it has also developed its own system engineering concepts, tools, languages, platforms and standards. Examples include PLCs, DCSs, alarm systems, CAD, etc. Today, this technology basis is drastically expanding to the variety of concepts and technologies, grouped conveniently under the title cyber-physical systems or industrial Internet. Machine learning, big data, deep learning and artificial intelligence are significant examples. What is still striking is that bringing these technologies into industry tends to depend on research initiatives, pilot experiments, proofs of concept, or in making real applications tailored, brittle, non-transparent and difficult to understand and manage. In other words, they are expensive or untrustworthy, or too low-level to be practical. Yesterday's technologies are engineered in place, which is very beneficial and practical; there is no need for experimenting or science. Reference architectures, design languages, application generators, design automation and respective standardisation are obviously constituents of such engineerable new solutions.

For condition monitoring, we can list specifically:

- Continuous/online/real-time monitoring of industrial equipment.
- High-resolution/continuous/online/real-time monitoring of environmental parameters for industrial farming.
- Fleet management, i.e. managing fleets of machinery, local and remote, benefiting from larger sets of similar components, etc., distributing experience, understanding common or similar characteristics and context-specific characteristics.
- Modelling and integration of processes and equipment.
- Benefiting from, or taking into account of, online conditions in other applications of a digital twin – i.e. MES, ERP, automation.
- Hybrid/linked simulation and analysis.
- Flexibility and robustness of production process, enabled by monitoring and predictions.
- Adopting of 5G to condition monitoring – this may become a game changer.

4.3.2.2. Competitive situation and game changers

The main players are coming from the US. They are dominating cloud-based solutions. However, the emergence of local edge-based intelligence offers an opportunity for Europe.

The biggest AI and machine learning acquisitions will continue with the acquisition by Facebook of Ozlo, Google of Kaggle and Halli Labs, as well as of AIMatter, Microsoft of Maluuba, Apple of Realface and Lattice, Amazon of Harvest.ai and Spotify of Niland.

The interest is very high and many are realising the potential benefits that can be obtained by using condition monitoring. On the 'use'-side, it is expected that those who use condition monitoring will be more competitive and profitable than those not using it. Furthermore, on the provider side, large companies are showing increasing interest in condition monitoring systems and investing in the market. Larger provider players include IBM, Schneider Electric, Microsoft, SKF and Bosch.

4.3.2.3. Expected achievements

- Capabilities to build digital industry with outperforming business.
- IoT devices supporting wireless and Ethernet-based connectivity.
- Tools for engineers to use and get information and knowledge at all levels of personnel.

The expected achievements are improved overall equipment efficiency and profitability through increased efficiency, flexibility and robustness of the production process. Applying these hardware and software concepts in the farming sector will lead to further intensification of agriculture production and reduce environmental impacts. This is enabled by improved risk management using condition monitoring and predictive ability.

4.3.3. **Major challenge 3: Generalising condition monitoring, to pre-damage warning on-line decision-making support and standardisation of communication scenarii to enable big data collection across huge (remote) sites**

The role of IoT is becoming more prominent in enabling access to devices and machines, which used to be hidden in well-designed silos in manufacturing and farming systems. This evolution will allow IT and IoT to penetrate digitised manufacturing and precise agriculture systems further.

Industrial IoT applications are using the gathered data, data analytics, cloud services, management information systems, enterprise mobility and many others to improve the industrial processes. The future IoT developments integrated into the digital economy will address highly distributed IoT applications involving a high degree of distribution and processing at the edge of the network by using platforms that provide computing, storage and networking services between edge devices and computing data centres (at the edge and/or at the cloud levels) with AI capabilities.

Most companies are now experiencing difficult times justifying risky, expensive and uncertain investments for smart manufacturing across company borders and factory levels. Changes in the structure, organisation and culture of manufacturing occur slowly, which hinders technology integration. Similar issues are also experienced in the digital farming sector.

There are many initiatives around Digital Manufacturing, Digital Farming, and IoT Platforms, thanks to the widespread research and innovation in the EU (C2Net, CREMA, FIWARE, FITMAN, ARROWHEAD, sensiNact, etc.). However, those IoT driven platforms have not yet led to a successful and effective digitisation of all the aspects and resources of manufacturing and farming industries. This is mainly due to the heterogeneity of the IT supply side and of the heterogeneity of the domains to be addressed and transformed in the industry demand side.

Questions to be solved:

- Are the digital platforms meant for manufacturing business processes also suitable for real time execution?
- Have performance and security issues been solved?
- Are the proposed platforms reasonable for low tech SMEs?
- Can we define a Meta-Platform that acts as the translator between the different digital platforms?

- Can we define something similar to AUTOSAR, a standard way to communicate between the different parts and platforms for the Intelligent Manufacturing/Farming ecosystem or something to solve the interoperability problem? Each of the actors in an Intelligent Manufacturing/ Farming ecosystem is using their own solution. Having a standard way to connect and have interoperability of those different digital platforms and different devices located at different levels of the factory/farm will provide a competitive position to the European intelligent manufacturing/farming ecosystem.
- IoT devices will have significant environmental impacts (e.g. waste management); therefore, development and use of recyclable and, ideally, biodegradable systems is needed. Can new material concepts provide electronic hardware meeting these requirements?

To resolve this last question, the Industrial Internet Consortium (IIC) has defined the so-called Connectivity Framework (IICF). The IICF defines the role of a connectivity framework as providing syntactic interoperability for communicating between disparate Industrial Internet of Things (IIoT) systems and components developed by different parties at different times. The IICF is a comprehensive resource for understanding connectivity considerations in IIoT. It builds on the foundation established by the Industrial Internet Reference Architecture and Industrial Internet Security Framework by explaining how connectivity fits within the business of industrial operations, and its foundational role in providing system and component interoperability when building IIoT systems.

EFFRA (European Factories of the Future Research Association): The diversity of approaches and implementations of Digital Manufacturing or Digital Farming platforms prompt the need for the creation of Meta-Platforms to connect existing platforms, including abstraction layers for interface, protocol and data mapping to provide interoperability as a service. There is a need for holistic interoperability solutions spanning all communication channels and interfaces (M2M, HMI, machine to service) in the factories/farms and supply chains. Moreover, Meta-platforms will need interoperability for security, semantic, data-bases, user interfaces, etc.

In addition, new players are arriving from the IT sector:

- Hadoop
- Kafka
- Apache STORM
- IBM (Bluemix)
- Microsoft Azure
- Digital Enterprise Suite (SIEMENS), MindSphere (Siemens, open IoT operating system, turn data into knowledge, and knowledge into measured business success).

How can they be considered in the intelligent manufacturing/farming ecosystem? How can these tools be integrated into the digital platforms? How can the IPR issues of the data and knowledge created by those tools be solved?

4.3.3.1. Scope and ambition

For Digital Manufacturing:

- Study for meta-platform that can communicate and provide services between different platforms and their integrated tools.
- Managing complexities with AI-based design, self-configuration, life-management and with many kinds of autonomous adaptation. “How to connect intelligence!”.

For Digital Farming:

- Continuous monitoring of crops and livestock, as well as environmental/nutrient parameters (in soil, water, air) influencing the growing cycles of plants and animals in farm environments.
- Operation, update and maintenance of large numbers of distributed devices in rural/remote areas, with scarce battery resources and lack of connectivity
- Combination of advanced models and artificial intelligence tools applied on collected data to support decision making (e.g. to optimise farm operations, predict diseases, etc.)
- Ensuring high security levels in the management of data.

4.3.3.2. Competitive situation and game changers

There are actually several benchmarking studies about digital platforms, either in progress or very recently completed. In the same way, companies are carrying out their own respective surveys. A general remark is that there are several digital platforms emerging, as research project outcomes, or actually as the result of several consecutive projects, both national and EU. Certain standardisation is under way, most notably by RAMI 4.0 (Reference Architectural Model 4.0) and IIC. Since the realms of respective applications are huge and, therefore, technologies as well, the standard actually consists of many standards that have been known and used for some time already; though there are needs to create new (sub)standards. The commercial digital platforms are also emerging, most notably Siemens MindSphere and GE Predix. At the time of writing, it is not clear which platform perhaps will win, or how the market positions will evolve. The situation very much resembles with the early stages of evolving operating systems of personal computers or mobile phones, or rather the early situation of industrial fieldbuses. As we well know, in some domains there have been clear global winners, but for instance with fieldbuses, several strong players seem to prevail. Due to the emergence of Industry 4.0, rectification of initiatives is apparently taking place.

The research origin platforms may be more versatile than the current commercial offerings. At the end of the day, application industries may start choosing more and more commercially supported platforms but, as we have seen in recent history of ICT, open source platforms may keep their strong position.

Digital platforms are clearly becoming ever more state-of-the-art technologies, i.e., they are pushed somewhat in the background as we have operating systems of PCs today. The applications have been dominating engineering, in the past and in the future. As is clearly recognised in industry, applications in all life-cycle stages and on all system levels, both in digital and physical realms, are most valuable. The digital assets themselves are important, as well as, the connectivity of ever more elaborate and diverse applications.

A similar situation exists in digital farming. Moreover, there are strong signals in favour of an increasingly deeper digitisation of the EU's agricultural sector. On the one hand, from a policy perspective, the upcoming EU's Common Agricultural Policy (CAP) 2021–2027 will have a special focus on digitisation. Additional stimuli are expected to happen at national or regional levels in those regions where agriculture is a key contributor to the local GDP.

On the other hand, in the private sector, the agriculture sector itself (the end users or demand side) has embarked on an increasing digital take-up that seems to be only in its beginnings. Therefore, the supply side of digital farming faces quite promising market opportunities on a vertical market that is expected to attract heavy investments in the upcoming years. Interestingly, the supply side of digital farming embraces a rich value chain of actors that ranges from component manufacturers to digital platform providers, application developers or agricultural machinery manufacturers.

The digitisation of food production will open the door to unprecedented productivity levels in the agriculture sector, while reducing the environmental footprint of the agriculture activity, thus becoming a real game changer.

4.3.3.3. High priority R&D&I areas

- Move focus on the industrial or engineering applications. It is important to win the global platform game on various application sectors (which are strong today) and in building effectively and on high-level outperforming applications and systems, for the actual industrial and business needs.
- Prepare for the era of 5G in communication technology, and especially its manufacturing and engineering dimension.
- Long-range communication technologies optimised for M2M communication, large numbers of devices, low bit rates are key elements in smart farming.
- Solve the IoT cyber-security and safety problems, attestation, security-by-design. Only safe, secure, and trusted platforms survive in industry.
- Next-generation IoT devices with higher levels of integration, low power consumption, more embedded functionalities (including artificial intelligence capabilities) and 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: artificial intelligence, modeling and analytics, in Cloud but also in Edge/Fog settings.

4.3.3.4. Expected achievements

- Meta-platform could be used with other platforms, systems and tools.
- Easier, more comprehensive and tools supported integration of compound applications, on top of digital platforms.
- Automated design features.
- Technologies to connect intelligence.

Availability of a new generation of smart farming-ready intelligent IoT components, devices, platforms and applications offering a high degree of interoperability, configurability, orchestration manager and security, that allows Europe to stand out as global leading supplier of smart-farming technology during 2020–2030.

4.3.4. **Major challenge 4: Developing digital platforms, application development frameworks that integrate sensors/actuators and systems**

There is undoubtedly a tendency to increase automation or the degree of digitalisation in industry, which will ultimately lead to 100% autonomous systems. Moreover, there are some outstanding flagship programmes – for autonomous driving, for example. Also, some mature manufacturing phases, or even entire production lines, are practically fully autonomous.

However, between the two extremes of entirely manual or fully autonomous there will probably always be 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: 1) a fully autonomous solution may simply be (technically) next to impossible to design, implement and test, 2) if fully autonomous solutions were achievable, they may be too expensive to be realised, 3) a fully autonomous solution may be too complex, brittle, unstable, unsafe, etc., to become accepted by industrial end-users, 4) a fully autonomous system may be too complicated and therefore unrealistic to modify or upgrade as requirements or conditions change, 5) a less-demanding semi-automatic solution may be easier to realise to a fully satisfactory level, and finally 6) there are examples where a fully autonomous solution may not represent a maximum performance, and instead an effective joint solution between human and machine would be better.

When automation and digitalisation degrees are gradually, reasonably and professionally increased, often portion by portion, they may bring proportionally significant competitive advantages and savings that strengthen the position of digital industries overall. However, since automation or digitalisation degrees remain well below 100%, the negative effects to employment are either negligible or non-existent. On the contrary, an increased market position could increase the need for more people in the respective businesses.

4.3.4.1. Scope and ambition

Overall, human–system interaction appears in the following contexts:

- Training: A higher level of formal training may be required for workers in production and maintenance due to tasks such as analytics and the use of advanced technologies. On the other hand, greater specialisation is constantly introducing product, process or company-specific further training.
- Extended human capabilities enabled by big data and artificial intelligence: AI will impact almost every industry with targeted (not general purpose) AI systems. Service businesses around AI will emerge as the next big opportunity, which will also provide opportunity for SMEs.
- Human operators in more autonomous plants and in remote operations: The production processes will acquire more autonomous parts as a result of development in extreme or hazardous conditions, or process industries located in remote/distant areas where much can be gained from increasing autonomy.
- 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) becomes more important. This involves increased and intrinsically safe collaboration between humans, robots and any machinery.
- Competence and quality of work: On a strategic level, the European automation and industrial IT industry depends on an ability to attract competent personnel to maintain their competence over time. To facilitate this, creativity and innovation processes need to be connected to the competence area, and there must be structured continuous professional education as well as transfer of knowledge from one to many.
- Human–machine interfaces and machine-to-machine communications: Augmented reality (or virtual reality) will be used to support a number of tasks, such as modelling/simulation of equipment behaviour or processes before making changes or additions, pre-testing action in simulation prior to real-world introduction, enhancing remote help/support by entering into the actual help/support case environment and showing what should be done and how to do it, and also being able to run simulations prior to making changes in configurations or set-ups. Enhanced visualisation of data and analytic results will be required to support decision making.

4.3.4.2. Competitive situation and game changers

To broaden out the scope, the following nine game changers can be listed, which are currently on different maturity levels:

- Modular factory for distributed and automated production.
- Live virtual twins of raw materials, process and products.
- Increased information transparency between field and ERP.
- Real-time data analytics.
- Dynamic control and optimisation of output tolerances.
- Process industry as an integrated and agile part of the energy system.
- Management of critical knowledge.
- Semi-autonomous automation engineering.
- Integrated operational and cybersecurity management.

4.3.4.3. High-priority R&D&I areas

- Human–machine relations, interaction, collaboration, complementarity.
- Human-in-the-loop, human-as-part-of-the-system and HMI, including intuitive systems, wearable and implantable systems, virtual and augmented reality as well as human–machine collaboration and collaborative decision making.
- New engineering tools that consider humans as part of the systems.
- Human–machine/human–robot collaboration, and an enhanced role for workers and customers in manufacturing.
- Manufacturing as networked, dynamic socio-technical systems, HUMANufacturing as a new era of automation and human interaction, customer-centric value creation networks.
- Human-driven innovation, co-creation through manufacturing ecosystems, customer-driven manufacturing value networks, social innovation.
- Hyper-personalised manufacturing, human-in-the-loop, inclusive manufacturing.

4.3.4.4. Expected achievements

- Increased productivity from improved ways of working, collaboration, life-cycle management, optimisations and distributed production and services.
- Decision-making based on data and facts.
- User-friendly design and operation of automation systems.
- Self-healing, redundant and resilient production and automation systems.
- Fast and improved decision support (both for humans and machines).
- Decisions based on data/big data as well as data from multiple sources.
- Fewer work-related injuries and improved work safety.
- Higher work performance/efficiency per unit of worked time (economic benefit).
- Augmented workers, implants and robotic parts.
- Structured knowledge management supported by adequate systems.
- Context-driven user-centric information based on big data.
- New designs of plants and production processes with higher automation levels and fewer but increasingly skilled workers.

4.3.5. Major Challenge 5: Sustainable manufacturing in a circular economy

Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2ºC. Rapid transformation of all sectors is required. Many European countries have set even more ambitious targets. Billions of mechanical devices, buildings, vehicles and industrial processes need to be changed, retrofitted or renovated. Social change, urbanisation, increasing wealth and consumerism have led to the rapid exploitation of natural resources beyond our planet's capacity. However, challenges can be addressed through resource wisdom. Tapping into yet-unutilised reserves and closing the loops will open new potential for economy. Industries benefit from renewables and unconventional raw materials. Design will enable high-performance for-need-only consumables. Non-conventionally produced food can help to feed the growing population while saving water and the environment.

The vision of SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) decomposes the above high-level goals into more concrete actions, as follows:

1. Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
2. Re-use waste streams and energy within and between different sectors, including recovery, recycling and re-use of post-consumer waste.
3. Replace current feedstock 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.
4. Reinvent materials and products to achieve a significantly increased impact on resource and energy efficiency over the value chain.

The EFFRA (European Factories of the Future Research Association) roadmap, on the other hand, discusses environmental sustainability of manufacturing as follows:

The new possibilities offered by advanced materials, digital technologies and manufacturing technologies should be exploited; generating a considerable reduction of the ecological footprint, CO_2 emissions and improvements in the recycling, use and re-use of resources on an eco-system level while still raising the performance of the manufactured products. For approaching an ultra-resource-efficient or circular approach, the understanding of impact, cooperation and resource-use must be improved along the life-cycle and across sectors. This will require the identification of appropriate metrics and parameters which allow optimisation along the life-cycle.

Finally, overall professional and experienced automation and digital technologies – which, for example, ECSEL represents – are needed. Once all environmental goals are achieved, we will have implemented an effective engineering and operation that, most obviously, will optimise performance in terms of quality, cost, flexibility, operational efficiency, safety and reliability.

4.3.5.1. Scope and ambition

Obviously, sustainable manufacturing and production need solutions and breakthroughs in many ways, but how ECSEL or electronics and software technologies can assist in this can be described as follows:

a) Life-cycle assessment
   Life-cycle assessment (LCA) is a comprehensive and ISO standardised method of evaluating the

environmental aspects and potential environmental impacts of products. LCA can also be applied in evaluating the impact of technologies and processes. An LCA study covers the whole life-cycle of products, and provides information to support decision-making in product and technology development projects. LCA is a prerequisite for holistic environmental evaluation, and is a simple but systematic method, but one 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.

b) Monitoring discharges, etc
Sustainable manufacturing needs, per se, comprehensive environmental and other measurements that may not at all be in place when particular manufacturing or production was initiated. On the other hand, this is a very typical application of many kinds of IoT sensor and system that can be informed by a careful LCA, for example.

c) Tracing material and energy streams
It is already commonplace in many industry sectors that material and energy streams need to be completely traced back to their starting point. Notable examples include food and medicine production. As more and more products, raw materials, etc, become critical, this implementation strategy must be expanded.

d) Optimisation
Discharges or losses mostly happen when production does not occur as planned, as is optimal, due to mistakes, bad condition of machinery, unskilled operation, and so on.

4.3.5.2. Competitive situation and game changers

Europe has been the most advanced and implemented the most in terms of sustainable production. This has been an issue of quality and reputation, but recent developments have also shown that it is becoming an absolute necessity to help save the planet, and that even an effective incentive to improve all engineering and operations. and all the other KPIs, may become not be enough. However, climate change seems to be hitting other continents harder than Europe, at least temporarily, meaning that the other threatened economies are starting to take these matters more seriously.

4.3.5.3. High-priority R&D&I areas

- Key performance indicators (KPIs) related to the environmental performance of processes (even online).
- Life-cycle analysis, simulations/optimisation and management driven by customer and societal demand.
- Consideration of electrical drives/motors.
- Monitoring and control (legislation, waste, energy).
- Design. economic, societal and environmental aspects go hand in hand.
- Complex system optimisation (energy efficiency, minimise emissions (CO_2, NO_x, etc.), ability to use/cope with by-products and produce less waste).

4.3.5.4. Expected achievements

- Reduced use of raw materials.
- Carefully and accurately designed and operated production that minimises or avoids discharges and wastes.
- New business models.
- Proofs through industrial cases that the best environmental production or operation actually means the highest quality, lowest cost and other KPIs.

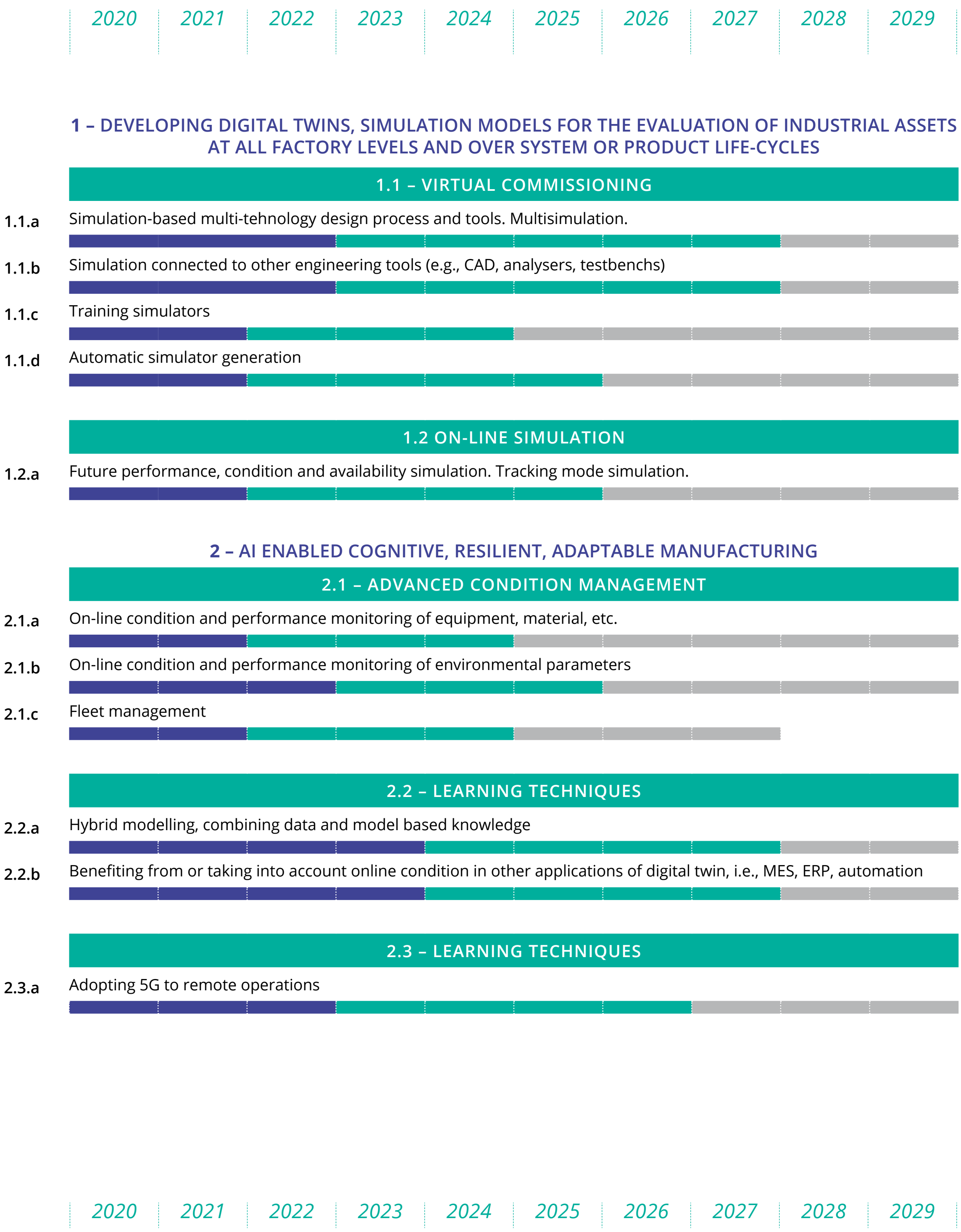
4.4.
MAKE IT HAPPEN

Some initial ideas on how to get involvement from industry to test research ideas. Participate and get in-field experience.

Gartner/ARC studies about 50 billion IoT sensors → communication + storage → applications needed that will create actual information and value from the data.
Sensor price / unit + storage capacity + application execution = investment price.
Existing standards can be used and there are a lot more applications based on standards.
Development cycle from chip provider to system designer and then to application can be shorter e.g. actual framework and faster design flow create stakeholder value

4.5.
TIMEFRAMES

The timeframe below contains some pre-steps to make actual targets feasible.



2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

3 – DEVELOPING DIGITAL PLATFORMS, APPLICATION DEVELOPMENT FRAMEWORKS THAT INTEGRATE SENSORS/ACTUATORS AND SYSTEMS

3.1 – PLATFORM TO PLATFORM COMMUNICATION

3.1.a	Meta-platform that can communicate and provide services between different platforms and their integrated tools
3.1.b	Ensuring high security levels
3.1.c	Faster and flexible system implementations based upon platforms
3.1.d	Data value related sharing mechanisms/incentives or business models – all contributors to data with increasing value added
3.1.e	Standards for interoperability – enable efficient integrations and interactions between stakeholders

3.2 – PLATFORM TECHNOLOGIES

3.2.a	AI-based design, self-configuration, life-management and with many kinds of autonomous implementation
3.2.b	Operation, update and maintenance of large numbers of distributed devices in rural/remote areas, with scarce battery resources and lack of connectivity
3.2.c	Continuous monitoring of crops and livestock, as well as environmental/nutrient parameters (in soil, water, air) influencing the growing cycles of plants and animals in farm environments
3.2.d	Prepare for the era of 5G in communication technology as outperfoming edge-cloud capabilities

4 – HUMAN CENTRED MANUFACTURING

4.1 – ON-LINE TRAINING

4.1.a	On-line, remote and on-site, training packages – product or process specific, to support training in work
4.1.b	Training in context
4.1.c	New designs of plants and production processes with higher automation levels and fewer but increasingly skilled workers

4.2 – AI AIDED HUMAN

4.2.a	Human-in-the-loop, human as part of the system and HMI including intuitive systems, wearable and implantable systems, virtual and augmented reality as well as human machine collaboration and collaborative decision making
4.2.b	New engineering tools considering humans as part of the systems
4.2.c	Context-driven user-centric information based on big data

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

4.3 – AUTONOMOUS PLANTS & REMOTE OPERATIONS

4.3.a Decisions based on data/big data as well as data from multiple sources

4.3.b Self-healing, redundant and resilient production and automation systems

4.3.c Hyper-personalised manufacturing, human in the loop, inclusive manufacturing

4.4 – HUMAN-MACHINE INTERFACES

4.4.a Augmented workers, implants and robotic parts

5 – SUSTAINABLE MANUFACTURING IN A CIRCULAR ECONOMY

5.1 – LIFE-CYCLE ASSESSMENT

5.1.a Life-cycle assessment methods and tools integrated to engineering tools (design and operational)

5.1.b Life-cycle assessment as integral part of decision making

5.2 – MONITORING, TRACING

5.2.a IoT based discharge monitoring

5.2.b Tracing connected to other engineering and operation systems

research or TRL 2-4; *development or TRL 4-6;* *pilot test or TRL 6-8*

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

4.6. SYNERGIES WITH OTHER THEMES

Connectivity & interoperability is one key factor for Digital Industry that it will work.

- Digital Life
  - Sustainability
  - Food security
  - Resources waste
- Connectivity: 5G in industry for
  - Fast communication
  - Indoor location
  - Interoperability
- Computing & storage:
  - Machine learning API for hybrid CPU&GPU, Edge computing
  - Storage for training data (wearable, low power & fast)

5

Digital Life

5.1. EXECUTIVE SUMMARY

Increasingly, digital services are part of almost everything we do, be it at work or during our free time. In all cases we want to have a safe, comfortable and fulfilling life in the right social context. The Digital Life chapter covers the intelligent (and preferably anticipating) applications that support our lives wherever we are and whatever we are doing.

Due to political, demographics and climate trends, Europe is facing major challenges across those spaces, for security, safety, privacy, mobility, efficient energy consumption, etc... The ubiquitous availability of smart devices and the advent of new technologies like IoT (Internet of Things), 5G, AI (Artificial Intelligence) with DL (Deep Learning), VR (Virtual Reality) and AR (Augmented Reality), BCI, Robotics and the like will shape new ways of how people interact with the world and with each other. The 24/7 always-online culture resulting from the ubiquitous connectedness has empowered citizens, they have evolved from consumer to prosumer (such as on YouTube), maker communities have emerged (enabled by the advent of 3D-printing) and simple initiatives as Neighbourhood Watch groups (based on WhatsApp) allow citizens to enhance their own security. More intelligent, secure and user-centred solutions are necessary to meet Europe's challenges, while keeping up with societal needs in a sustainable way, guaranteeing citizens' privacy and reaching broad acceptance in the public.

Four Major Challenges have been defined to ensure safe, secure, healthy, comfortable, anticipating and sustainable spaces, in the personal, private, professional and public context.

5.2. INTRODUCTION

The Digital Life is at the heart of a modern smart society and hence tightly related to the overall need of "liveability", which implies all Maslow's hierarchy of *needs*: physiological (sufficient housing, food, energy, etc.), safety (individual protection from external threats), love and belongingness (social inclusion and recognition) and self-fulfilment (artistic expression). Given the state of the planet, there is also an underlying requirement of sustainability. In this context, importance of rights in the digital life domain brings new challenges related to technology implementation, Internet access for all, trust, security, safety, privacy, surveillance and encryption, awareness, protection and realisation of needs and rights,

Major Challenges

The Major Challenges aim to improve our Digital Life and are associated to the spaces we live in:

1. Ensuring safe and secure spaces
2. Ensuring healthy and comfortable spaces
3. Ensuring anticipating spaces
4. Ensuring sustainable spaces

Nowadays, and certainly in the next few years, we need to drastically improve our safety and security requirements to live comfortably to enjoy many healthy years of life. Furthermore, comfort and acceptance of application can be further enhanced through anticipation. And above and beyond this, sustainability is a key prerequisite.

The table below shows the different Major Challenges that address the needs of people in the four different spaces identified [68]. This results in the following sixteen innovation areas (examples given):

IDENTIFIED SPACES:	PUBLIC SPACE	PROFESSIONAL SPACE	PRIVATE SPACE	PERSONAL SPACE
Characteristics: *Major Challenges:*	*in a public environment, with anyone*	*in the work environment, with your colleagues*	*in the home environment, with your family*	*with yourself*
Safety & security	Public safety Emergency and crowd management	Access control Surveillance	Anti-burglary Surveillance	e-Wallet Biometrics Privacy
Healthy & Comfortable	Navigation Guidance Public Address	Healthy office Productivity	Smart Home Home Assistant Cobot	Werables Quantified self Personal assistant Media content consumption
Anticipating	Traffic management Asset tracking	Adaptive work space	Smart home e-Butler	Coaching wearables
Sustainable	Energy saving Water saving Air-pollution	Carbon neutral offices	Off-grid living Micro housing	Sharing rather than owning

F.39 *Major Challenges*

These imply ample business opportunities for Europe in related application areas, *for example*:

- Anti-burglary solutions and comfortable domotics at the Smart Home
- Energy saving and productivity enhancers in Smart Buildings
- Public safety and crowd management in Smart Cities

68 *The model with the four spaces in varying levels of trust and intimacy does not explicitly mention the domain between the personal and the public spaces which includes friends, sport mates, neighbours, etc.*

Innovative solutions and services called for in this context may either be completely new (e.g. hologram-based 3D-video communication) or based on existing systems that are extended, bridged or merged (e.g. integrating autonomous service vehicles and fleets of surveillance drones to assist on massive gatherings in urban management solutions and/or disaster recovery).

5.2.1. Vision

5.2.1.1. Safety & Security

In our daily lives we expect our environment to be safe, meaning that it is designed and managed to cause no harm, and to be secure, meaning that is difficult to be attacked by external agents. These requirements are applicable in all our living areas, at home, while walking in our city, attending an event, exercising, working or travelling. Safety and security are always moving targets since, beside the known threats, new forms of cyber-crime and terrorism are constantly emerging. Moreover, as we rely more and more on digital services to be available, unavailability may have drastic consequences and should also been regarded as a safety concern.

New systems that are deployed should be more robust and reliable, or at least not reduce the level of safety. With more digital devices connected to the Internet of Things, safety and availability of these connected systems cannot be taken for granted and so careful planning is required. New opportunities are also provided for cities to enable active participation by its citizens, like neighbourhood watch groups.

Digital Life brings a paradigm shift for the concept of trust as an element with multiple dimensions, combining, for example, privacy, security, reliability, availability and integrity with human and machine behaviour. In this context, there is a need for greater understanding of how individuals interact with machines (cognitive science) and how machines/things interact with other machines/things (semantic interoperability) with respect to the extension of trust to assure a safe and secure environment that combines elements of physical, digital and virtual worlds.

The vision is to provide products and solutions that help to ensure high levels of security and safety wherever we are, while at the same time ensuring an adequate level of personal data protection to ensure privacy.

New surveillance systems based on AI could help in the early detection of threats or alarm conditions of all sorts (from accidents, burglary, vandalism or terrorist attacks), while other technologies (like augmented reality and advanced robotics) will help to bridge the gap between the virtual and the real world, offering new safe and secure ways for users to access the new services.

Given the ever-increasing dependency on digital products and online services much attention must be paid to address the demand for a permanent uptime and the vulnerability in case of failure. This also implies an increasing need to have a high data rate communications infrastructure that can offer real-time and continuous secure and reliable services.

5.2.1.2. Health & Comfort

The pervasiveness and the increasing proliferation of digitisation in different application domains is an enabler for innovative environments. The ever-smarter environments in which people will live are characterised by a high degree of heterogeneous interaction, seamlessly providing services to ever better support of our habits and actions for health, comfort and leisure.

We want to foster these smart spaces, envisaging the expected benefits they can provide, also on health, comfort and leisure:

- At **personal space**: improving the awareness of our body 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) and possible future injury or disorders.
- Smart systems can also offer an immersive experience, on vision, gaming and sensory interaction though VR or AR. Consumers can be offered the Immediacy, Individualisation, Interactivity, and Immersion they expect for media content consumption.
- At **private space** with healthier and more comfortable environment based on personal preferences (on temperature, humidity, air flux) in the context of running activities and clothing: adapting lighting and acoustic quality to one's own sense of wellbeing. Providing capability to comfortably communicate and interact remotely with people, institutions and sellers, possibly without leaving home.
- At **office space**, remote connections and large interoperability enable office operations and business opportunities around the world. AR vision and AI will assist operators and workers. Work is made more comfortable and personalised to the actual workers' condition and age.
- At **public space**, a smart guidance system will interact with the public showing relevant information on promotion, on opening hours, or tourist info. Augmented and virtual reality can extend what we see in meaningful way and provide new experiences while visiting a city and/or a museum.

These are just a few examples for the implementation of the Digital Life. New products and solutions will make our everyday life healthier and more comfortable and should enhance social cohesion through digital inclusion.

5.2.1.3. Anticipation

The increasing awareness of the smart environment allows observations of behaviour to be extrapolated into profile-based predictions of human intent. Such predictions can be used to anticipate events and offer an appropriate service at just the right moment (before asking) which includes user-friendliness, usability and usefulness and calls for contributions from the social sciences.

- In a **personal space**: anticipation can be provided through a digital watch or other personal coaching device (serving as a kind of "digital twin"), offering remarks for self-improvement activities such as fitness, diet, set goals and agenda.
- In a **private space** with trusted people: anticipation can imply the e-butler functionality by providing suggestions for recipes and meals, or entertainment/gaming in-house or external, based on the proclivities of the individuals in the group.
- In an **office space** with colleagues: anticipation can be based on asset tracking, organising activities under consideration of availabilities, absence and replacement.
- In a **public space**: aanticipation can be provided through smart traffic management and/or asset tracking, considering forecasted values derived from analysis of historical data. This is also true for retail environments, both physical and virtual.

5.2.1.4. Sustainability

Based on the motto of "Towards a sustainable Digital Life" the vision for this Major Challenge 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. Energy consumption is increasing year over year. Smart products and IoT devices for a Digital Life will help to reverse this trend. In particular, we are addressing the following spaces:

- Sustainable **personal spaces**: Optimised energy consumption with sleep mode / feedback / reminders / coaching / guidance to users about usage and waste of resources as part of the "quantified self" (incl. efficient charging of smart device and wearables) …
- Sustainable **private spaces**: Comprehensive assessment of resource usage to identify largest areas of consumption. Offer solutions for lighting, heating, computing with reduced usage of energy and other resources. Also, solar panels and batteries, home-grown vegetables and city farming systems.
- Sustainable **professional spaces**: Providing IoT/smart systems that support the digital business life with the minimum amount of resources (energy, water, paper, …) ensuring a highly efficient, productive and sustainable working environment. Furthermore, the reduction of (food) waste in supermarkets and restaurants as well as resource recycling.
- Sustainable **public spaces**: Traffic management for efficient use of energy supporting different types of mobility. Smart water management to protect resources. Intelligent management of energy at public places such as football stadiums and railway stations, including smart street lighting. Promoting green areas in the cities and enable citizens to provide their own sustainable solutions.

5.2.1.5. Game changers

Europe is in the middle of a changing world with an ageing population that is living more and more in urban environments. This is challenging the preservation of natural resources, air quality, clean and efficient transportation, new infrastructures, and the like, all in relation to the quality of life. Together with a climate change in progress this poses major challenges.

Apart from technological advancements, important driving forces for futures changes are the general desire for access to any information and the adaption to rapidly changing circumstances. Moreover, the increasing possibilities to take control as (a group of) citizens without authority involvement can have far reaching consequences (e.g. bitcoin, Twitter, maker communities, …).

The general trend in which the service providers are becoming ever more the mere carrier of demand and response of services without requiring the ownership of the resources themselves potentially impacts everyone's life and habits. Additionally, instruments provided by the pervasive digitalisation and extended interconnection reinforce the convergence between traditionally "institutional" and/or "professional" service providers and less "professional" and possibly "occasional" or "temporary" providers. The obvious examples concern B&B and taxi services, but it is also in the concept of prosumers within a smart grid. The mobile digital payment trend, triggered by EU regulation PSD2 (2015/2366/UE), is further stimulating this.

The in-vehicle transit / on-the-move experience will increasingly be a defining feature of the future of mobility. As shared and autonomous mobility proliferate, a tremendous opportunity arises for companies seeking to sell content, entertain and generally enhance the time spent in-transit. "Experience enablers" — content providers, in-vehicle service providers, data and analytics companies, advertisers, entertainment equipment providers and social media companies — will clamour to make the in-transit experience whatever we want it to be: relaxing, productive or entertaining [69].

↑

[69] *The future of mobility: What's next? https://dupress.deloitte.com/content/dam/dup-us-en/articles/3367_Future-of-mobility-whats-next/DUP_Future-of-mobility-whats-next.pdf*

Many anticipating devices will be wearables. Often there appears to be a demographic divide among the users, mainly in the age bracket between 25 and 54 and encompassing the fittest users. Recently the market has grown and opened up to younger consumers and those doing moderate or no exercise [70]. The smart phone as the only connection to cloud and internet will be complemented and partially replaced by wearables. These, in turn, will become the most personal devices. They will replace items such as watches, GPS, glucose and blood pressure monitoring, identification documents and will support the user in relevant situations.

	POSITIVE FACTORS	NEGATIVE FACTORS
Internal factors To the EU ECS industry [71]	**Strengths:** Presence of strong industrial players in EU Citizen protection by EU through privacy regulations Much creativity in EU Great design capabilities in EU Experience in embedded systems	**Weaknesses:** Fragmented market across countries Limited start-up / VC culture Few social media companies in EU Personalised cloud providers from US …
External factors To the EU ECS industry	**Opportunities:** Ubiquitous availability of smart phones Low-cost availability of accurate sensors Advent of IoT, 5G and AI/DL Advent of VR, AR, BCI, Robotics, … Advent of self-parking car, …	**Threats:** Ageing population Rural-urban migration Climate change Competition from other continents …

F.40 *SWOT analysis / game changers*

5.2.1.6. Competitive situation

There are many different market segments involved. Most of them are dominated by US companies, but with strong competition from the EU, Japan and China. In a recent study, five of the top ten global suppliers for smart cities are American, three European and two Japanese.

However, there are some markets where the situation is quite the opposite, like the professional mobile radio whose market leader is a European company, or the surveillance segment where US and European companies account for one third of the market share each.

- The United States tends to compete in the field of sustainability through corporate-driven R&D&I, science and technology. For instance, large companies such as Google and Apple invest in home automation (e.g. Nest and HomeKit), expecting benefits for the consumer primarily in convenience and home security but at the same time unlocking a huge energy-saving potential if properly used.

- China has a mixed open/controlled model of central government-driven science, technology and corporate RDI aiming at sustainable growth. It will spend USD 361 bn on renewable energy by 2020 and USD 146 bn on semiconductors in "Made in China 2025". These gigantic programmes will enable smart systems that support sustainability according to China's positioning as world's climate leader and they will flood the world market just as smart phones are doing this today.
- The Japanese science and technology agency JST aims to realise a sustainable society by developing game-changing technologies for a low-carbon society and solving food and water issues. IoTs are used in Smart City projects in Japan initially as smart meters. Gradually the system will be linked to household appliances and individual as well as public transport to create sustainability via big data
- In China IoT has been announced as one of the strategic industries by China's State Council. Focal areas include Smart Cities, Environment and Sustainable Development and Big Data also in the MC2025 programme. Surveys (https://www.ericsson.com/en/trends-and-insights/consumerlab/consumer-insights/reports/wearable-technology-and-the-internet-of-things) in major markets worldwide show that the purchase intention for wearables such as fitness trackers, allergy alert scarfs, emotions sensing tattoos is highest among Chinese consumers [72].
- Japan has a long tradition in robotics research to compensate the effects of demographic development. The latest items are exoskeletons controlled by bio-electric signals from the user to lift heavy loads. Vision of smart home.
- Taiwan's government supports academic edge AI chip development project
- See http://www.design-reuse-embedded.com/news/201708054#.WZ8W4mcUlD8
- Qualcomm boosts machine learning capability by buying Scyfer (same link as above)
- AI Sees New Apps, Chips, says Qualcomm (same link)
- (Leisure) Creative Industries are a major player in the EU economy: the industry provides 7.7 million jobs in 2.2 million companies of which 85% are SMEs creating yearly revenue of EUR 625 billion [73]. The aggregate revenues for all media technology products and services providers in 2016 were USD 50.97 billion, where Europe and the Middle East together accounted for 43.3%, the Americas for 37.6% and Asia Pacific for 19.1% [74].

←

70 *Wearable technology and the IoT, Ericsson*

71 *EU industry here means the full Large Industry + SME + RTO + University eco-system*

→

72 *Wearable technology and the IoT, Ericsson*

73 *New challenges in media, content, and creativity sectors in Europe, by Albert Gauthier, Policy Officer Data Applications & Creativity, DG CONNECT, 2016 https://nem-initiative.org/wp-content/uploads/2016/11/ec.pdf*

74 *2017 IABM DC Global Market Valuation Report*

5.3. MAJOR CHALLENGES

5.3.1. Major Challenge 1: Ensuring safe and secure spaces

First and foremost, the spaces we live in must be safe and secure, both physically and virtually. Moreover, the digital services that we rely on must indeed be available.

5.3.1.1. Scope and ambition

The **scope** of this chapter covers many different locations:

- At **personal space**: Personal data should be protected to ensure privacy by developing and deploying the proper security and private mechanisms according to GDPR[75] EU regulation to avoid malicious tracking and attacks in the personal devices such as wearables, tablets and new other devices.
- At **private space**: Although we usually feel safe at home, statistics show that a high number of physical accidents happens at home, falls, poisoning and drowning being the main cause. Extra attention should be paid to the higher-risk groups of young children and elderly people. In the virtual domain, own control over personal data storage is necessary for privacy, where people are the owner of their data and decide for themselves whom to give access.
- At **professional space**: Activities related to smart manufacturing and healthcare are outside of the scope of this chapter, however safety and security in all other work environments are within the scope, covering office environments, agriculture and farming, construction sites, etc.
- At **public spaces**: Except for transportation, all other activities in public areas in a city are within the scope of this Major challenge.

The **ambition** of this MC is to provide systems and technologies that help avoid dangerous or harmful situations in any of the above-mentioned environments, while ensuring early detection and fast management of the incidents when they occur. The objective is to reduce the number of incidents and their impact while maintaining a low number of false alarms. These incidents include all that is caused by fortuitous accidents and by malicious acts. A critical aspect of the challenge is to ensure an adequate level of privacy for the users.

←

[75] *General Data Protection Regulation (GDPR) REGULATION (EU) 2016/679 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC Official journal of the European Union, online at: https://gdpr-info.eu/*

5.3.1.2. High priority R&D&I areas

- Emergency management and evacuation systems
- Real-time dynamic malware avoidance and detection systems
- Mission- and safety-critical, feature-rich communication systems for law enforcement
- Autonomous, dynamic user authentication, authorisation and trusted relations
- Distributed AI, cognitive learning and distributed security (based on blockchain technology or other concepts) and,
- Surveillance systems for both indoor private use and outdoor public use employing advanced video pattern recognition to allow large numbers of resulting video streams to be automatically monitored
- New concepts and architectures for increasing the trustworthiness and high availability of digital services and platforms, addressing ways to perform trade-offs between safety, security and availability

5.3.1.3. Expected achievements

Reduction of the number of incidents with respect to the current baseline, and mitigation of their impact through the usage of the new technologies, integrated in an emergency management system that enables adequate, well-coordinated response in time.

5.3.2. **Major Challenge 2: Ensuring healthy and comfortable spaces**

All spaces must support a healthy life, while providing comfort.

5.3.2.1. Scope and ambition

Exploiting Smart System Integration capabilities with Cyber Physical System approaches and integrating them into efficient IoT systems is required to provide the right collection of data for a true exploitation of digital analysis and to implement innovative services and appropriate physical actuation. Hence, there is interest in:

- SSI: sensors, actuations, harvesting, power management, miniaturisation, embedded computing, communication, etc.
- CPS: systems of systems, communication protocols and architectures, devices virtualisation, networking and ICT, edge computing, etc.
- Smart data analytics: systems virtualisation, digital twin, AI and machine learning methodologies (such as deep learning), taking into consideration that the things belonging to the IoT infrastructure can establish social relationships in an autonomous manner with respect to their owners, which derives from the integration of social networking concepts into IoT, virtual spaces and AR.

The ambition is to raise the awareness of the potential and the (social) impact of smart solutions for their adoption in critical situations and their essence in normal life. For example, providing a vehicle that is responsive to the driver’s physiological status (fatigue, alcohol rate…) is part of assisted driving and a safety issue from the point of view of the vehicle’s occupants as well as other drivers and pedestrians nearby; these smart solutions make their trip safer and more comfortable. Research and development should address the future implementation of Digital Life ensuring a right, safe and confidential environment in which to improve our quality of life.

The quality of life is also determined by the way consumers spend their leisure time, at home and on the move. Mobile technology is transforming the way people around the world consume media content and will continue to drive the expansion in overall media consumption. More technological advances will make it possible to place audiences in the middle of the action and to offer them *Immediacy, Individualisation, Interaction and Immersion*.

5.3.2.2. High priority R&D&I areas

- Development of sensor devices to measure and digitise physical quantities through low-cost, energy-efficient, highly accurate implementations, i.e. inertial and micro-nano-bio systems, air sensors, water quality sensors and more generally resource quality and environmental variables measurements, monitoring of infrastructures, skin and tactile sensors, utility smart metering, water quality analysis, etc.
- Compact, energy-efficient actuators to allow better physical activation using new mechatronic technologies, robotic concepts, self-navigating features and haptic interaction.
- Sensor and actuator data fusion technology and application of data analysis methodologies (possibly based on deep learning) and adaptive solutions in order to provide richer information derived from the data to allow users to make more efficient and more worthwhile decisions.
- Innovative edge computing solutions that allow a larger use of the more intelligent edge nodes (based on AI mechanisms), making them more effective in terms of communication, data processing, data storage, power consumption, security and privacy, so to ensure high autonomy (under battery operation) supporting wireless communications.
- Improvement on interoperability among different vertical domains to make the awareness of each context appropriately available (privacy, security and safety) to the other. Multi-protocol hardware and software platforms, standardised solutions.
- Improvement on wireless networking capability (on throughput, on consumptions, reliability, etc.) from Personal, Home and Local Area Networks up to Wide Area Network (based on Internet protocols) and promote the introduction of IoT applications including sensing and actuating for the development of more intelligent and easy to use solutions.
- For media content creation the move to IP, use of virtualised, software-based environments, UHD, and Virtual Reality will continue to alter the landscape of media. Humans and machines are becoming more interchangeable in many areas as data-driven automation increases. Data-driven automation will enable increased efficiency in live productions and new business models for multi-platform content delivery.

5.3.2.3. Expected achievements

Development of future solutions that contribute to healthy and comfortable life:

- Human-centric, open interaction platforms including wearables and portables connected, via IoT systems, to smart spaces (personal, office, public) in order to provide new kinds of services and enhanced personal experience.
- A large diffusion and adoption of IoT systems and more intelligent devices for smart home, smart building, smart office, smart grid, smart manufacturing, “SmartX”, favoured by improvement on wireless communication networks and on power harvesting capabilities.
- Collaborative robots (“cobots”) and cooperation with other machines and humans.
- Integration of physical things/objects with augmented reality and virtual spaces, as well well with AI / Machine / Deep learning capabilities.
- Distributed AI, AR vision and virtual spaces
- Smart media content generation and multi-platform content delivery
- Automatic adaptation to operator conditions and operator age
- Advanced sensors, data fusion, AI capabilities for autonomous vehicles, distributed augmented reality

5.3.3. Major Challenge 3: Ensuring anticipating spaces

Additional added value can be provided through anticipation mechanisms that provide the service *before* it is explicitly required.

5.3.3.1. Scope and ambition

The scope of ensuring anticipating spaces is formed by smart systems such as personal devices and robots that facilitate daily routines in all aspects of the digital life. These range from smart phones for personal organisation, robots at home/personal assistant, and large-scale systems to organising life at work and in the city. The ambition is to provide more intelligent systems that pro-actively support individuals (and society) in their daily affairs. Anticipating systems and services will have a sense of what is desired and required.

5.3.3.2. High priority R&D&I areas

- **Personal space**: wearables and smart phone as personal assistants can provide anticipation at the personal level.
- **Private space**: robotics in care and smart assisted living environments, enabling elderly people to lead a self-determined life. Imminent needs for support can be predicted through observation and monitoring of habits, regular events, and daily routines.
- **Office space**: anticipate and prepare events incl. reservation of meeting rooms, catering, travel booking providing of necessary elements, etc.
- **Public space**:
  - Providing navigation tips to avoid congestions, indication of free parking space, self-parking, street lighting on demand/need, public transportation schedules, etc.
  - Identification of the emergence of potential dangerous situations, technologies that use VR, AR and AI to provide education of security measures / crowd management (situation awareness, pedestrian circulation, …)
- Further development of data analytics (performed at the edge using machine learning capabilities) to perform the anticipation functionality in real time.

5.3.4. Major Challenge 4: Ensuring sustainable spaces

The state of the planet implies extra requirements to ensure survival in the long run. These include not only carbon neutrality, but also the managed use of scarce water resources and the availability of affordable housing in large megacities.

5.3.4.1. Scope and ambition

- The scope of the research and development efforts cover electronic components and systems to support smart energy, smart lighting, smart water management, and other “green” facilities in smart cities, smart buildings, smart homes, and smart agriculture.
- One important goal is to create a wide acceptance for energy saving products and services by ease of use and transparency of functionality in all aspects of the digital life.

5.3.4.2. High priority R&D&I areas

These are priorities for the R&D&I on technologies which are enabling the applications:

- Multi-modal traffic and parking management in congested areas (up to 40% of traffic in these areas is created by searching for parking spaces).

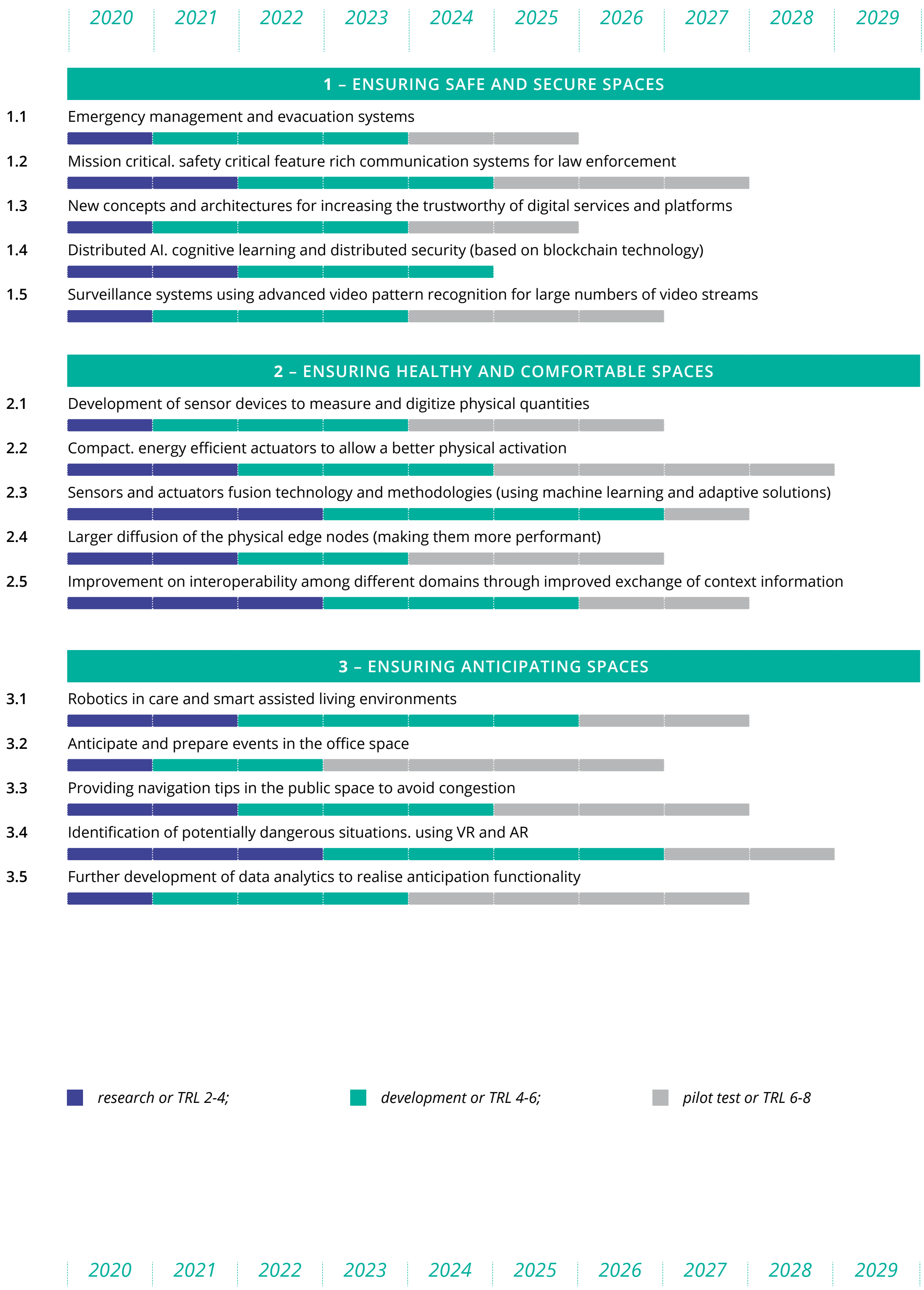
- Multi-modal (intermodal) traffic in sparsely populated areas (e.g. autonomous vehicles called on demand to/from the stations of the backbone railway line, since frequent public bus transport does not pay off, etc.), "Tram (small train units) on demand" etc.
- Overall transport automation in European regions (automated "robot taxis" vehicles complementing high speed railway lines, last-mile freight transport by automated vehicles or by small autonomous train units, etc.)
- Solutions addressing circular economy concepts to identify and separate recyclable material over the life-cycle of a product.
- Smarter edge devices (in sensor nodes/end devices, smart hub/gateway) including data analysis to reduce latency, data communication and power consumption.
- Monitor life-cycle of materials as part of circular economy to save resources.
- Concepts for smart street lighting (reducing energy usage while enhancing safety).
- Embedded air quality monitoring (particles/gas) solutions for efficient energy usage e.g. ventilation of buildings.
- Integrated sensors to detect leakage in ageing infrastructures.
- Systems solutions for sustainable agri-food industry preserving natural resources, reducing production waste, minimize the use of pesticide and/or facilitate the use of organic products to shift more and more to organic production.
- Energy-efficient horticulture lighting and animal-friendly poultry lighting.
- Serious gaming and gamification for educational purposes.
- Context awareness for energy reduction and improved living.
- Smart sleep mode for smart devices and wake-up functionality to conserve energy.
- Assessment tools for energy-saving technologies: well-to-wheel, total energy consumption including production phase as support for decision-making

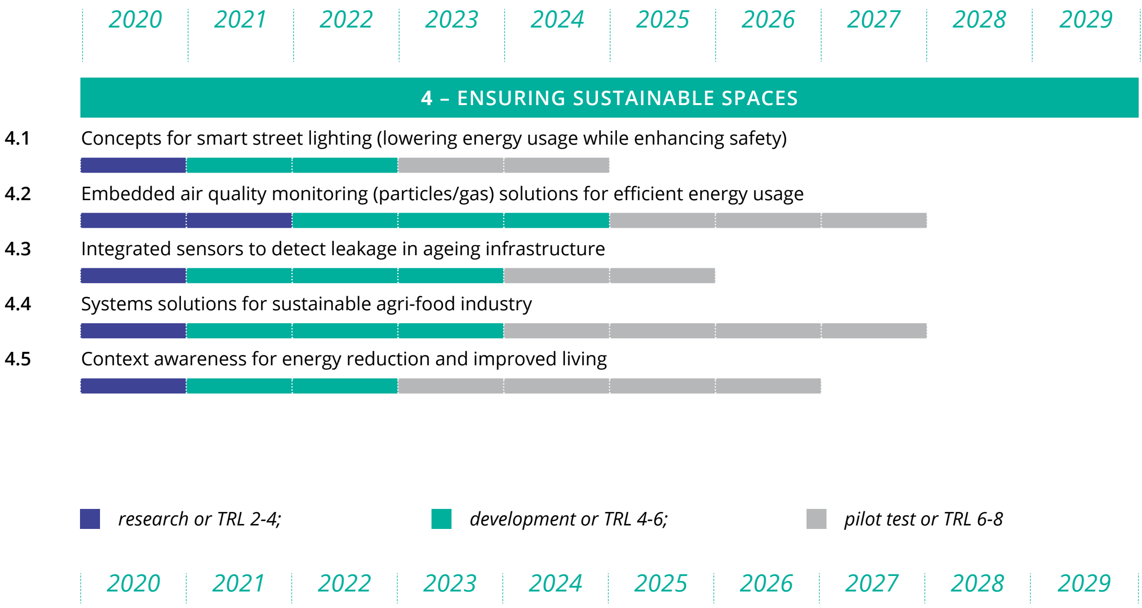
5.3.4.3. Expected achievements

Development of future solutions that contribute to sustainability and preserve natural resources

1. Smart energy monitoring by IoT devices embedded within Distributed Energy Resources
2. Extended battery life by ultra-low-power techniques
3. Creating frontrunners for sustainable Digital Life, i.e. projects in selected cities
4. Energy-efficient smart parking management systems, reducing traffic congestion
5. Energy efficient public safety systems, including alarming and evacuation of crowds (in a station or stadium) through personalised digital services

5.4.
TIMEFRAMES



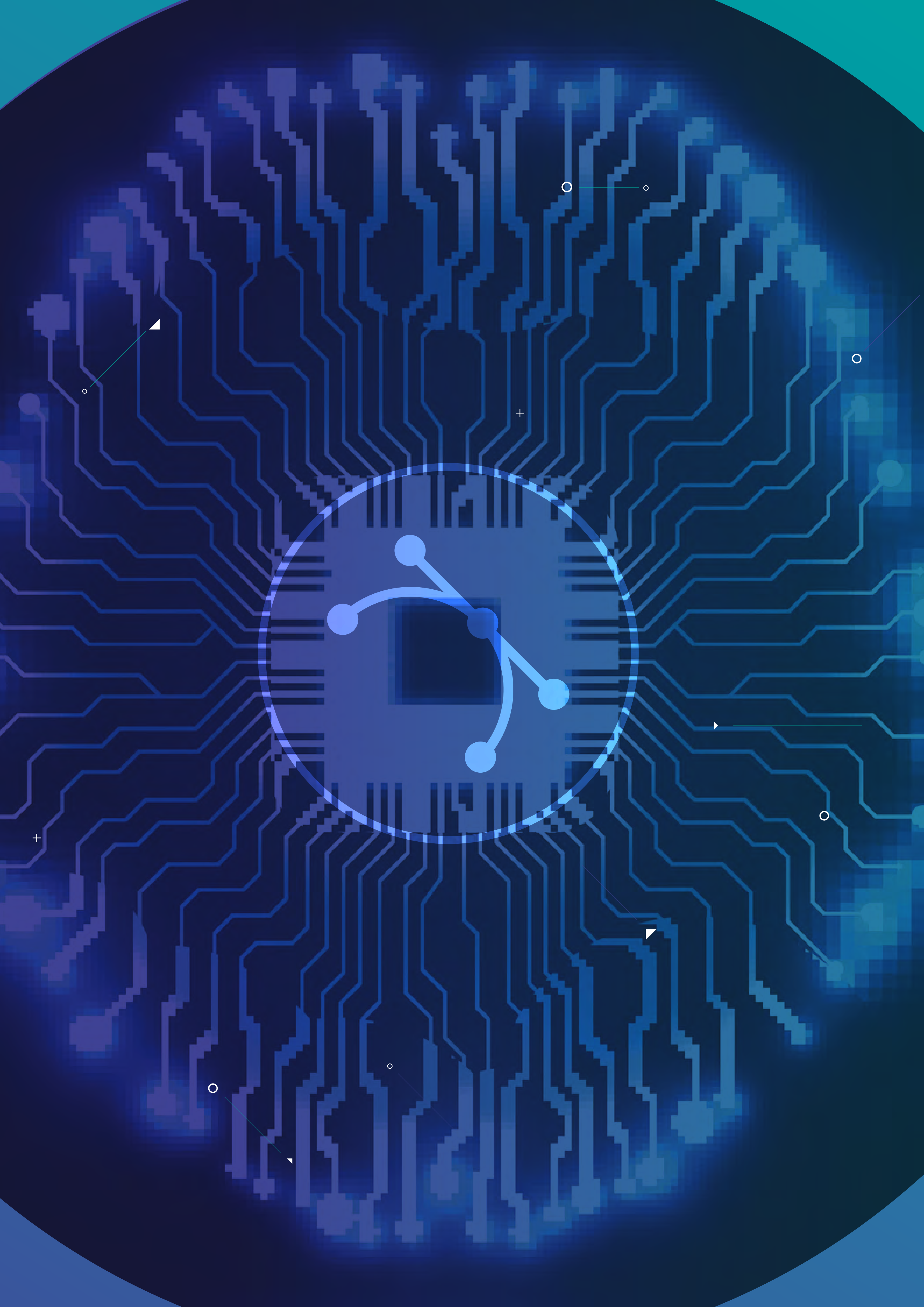


F.44 *Digital Life roadmap*

5.5.
SYNERGIES

With three other ECS SRA chapters there is some synergy, which has been delineated as follows:

- Health & Wellbeing: Where Healthcare aims to cure people of diseases, wellbeing implies measures to keep healthy people healthy. The Major Challenge “Ensuring healthy and comfortable spaces” will contribute to the aim to keep healthy people healthy by Digital Life supportive products and services.
- Multimodal Transportation / Mobility: Where the transportation chapter will mainly address infrastructure related aspects, Digital Life implies “being on the move” from time to time. The aspects address by the Major Challenges for Digital Life also apply when being on the move.
- Energy: Electrical Energy is a pre-requisite of a Digital Life, as smart devices live from 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 smart phones and other wearables can be an essential element of a Digital Life.



6

Systems and Components: Architecture, Design and Integration

6.1.
EXECUTIVE SUMMARY

Effective design technologies and (smart) systems integration, supported by efficient and effective architectures, are the ways in which ideas and requirements are predictively transformed into innovative, high-quality and testable products, at whatever level of the value chain (see in Figure 42).

The word system is used in this context for the respective highest level of development that is targeted within the given part of the value chain. 'System' may range from semiconductor device characteristics along chip or block level or from simple collections of software functions ('operating system') up to complex Cyber-Physical Systems of Systems (SoS) and products at the application level. A (hardware and/or software) 'system' designed and implemented at a given hierarchy level following a specific development process may be integrated as a 'component' into a higher-level 'system' within another development process.

On every level of the value chain, the top-level artefact to be developed is usually called "the system", even if it is used as a component on higher levels of the chain

F.42

These technologies aim at increasing productivity, reducing development costs and time-to-market ensuring the level of targeted requirements such as new functionalities, quality, system level performance, cost, energy efficiency, safety, security and reliability.

Design Technologies include methodologies involving hardware and software components, design flows, development processes, tools, libraries, models, specification and design languages, IPs, manufacturing and process characterisation. In addition, the creation of efficient, modular architectures and digital (software and/or hardware) platforms is needed to enable the system's intended functionality at the required quality, and support efficient, cost-effective validation and test methods.

Physical and Functional Systems Integration (PFSI) is targeting application-independent methodologies and technologies to develop and produce Electronic Components and Systems (ECS). Although, in practice, PFSI is often geared towards specific applications, the materials, technologies, manufacturing and development processes that form this domain are generic. Therefore, PFSI is one of the essential capabilities that are required to maintain and to improve the competitiveness of European industry in the application domains of ECS.

Mastering design and integration technologies for hardware and/or software components and systems, and extending them to cope with the new requirements imposed by modern and future ECS, are highly important capabilities of European industries to ensure their leading position in ECS engineering and to move innovations into products, services and markets.

The objective of the proposed R&D&I activities is to leverage progress in **Systems and Components Architecture, Design and Integration Technologies** in order to create world-class innovations on the application level, as described in Chapter 1–5 of this SRA.

6.2. RELEVANCE

Effective architectures, design methods, development approaches, tools and technologies are essential to transform ideas and concepts into high-value innovations, realised by innovative, cost-effective, producible and testable ECS, and by products and services based on them. They provide the link between the ever-increasing technology push and the high demand for new and innovative products and services of ever-increasing complexity that are needed to fulfil societal needs (application pull). At the same time, they aim at increasing productivity, reducing development costs and time-to-market, and to ensure the meeting of all requirements – such as on quality, performance, cost, energy and resource efficiency, safety, security and reliability.

Design technologies enable specification, concept engineering, architecture exploration and design, implementation and verification of complex ECS. In addition to design flows and related tools, design technologies also embrace platforms and frameworks (hardware and software), artificial intelligence and learning technologies, libraries and IPs, process characteristics and methodologies, including those to describe the system environment and intended use cases of products. They involve hardware and software components, including their interaction and the interaction with the system environment, and also covering integration with (cloud-based) services and ecosystems. They include reference architectures, digital platforms and other (semi-) standardised building blocks, as well as methods and processes to support new technology innovations – like e.g., advances in artificial intelligence techniques and deep learning – and their application within the products to be designed. Ideally, they are based on standards, i.e. for production quality assurances such as on safety, reliability, etc.

Moreover, the importance of software in ECS is increasing since one current trend involves a shift of features from hardware to software. This trend aims at increased usage of standardised hardware components (reducing the costs due to higher volumes), and creating advanced and customisable features in software (increasing flexibility and allowing easier updates and improvements). This trend is even more pronounced at the higher levels of the value chain. According to a recent study, for the highest-level ECS-based systems, applications and solutions, "the market is expected to grow tenfold [from 2016 to 2025], reaching between €3.9 and €11.1 t[rillion], according to McKinsey. This [level] is strongly driven by software content, and the ability to capture this growth will be heavily dependent on (i) building software engineering and development capabilities, and (ii) relying on scalable business models and infrastructures to operate as global platforms in Europe and beyond." [76] This shift is thus required to meet the needs of the market, which requires not only safety and security but also short time-to-market and development cycles. Systems architectures, design technologies and especially validation and testing processes have to follow this shift to enable European industry to target a continuously changing market.

Future smart systems will feature new applications, higher levels of integration, decreased size, and decreased cost. Miniaturisation, functional integration and high-volume manufacturing will allow to install sensors even in the smallest devices. Given the low cost of sensors and the large demand for process optimisation in manufacturing, very high adoption rates are possible. By 2025, 80–100% of all manufacturing could use IoT-based applications. Then, improved integration technologies and miniaturisation will enable patient monitoring devices for a broad range of conditions. Furthermore, cost-efficient manufacturing will increase the market penetration of advanced driver assistance systems and will enable highly automated and even autonomous driving.

Components are versatile in terms of design (size, flexibility), material or composition, and thus the network of stakeholders involved in a production process of smart systems is equally complex. If one keeps in mind that Europe's supply chain towards smart systems production consists of more than 6,000 large companies and SMEs [77], new models for more efficient production processes that can react instantly to sudden market developments need to be developed. Short lifecycles of products and fabrication on demand are two important issues, as is the increased demand for smart technologies regarding size, performance, quality, durability, 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 further importance and be regulated progressively

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[76] *ARTEMIS-IA and Advancy (eds.). Embedded Intelligence: Trends and Challenges, 2019, page 17, available at https://artemis-ia.eu/publications.html.*

[77] *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.*

6.2.1. Game Changers

While the objectives outlined above have been pursued even for the very first instances of electronic systems embedded into products, a number of new demands are coming from the rapidly increasing complexity of ECS to be designed. Even more critical is the appearance of 'game changers' arising from the stepwise changes in system evolution. Among these 'game changers', many of the ones described in Section 0 apply for Architecture, Design and Integration Technologies, too: Safety and Security (cf. Sec. 0.2.3, and also Chapter 8) are overarching goals that we have to target. Increased connectivity of ECS, increased importance, capabilities and complexity of software, including the advent of Artificial Intelligence and learning systems (cf. Section 0.2.1), all increase the complexity of the design and integration task and require new methods, processes and tools supporting their cost-efficient design, development, integration, and verification, validation and tests.

Among the 'game changers', the most critical are:

- **Highly automated (up to autonomous) networked systems and systems of systems:** ECS are becoming increasingly networked with each other as well as with 'cloud-based' services. This forms tightly interacting Systems of Systems (SoS) and creates machine-to-machine interactions without any human intervention in the control loop. Engineers need to be able to handle the added complexity of creating and interfacing different subsystems introduced into the market at different times and adhering to different and evolving standards. Moreover, there is typically no single 'system integrator', but networked SoS are formed in a dynamic and ad-hoc manner. These include constituent sub-systems that evolve and are updated at different intervals and times with possibly unforeseen emerging behaviour. This requires completely new methods and techniques, such as scenario and model-based safety analysis, online safety assessment, re-certification, architectural support not only for the functionality but also for verification, and many similar.
- **Artificial intelligence and machine learning:** While recent advances in this area enable a huge potential for new and advanced features of future ECS and Cyber-Physical Systems (CPS) – prominent examples of which are self-evolving systems, autonomous systems and similar (see also Chapter 0.2.1) – they bring enormous challenges as well as large potential benefits for System Design and Integration. These challenges are in safe design, verification and validation (V&V) technologies and testing, due to the fact that analysing AI-based systems and guaranteeing their system properties like safety, security, dependability is still a mostly unsolved problem yet an indispendable activity in System Design (keywords 'Safe AI', 'Explainable AI'). On the other hand, employing these techniques in the design process itself – i.e. for test case generation, architecture exploration, solution space searches, etc., as well as for collecting and analysing run-time data from the field for continuous processes – has a very high potential of improving design and integration activities substantially. Additionally, these applications require new computation platforms for both server-based execution and embedded platform execution.
- **Design for a larger world:** ECS span more than one application domain. Example domains include Embedded Systems and the Internet / Cloud, or consumer electronics and assistance systems in cars. Moreover, ECS based products in general have a long lifetime (up to several decades, e.g. for airplanes), during which they might encounter new situations in the environment in which they are meant to operate, and new unforeseen requirements to their behaviour (e.g. changing regulations, etc). The design therefore has to expand its scope including the full ECS system, its application environment and its evolution. The complete (foreseeable) lifecycle of the product must be covered, and potentially different lifecycles/lifetimes of its components must be taken into account.

Tough challenges are also coming from the trends already present in ECS evolution today, including:

- **Human Machine Interaction:** ECS and especially CPS interact with each other and with human beings: Human Machine Interaction, Human Machine Cooperation and adaptation of machines to human needs thus are increasingly important topics in systems design.
- **Personalised functionalities and Variant Management:** ECS based products are often highly configurable to adapt to users' needs and requirements. Thus, product variability is increasing vastly. The challenge here is to adapt and enrich the Design Methodologies (especially the Software Engineering ones) and have corresponding tools to support these changes.
- **Increasing importance of software and data:** Features are shifting from hardware to software to improve variability, adaptability, upgradability and evolvability. Therefore, software engineering (approaches, tools, frameworks and platforms) is of increasing importance and needs to be adapted to the specific requirements of ECS. (Big) Data is taking a central position for future business, and so efficient software tools, co-designed with hardware systems, have to be considered a key issue in the design of next generation electronic systems.
- **Increasing and different speed in development processes:** Consumer electronics technologies used in industrial, infrastructure or automotive applications, for example, have much shorter development cycles and must therefore be updated/exchanged significantly more often than the core technologies in the other areas.

These game changers for developing modern and future ECS give rise to seven 'Major Challenges', that are detailed in Section 6.3.

6.2.2. Competitive value

Traditionally, European industry has had a leading position in Systems Engineering, allowing it to build ECS based products that meet customer expectations in terms of innovative functionality as well as quality. Design technologies – processes and methods for development, testing and ensuring qualities of the Hardware, the Software and the complete system, as well as efficient tools supporting these – are a key enabler for this strong position. Facing the new requirements and game changers explained above, it is of utmost importance for these industries to put significant resources into R&D&I activities to maintain and strengthen this leading position and to enable them to satisfy the needs of the different domains while reducing the development cycles and costs.

Europe also has very strong system houses producing complex innovative high-tech designs for products in the areas of aeronautics, automotive, industrial applications and manufacturing, healthcare, and communications. To maintain their world-leading positions, a continuously push for improved electronic systems at increasing levels of automation is essential while sustaining high quality in parallel. "The starting position seems relatively good, with the EU's market share currently estimated at 13% of the markets for [equipment and tools used to create ECS/CPS, electronic components and electronic boards] and between 20% and 40% for [system of systems, applications and solutions]. However, given the rapid, ongoing changes and the scale of growth expected for this last stage, cards are likely to be reshuffled and it is in no way guaranteed that Europe's position in a solution-oriented market will become ten times larger than it is today [thus matching expected market growth in this level]" [78].

Large EDA (Electronic Design Automation) companies currently provide mainly tools and methodologies for specific design domains (digital macros, analogue & RF macros, SW, package, PCB) which are only roughly linked and mostly not focused on European needs in design technology. Higher design levels are not well covered, even though some initiatives for the support of higher levels of abstraction do exist. Large system and semiconductor companies normally combine available (partial) solutions with (non-standardised) in-house solutions. A comprehensive seamless open and extendable open design ecosystem across the whole value chain must therefore be created, especially for supporting heterogeneous applications. Yield, heat, and mechanical stress need to be addressed in a more holistic way. This will become increasingly critical as parts are deeper embedded into packages (e.g. SiP, SoC) and opportunities for re-work, inspection and repair diminish. For the same reasons, design for testability and manufacturability are critical with a need to model and simulate processes as well as product behaviour.

To remain competitive, it is of utmost importance for Europe to develop and offer, at the right time, sophisticated feature-rich innovative products with the superior performance and quality needed to justify a higher price tag. Time-to-market is crucial, since even a one-month delay in market introduction can result in a significant loss of revenue in fast moving markets, or in the complete loss of seasonal consumer markets. Life cycle cost analysis is also critical to ensure that installation, operation, maintenance, re-configuration resp. updates and evolution over the complete product life cycle, re-cycling, etc. are all taken into account. Europe's competitiveness in ECS offerings will be enhanced for many applications when such a holistic assessment is undertaken.

The Smart Systems sector in Europe covers nearly all required technologies and competencies. With more than 6,000 innovative companies in the EU, the sector employs approx. 827,600 people (2012), of which 8% or 66,200 are involved in R&D with a budget of EUR 9.6 bn per year [79]. New R&D&I actions are expected to further strengthen the European leadership in Smart Systems technologies and to increase the global market share of European companies in the sector. New Smart System solutions will feature higher levels of integration, decreased size and decreased cost. Time to market for subsequent products will be reduced by new designs, building blocks, testing and self-diagnosis strategies, methods and tools capable of meeting the prospect use-case requirements on reliability, robustness, functional safety and security in harsh and/or not trusted environments.

Tackling the Major Challenges introduced in Section 3 will enable European Industry as a whole to benefit from the progress made in innovative electronic components and systems.

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[78] *ARTEMIS-IA and Advancy (eds.). Embedded Intelligence: Trends and Challenges, 2019, page 17, available at https://artemis-ia.eu/publications.html*

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[79] *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*

6.2.3. Societal benefits

Society wants high-end technologies on a large scale and at affordable cost. Within the global trends of becoming a world where everything is connected, everything is smart and everything is safe and secure, design technologies and physical and functional systems integration are two of the key enablers for this development. First, they enable modern and future ECS based products with the required functionality and quality to be built at all. Second, they ensure products that meet and exceed the required quality – i.e., products that are safe and secure, dependable and reliable, recyclable, serviceable, etc. – thus allowing these products to enter the market and increase user trust and confidence in using these products. Third, they enable cost-efficient production of these products, thus making them affordable. Last, but not least, they allow increasing 'smartness' of products and, together with the 'Digitalisation' process – allow disruptive improvements in each aspect of human life; therefore market opportunities are huge.

6.3. MAJOR CHALLENGES

The 'game changers' identified above and the new requirements stemming from societies needs for innovative, high-quality, testable, deployable and affordable ECS based products give raise to the following Major Challenges in Architecture, Design Technologies and Integration:

- Managing critical, autonomous, cooperating, evolvable systems
- Managing complexity
- Managing diversity
- Managing multiple constraints
- Integrating features of various technologies and materials into miniaturised smart components
- Effectively integrating modules for highly demanding environments
- Increasing compactness and capabilities by functional and physical systems integration

These challenges are strongly interdependent and address each system from two sides: While the first four challenges focus on perspectives of architecture and design prior to the ECS fabrication, the last three challenges take the perspective of application-independent integration technologies of ECS at the different aggregation levels. Feedback from these integration technologies closes the loop as an important input for the continuous improvement of architecture and design.

Challenges are not disjoint, since various interactions exist between them. For example, diversity and multiple constraints may significantly contribute to an increase in complexity. Hence, each challenge emphasises a specific set of obstacles to be overcome in order to realise the vision, but always closely interacts with the other challenges.

Furthermore, all challenges commonly face the demand of integrating design technology aspects into an ecosystem for processes, methods and tools for the cost-efficient design working along the whole value chain and lifecycle (cf. Section 6.5).

6.3.1. **Major Challenge 1:** Managing critical, autonomous, cooperating, evolvable systems

6.3.1.1. Vision

Many new and innovative ECS products exhibit an ever-increasing level of automation, an ever-increasing capability to cooperate with other technical systems and with humans, and an increasing level of (semi-) autonomous and context-aware decision-making capabilities in order to fulfil their intended functionality. Increasingly, software applications will run as services on distributed system-of-systems involving heterogeneous devices (servers, edge devices, etc.) and networks with a diversity of resource restrictions. In addition, ECS need the capability to evolve and adapt during run-time, e.g. by updates in the field and/ or by learning. Building these systems and guaranteeing their safety, security and certifiability requires innovative technologies in the areas of modelling, software engineering, model-based design, V&V technologies, especially for AI-based systems, and virtual engineering for high-quality, certifiable ECS that can be produced (cost-)effectively. 'Modelling' has to tackle systems and their environment, heterogeneity in processing environment, humans as operators and cooperation partners of these systems, as well as use cases and scenarios. On the other hand, software engineering comprises quality of the process, the service and the product, innovative development approaches, including continuous development, usage of software platforms in the application and frameworks for the development, integration/re-use of legacy (software) components/models, digital twins, etc.

6.3.1.2. Scope and ambition

R&D&I activities in this challenge aim at enabling seamless and concurrent model-based development methods and tools for critical systems, with a strong focus on V&V and testing activities and is strongly connected to technologies for dealing with heterogeneous, dynamic, distributed processing environments (abstraction, application of local-global principles, …) covered in major challenge 4. Important topics include models, model libraries and model-based design technologies, V&V and test methodologies and tools, and (virtual) engineering of ECS.

6.3.1.3. High priority R&D&I areas on critical, autonomous, cooperating, evolvable systems

The topics of major challenge 1 are collected into three categories (high priority R&D&I areas), which are described here. For each of the areas, the timelines in section 6.6 contain an elaborated list of the corresponding R&D&I topics, the full list for each area is given in section 14 of the document, "Appendix to Chapter 6".

Models, model libraries, and model-based design technologies

Topics grouped under this heading include re-usable, validated and standardised models and model libraries for systems behaviour, systems' context/environment, SoS configuration, communication and dynamics, and humans (as operators, users and cooperation partners). Additional important topics in this area are model-based design methods, including advanced modelling techniques for future ECS and extended specification capabilities, all supported by advanced modelling and specification tools.

Verification and Validation (V&V) and Test for critical systems: Methods and Tools

This area comprises model-based verification, validation and test methodologies and technologies, as well as interoperable tool chains and platforms for critical systems, applications and services running on distributed heterogeneous system-of-systems. Furthermore, it deals with automated derivation of verification procedures and back annotation, V&V and test methods for the lifecycle and in-service phase, system-of-system reconfigurations, resource constrained communication and distributed processing and control, and V&V and test methods for AI-based adaptive, cognitive and learning systems and autonomous systems.

(Virtual) Engineering of Electronic Components and Systems

Collaboration concepts and methods across groups, organisations, and disciplines for holistic (virtual) engineering of ECS over the whole value chain is the main topic in this R&D&I area. This includes methods, interoperable tools and frameworks for virtual prototyping of complex ECS, including dynamic heterogeneous SoS configurations and appropriate engineering support (libraries, platforms, digital twins, and interoperable tools for evolvable, adaptable Open World Systems, including cognitive and cooperative systems).

6.3.2. Major Challenge 2: Managing Complexity

6.3.2.1. Vision

With the increasing role of electronics systems and especially under the influence of connected systems, e.g. in IoT, CPS, etc., the complexity of new and innovative ECS (including its increased amount of software while miniaturising components and systems) is continuously increasing. Better and new methods and tools are needed to understand and handle this new complexity, and enable the development and design of such complex systems and SoS. This allows meeting all functional and non-functional requirements, and to achieve cost-effective solutions with high productivity. This challenge focuses on complexity reduction techniques in the design and analysis of such ECS, in order to increase design productivity, efficiency and reduce costs.

6.3.2.2. Scope and ambition

R&D&I activities in this area aim at developing solutions for managing the design of complex ECS in time at affordable costs. They focus on architecture principles for components, systems, and system-of-systems, and on systems design topics to reduce complexity for the design, V&V and testing of such ECS systems, methods and tools to increase design efficiency and reduce the complexity of V&V and Test methods.

6.3.2.3. High priority R&D&I areas on Managing Complexity

Topics of Major Challenge 2 are grouped into four categories (high priority R&D&I areas) described here. For each of the areas, the timelines in section 6.6 contain an extensive list of the corresponding R&D&I topics, the full list for each area is given in section 14 of the document, “Appendix to Chapter 6”.

Systems Architecture

This area groups extended methods for architectural design on all levels of the hierarchy from components via groups of components to systems and SoS. It covers support for systems (of systems) with thousands of possibly distributed components, spanning Embedded Systems, Cloud-, Edge- and Fog Computing, metrics for functional and non-functional properties, and early architectural exploration. It includes design methods and architectural principles, platforms and libraries supporting V&V, Test and Lifecycle Management of complex, networked ECS, including support for self-management, self-awareness and self-healing. In addition, support for distributed control, for big data handling (data gathering, monitoring and analytics for anomaly detection and preventive maintenance), for Artificial Intelligence and Deep Learning techniques, as well as for cognitive and adaptive systems is included.

System Design

Design and Analysis methods for all ‘Systems’ within the Design hierarchy (from the simplest component via systems and system of systems, cf. Figure 42) are the focus of this area. Beyond the methods and techniques already covered in the other three categories of this challenge, system design includes general design techniques supporting multi-/many-core systems, IP modelling and component-based HW/SW co-design approaches. It also includes handling of big data applications, artificial intelligence and deep learning technologies as well as handling functionalities allocated across various resources both local and distributed in the Cloud, and methods and tools for virtual prototyping and digital twins.

Methods and tools to increase design efficiency

The main topics of this area are seamless and consistent design and tool chains for automated transfer (extraction, synthesis, …) of system design descriptions into functional blocks, strong support of package and board and sensor/MEMS co-design. Furthermore, it comprises new methods and tools to support new design paradigms (like multi-/many cores, SoS configurations, increased software content, GALS, neural architectures, etc.), new technologies (FD-SOI, graphene, etc…) and new approaches to handle analogue/mixed design.

Complexity reduction for V&V and test

Coping with the complexity of V&V and test methods for modern ECS (including software running on heterogeneous SoS configurations, involving legacy software, devices and components) is the focus of this area. This includes techniques (and tool support) for (automatic) complexity reduction, handling of variability, methods and tools to support scenario-based V&V and test, virtual platforms in the loop and similar, as well as techniques to assess the safeness, soundness and compliance to (safety and security certification) standards of these complexity reduction techniques.

6.3.3. Major Challenge 3: Managing Diversity

6.3.3.1. Vision

In the ECS context a wide range of applications has to be supported. With the growing diversity of today's heterogeneous systems, the integration of analogue-mixed signal, digital, sensors, MEMS, actuators/power devices, transducers and storage devices is required. Additionally, domains of physics like mechanical, photonic and fluidic aspects have to be considered at system level and embedded and distributed software. This 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).

6.3.3.2. Scope and ambition

R&D&I activities in this area aims at the development of design technologies to enable the design of complex smart systems and services incorporating heterogeneous devices and functions, including V&V in mixed disciplines like electrical, mechanical, thermal, magnetic, chemical and/or optical.

6.3.3.3. High priority R&D&I areas on Managing Diversity

The main R&D&I activities for this third challenge are grouped into four categories (high priority R&D&I areas):

Multi-objective optimisation of components and systems

The area of Multi-objective optimisation of components, systems and software running on SoS comprise integrated development processes for application-wide product engineering along the value chain. This includes modelling, constraint management, multi-criteria, cross-domain optimisation and standardised interfaces. Furthermore, it deals with consistent and complete co-design and integrated simulation of IC, package and board in the application context and modular design of 2.5 and 3D integrated systems (reuse, 3D IPs, COTS and supply chain integration, multi-criteria design space exploration for performance, cost, power, reliability, etc. …).

Modelling and simulation of heterogeneous systems

The area of modelling and simulation of heterogeneous systems comprises hierarchical approaches for modelling on system level, modelling methods considering operating conditions, statistical scattering and system changes as well as methods and tools for the modelling and integration of heterogeneous subsystems. Furthermore, it deals with methods for HW/SW co-simulation of heterogeneous systems and software running on SoS at different abstraction levels, different modelling paradigms, modelling methods and model libraries for learning, adaptive systems and models and model libraries for chemical and biological systems. Finally, there is a need for the development of tools for heterogeneous model management and analytics, probably supported by AI techniques such as machine learning.

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 AMS designs, harmonisation of methodological approaches and tooling environments for analogue, RF and digital design and automation of analogue and RF design.

Connecting the digital and physical world

The area of connecting the digital and physical world comprises advanced simulation methods (environmental modelling, multi-modal simulation, simulation of (digital) functional and physical effects, emulation and coupling with real, potentially heterogenous hardware) and novel More than Moore design methods and tools.

6.3.4. **Major Challenge 4:** Managing Multiple Constraints

6.3.4.1. Vision

Beyond its pure functionality, different types of properties characterise ECS designs. Non-functional properties especially tend to determine the market success or failure of a product. Since many of them originate in the physical realisation of the technology, these properties cannot be analysed or optimised in isolation. Hence, we need appropriate models, methods and tools to manage multiple constrains (e.g. design for yield, robustness, reliability, safety), functional and non-functional (e.g. low-power consumption, temperature, time, etc.) properties as well as constraints coming from the (distributed, networked) applications themselves. As a long-term vision, we aim at an integrated toolset for managing all relevant constraints.

Managing multiple constraints will require the standardisation and integration of methods, tools and flows for analysing and optimising multiple constrains in a single holistic approach. This includes ultra-low power design, monitoring and diagnosis methods and tools, building secure extendable or evolvable systems and assessing opportunities to harvest from ambient energy sources to replenish power sources. Furthermore, a conditional monitoring of systems for anomalous behaviour of equipment and infrastructure and on-going dynamic functional adaptability to meet application needs is needed. The tackling of new technology nodes and efficient methodologies for reliability and robustness in highly complex systems, or SoS software, including modelling, test and analysis, considering variability and degradation is mandatory.

6.3.4.2. Scope and ambition

This major challenge tackles the development of design technologies considering various constraints (e.g. design for yield, robustness, reliability and safety), functional and non-functional properties (e.g. power, temperature, time, etc.) as well as constraints coming from the (distributed, networked) applications themselves. The cross-propagation of constraints among the different domains, nowadays involved in systems and their application contexts, is an important issue to be considered for system design.

6.3.4.3. High priority R&D&I areas on Managing Multiple Constraints

R&D&I activities in this challenge are grouped into three categories (high priority R&D&I areas)

Ultra-Low Power Design methods

The area of Ultra-Low Power Design methods comprises advanced methods for ultra-low power design – including e.g. the use of low-temperature electronics[80], design methods for (autonomous) ultra-low-power systems considering application-specific requirements and methods for comprehensive assessment and optimisation of power management and power consumption including the inclusion of parasitic effects.

Efficient modelling, test and analysis for reliable, complex systems taking into account physical effects and constraints

The area of efficient modelling, test and analysis for reliable, complex systems taking into account physical effects and constraints comprises hierarchical modelling and early assessment of critical physical effects and properties from SoC up to system level. Then it includes design and development of error-robust circuits and systems including adaptation strategies, intelligent redundancy concepts and adaptive algorithms. Furthermore, it deals with production-related design techniques, consistent methods and new approaches for (multi-level) modelling and analysis. It also addresses verification and formalisation of ECS's operational reliability and service life taking into account the operating conditions and dependencies between hardware and software, distribution and network issues in SoS and detection and evaluation of complex fault failure probabilities. Additionally, the area is about a consistent design system able to model and optimise variability, operational reliability, yield and system reliability taking into account dependencies and analysis techniques for new circuit concepts and special operating conditions. Last, but not least, it comprises advanced test methods, intelligent concepts for test termination, automated metrics/tools for testability and diagnosis, extraction of diagnostic information and methods and tools for monitoring, diagnostics and error prediction for ECS, including SoS.

Safe systems with structural variability

The area of safe systems with structural variability comprises architectures, components and design methods and tools for adaptive, expanding systems and SoS software. This comprises (self-) monitoring, diagnostics, update mechanisms, strategies for maintaining functional and data security, life-cycle management and adaptive safety and certification concepts. Additionally, it contains the realisation of real-time requirements, high availability and functional and IT security, evaluation of non-functional properties, analysis of safety and resilience under variable operating conditions. Furthermore, it is about novel simulation approaches for the rapid evaluation of function, safety and reliability and security concepts for adaptive, expanding systems and SoS software (self-monitoring, environmental analysis, ageing-resistant chip identification techniques, ensuring functional safety).

6.3.5. Major Challenge 5: Integrating features of various technologies and materials into miniaturised smart components

6.3.5.1. Vision

Components for ECS will use technologies from chapter 10 and additional technologies (based on polymere, ceramics, graphene, quantum effects, etc.) in an unprecedented variety by utilising heterogeneous integration technologies. Thus, they combine features based on nanoelectronics, micro-electro-mechanic, magnetic, photonic, micro-fluidic, acoustic, radiation, RF, bio- and chemical principles. Physical fabrication and integration of these components will require a multitude of materials and processes from silicon and non-silicon micro-nano, printing, lamination and other joining and assembling technologies as well as hybrid combinations of them. According to Yole Développement [79] the global MEMS and sensor market (excluding RF filter modules) will almost double from $48B in 2018 to $93B in 2024. Artificial intelligence and machine learning are increasingly migrating to the forefront of the information processing chain, and thus entering the systems, modules and even components level of integration. Despite the complexity, manufacturing will flexibly support multi-scale fabrication for the sake of appropriate unit costs.

6.3.5.2. Scope and ambition

Technologies for smart components such as sensors, actuators, semiconductor technologies, energy generators, storage devices, micro-nano-bio systems (MNBS), MEMS and LAE, need to be integrated into smart products to enable smart and sustainable functionalities and services. The components for these integrated smart systems represent a fusion of functionalities enabled by a set of materials, structural elements, parts or subsystems. The total complexity and diversity exceed that of the mere microelectronics components substantially, necessitating a tremendous increase in scope and efficiency. This also holds for the methods, processes and schemes to be utilised in the production, assembly and testing of these various components.

6.3.5.3. High priority R&D&I areas on Component Level Integration

The three high priority R&D&I areas identified to master the challenges in component integration are: i) Functional Features, ii) Materials, and iii) Integration Technologies and Manufacturing. The specific actions are noted and incorporated in their respective "Timeframes" section, while their full text can be found in section 14 "Appendix to Chapter 6" of this document.

Functional features

Innovative solutions are necessary regarding the long-term stability of the relevant components. The calibration effort has to be reduced drastically, especially in cases where e.g. the new generation of sensors is located inside the monitored processes and where the access by service/maintenance is too cost-intensive. Dramatically higher requirements in functional safety and system availability of safety-relevant components for the new solutions (e.g. automated cars, industrial automation, smart energy systems) have to be met, while keeping the systems affordable for a broader public by integrating micro- and nano-scale detectors for self-monitoring of essential integration features like interfaces (prone to delamination) and joints (risk of cracks).

Materials

Components for smart systems will use all kinds of semiconductors and other materials like polymeres and ceramics, as well as materials used by completely new technologies (e.g. graphene, quantum effects), utilising heterogeneous integration.

←

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

Integration Technologies and Manufacturing.

Highest volume production of smart components at minimum cost is necessary for the new consumer and industrial products by further advancement of miniaturisation, resulting in new challenges, as this brings e.g. sensors and signal processing for health monitoring and performance control in very close vicinity to wide bandgap power devices, which can be operated at high temperatures.

6.3.6. Major Challenge 6: Effectively integrating modules for highly demanding environments

6.3.6.1. Vision

Progress in performance and miniaturisation make ECS increasingly attractive and suitable for direct integration into all fields of applications, in which form factor, material behaviour or cost of the existing solutions have prevented their use so far. For example, motors can be improved in smart drives, which actively adapt to the various use conditions. Machine tools can gain precision, efficiency and versatility. Automotive systems can take over duties of the human driver. Energy or other infrastructure can flexibly adjust to the actual needs, perhaps even by changing from receiver to supplier. Exo- and endoskeletons can interact with the patient proactively etc. All with the help of smart electronic modules to be integrated.

6.3.6.2. Scope and ambition

In many of the new applications, the electronic modules will be exposed to very demanding conditions. At the same time, the dependence of human life on the safe function of the electronic modules will increase dramatically with the new applications. Hence, the future structures of electronic modules will not just show a strong increase in functional and structural complexity but also in diversity. They will show yet higher compactness with more features and materials integrated within a given volume. The new structural and fabrication concepts to be developed will make this possible but need to be able to reliably suppress any unwanted interactions and parasitic effects that may threaten the safe and dependable function of the new modules.

6.3.6.3. High priority R&D&I areas on Board / Module Level Integration

High priority R&D&I areas identified for the mastering of the challenges in Module Integration are also: i) Functional Features, ii) Materials, and iii) Integration Technologies and Manufacturing. The specific actions are noted and incorporated in their respective "Timeframes" section, while their full text can be found in section 14 "Appendix to Chapter 6" of this document.

Functional features

Smart system's modules are characterised by a significant increase in the level of complexity and heterogeneity, raising new sets of research challenges in addition to those covered in Challenge 2 and 3. Different types of components will be integrated in the same module for instance as SoC or SiP. Some components are packaged by microelectronics suppliers and some are developed for the specific application in a single compact module. Moreover, since module compactness is a key factor, solutions must be found to remove heat efficiently, especially when power devices are involved.

Materials

Smart ECS modules are intended to operate in a variety of environments, from harsh environments with extreme operating temperatures, exposed to vibration and chemicals in industrial and automotive applications, to the bio-compatibility and long-term stability required for implantable medical applications. A corresponding variety of materials has to be developed for the boards, the sealing and the packaging of the modules, also coping with the dramatically higher requirements in functional safety and system availability for the new solutions in all fields of applications.

Integration Technologies and Manufacturing.

System affordability for a broader public remains one of the key requirements for the module integration and manufacturing technologies. New solutions must be developed, including direct embedding of electronic components and SiPs into substrates/PCBs or even structural components. Manufacturing technology must include both fabrication of low-volume customised electronic modules at the process efficiency of high-volume production by implementing new manufacturing technologies based on 3D printing, roll-to-roll, stamping, injection moulding etc. and highest volume production of smart power components at minimum cost for the new consumer and industrial products by further advancement of miniaturisation.

6.3.7. Major Challenge 7: Increasing compactness and capabilities by functional and physical systems integration

6.3.7.1. Vision

Smart ECS will be used in a variety of application fields (chapters 1-5), introducing an increasing level of “smartness”, being more user-friendly, interacting with each other as well as with the outside world and being reliable, robust and secure, miniaturised, networked, predictive, able to learn and often autonomous. They will be integrated with existing equipment and infrastructure - often by retrofit. Enabling factors will be: interoperability with existing systems, self- and re-configurability, scalability, ease of deployment, sustainability, and reliability, e.g. by self-repair capabilities. SoS, upgradable and automatically configurable suits of sensors and actuators may share computer power or – alternatively – will be customised to the application scenario (sparse, slim and ubiquitous). A hierarchy of SoS will help industries to cope with the growing variety of production processes, enabling all the applications described in Chapters 1–5 and facilitate better living for individual end users.

6.3.7.2. Scope and ambition

Many of the new ECS will benefit from the same transversal technologies. For the sake of European R&D&I efficiency, common challenges in smart systems for different applications need to be addressed by application-independent developments of system and application level integration technologies. Thus, shared usage of these technologies (like heterogeneous 3D integration) of building blocks needed for advanced driver assistance systems as well as minimally invasive surgery devices, or wireless communication devices needed for intraocular measurement devices and for environmental sensors. Harsh environments with high temperatures, humidity, vibration and electromagnetic fields must often be endured for a very long lifetime, with zero defects and error-free. In the case of human health monitoring (hyperpiesia, diabetes, stroke, infarct), solutions increasingly need to be based on non-invasive principles. In all cases, the highest quality raw sensor signals with high reproducibility need to be provided by the next generation of extremely miniaturised innovative sensors, with lowest power consumption and at mass production levels.

6.3.7.3. High priority R&D&I areas on System & Application Level Integration

The main R&D&I activities identified are: i) Physical systems integration, ii) Functional systems integration. Detailed actions are listed under “Timeframes” and in section 14 “Appendix to Chapter 6” of this document.

Physical systems integration

Smart systems integration in the final product will need to satisfy the specific requirements of the application in terms of compactness, safety and reliability. The systems must also adapt to the resources available in the final applications, e.g. in terms of available power, down to the limit of energy scavenging, footprint and compatibility with demanding environments (harsh, in vivo ...). The innovation potential of smart systems can be exploited only if their integration in the application goes beyond the mere introduction of add-on modules, but instead is the result of a full co-development.

Functional systems integration

Full integration of ECS also requires mastering the integration of smart systems SW with the general SW layers of the final application and the development of testing procedures for systems of much higher complexity at the level of comprehensiveness and efficiency at the same time, which is needed for high-volume consumer and industrial products (automated cars, production robots, ...). The high requirements on functional safety and availability of the new applications for complex systems comprising several modules with heterogeneously integrated components will need the implementation of efficient and safe health monitoring for systems with many different critical elements and a multitude of similarly probable failure modes.

6.4. EXPECTED ACHIEVEMENTS

Overcoming the challenges in section 6.3 will enable European Industry to maintain and increase its leading position in developing, producing and selling future Electronic Components and Systems that meet societal needs in a way that is cost-efficient, yet yields products of highest quality. Especially expected achievements are:

- the creation and extension of modelling and specification techniques and languages matching the new properties and requirements for critical, autonomous, cooperating and evolvable systems, supporting various new technologies like Artificial Intelligence, Deep Learning, Big Data Gathering and Handling, etc.
- the development of standardised architectural measures and design methods and tools to enable and/or ease validation and testing of such systems as well as appropriate V&V and Test methodologies to ensure their expected and needed qualities.
- the establishment of standard languages and ontologies and associated tools and methods to develop system models, that can be shared across the system design value chain.
- the establishment of standard languages plus associated tools and methods to build integrated design flows and platforms, targeting heterogeneous SoC and SiP.
- the establishment of common platforms and libraries of parts/components that enable modular development, reusable IP, standardised software and middleware solutions, etc.
- enabling systematic reuse of (models of) components, environments, contexts, etc.
- a drastic increase in the scalability of methods to match the increased complexity of systems.
- improved capabilities to develop, validate and optimise system properties and qualities (from power consumption, distributed control functions, maintaining robust stability of feedback control to functional and non-functional system properties like safety, security, reliability and real time).
- methods and tools to facilitate online monitoring and diagnostics with embedded context awareness.

The general strategic actions required are:

- Demand – individual manufacturing, personalised (medicine, smart home, smart transportation und smart environments)
- Shortening time-to-market – from research and testing to production
- Automation of fabrication processes for smart devices
- Creating open-innovation platforms to enable easier stakeholder cooperation
- Securing R&D&I financing in a complex ecosystem (regarding SMEs)
- 'Deploy and forget' retrofitability – self-sustaining IoT devices requiring no maintenance

6.5. MAKE IT HAPPEN

Design Ecosystem: The key success factor of this roadmap is the actual adoption by European Industry of the new methodologies in Systems and Components Engineering. This implies not only traditional technology transfer but also changes in the way of working in industry towards a much more comprehensive structured approach.

Many of the R&D&I topics described in the previous sections cannot be solved by a single company or organisation. Most noteworthy, this includes all standardisation and pre-standardisation activities, but also

- the development of a common design and validation methodology applicable along the value chain, that is (a) accepted by public (certification) authorities, (b) accepted by the general public as yielding trustworthy products, (c) based upon a V&V and Test methodology using standardised catalogues of system contexts/scenarios as test cases, and (d) enabling cost-efficient processes and allowing reuse and re-certification.
- support for validation of methodologies in industrial practice
- support for industry in the process of adopting new methodologies
- support for heterogeneous applications addressing yield, heat and mechanical stress in a more holistic way.

Therefore, a seamless, open, sustainable and extendable design ecosystem for processes, methods and tools for cost-efficient design is needed, focusing on design technologies based on standards, enabling cooperation between leading European industries. It has to start at system level and has to contain flexible, seamless design flows for all design domains and heterogeneous subsystems to (co-)design ECS with and for sophisticated feature-rich innovative products of superior performance and quality.

PFSI Technologies and Production Processes: The ambition is to find optimal models to enable effortless processes for the production of smart devices, while taking into account the overall spectrum of relevant aspects and the entire palette of stakeholders – from manufacturers and users to decision-makers, regulators, product- and service providers and researchers and developers.

When speaking about the smart ECS ecosystem in Europe, it is essential to develop new forms of stakeholder cooperation on market-ready products, thereby creating a special impact on SMEs and start-ups to maintain or increase their presence and competitiveness in international markets through their innovation, autonomy and agility capabilities. Besides, companies that are not yet visible on the smart systems radar should be motivated to join and enrich the community with their innovations and expertise.

The creation of such ecosystem(s), involving all stakeholders along the respective value chain, is a key success factor for European industry to maintain its leading role in Engineering ECS.

6.6. TIMEFRAMES

The timeframes given in this section denote for each R&D&I activity (topic) in each high priority R&D&I area the foreseen development lines. Each timeline is divided in three parts, for producing results of TRL2-4, 4-6, and 6-8 respectively. The concrete meaning of this section is that we envisage in a given year projects producing results of this TRL level or *higher* to be started (cf. Section 0.6.2).

The Topics (actions) are abbreviated if necessary and therefore also listed with a full description in section 14 of the document “Appendix to Chapter 6”.

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 1: MANAGING CRITICAL, HIGHLY AUTONOMOUS, COOPERATING, EVOLVABLE SYSTEMS

1 - MODELS, MODEL LIBRARIES, AND MODEL BASED DESIGN TECHNOLOGIES

1.a Re-usable, validated and standardized models and libraries for (a) systems contexts, (b) environment and (c) humans

1.b Re-usable, validated and standardized models and libraries for systems behavior, including systems-of-systems configuration, communication, and dynamics, environment/situation perception, interpretation and prediction, self-X and handling of uncertainty

1.c Advanced modelling techniques for future ECS

1.d Model based design methods and interoperable tool chains for critical systems, supporting constraint driven requirements and (incremental) certification and homologation

1. e Extended specification capabilities to enable executable and consistent specifications of all design aspects

2 - V&V AND TEST METHODOLOGY AND TOOLS FOR CRITICAL, HIGHLY AUTONOMOUS, COOPERATING, EVOLVABLE SYSTEM

2.a Model based verification, validation and test methodology and interoperable tool chains and platforms for critical systems

2.b Automated derivation of verification procedures and tools from requirements and models, back annotation of verification results, interface between requirement engineering and V&V environment

2.c V&V and test methods including tool support for Life-Cycle and in-service phase

2.d V&V and test methods including tool support for adaptive, cognitive and learning systems (especially for AI-based systems)

2.e V&V and test methods including tool support for Human-Machine Interaction, collaborative decision making, cooperation strategies and activities

2.f V&V methods and analysis tools for autonomous systems including environment/situation perception, interpretation and prediction, handling of uncertainty, inaccuracy and faults

2.g Methods for the hierarchical verification of the whole system

2.h Concepts and procedures for the evaluation of functional safety, robustness and reliability

3 - (VIRTUAL) ENGINEERING OF ECS

3.a Collaboration concepts and methods, platforms and interoperable tools for interdisciplinary, holistic virtual engineering of ECS covering the whole value chain, spanning organisations, engineering domains, and development activities

3.b Methods and interoperable tools for virtual prototyping of complex, networked systems (including usage of Digital Twins, support of distributed development, etc.)

3.c Engineering support (libraries, platforms, interoperable tools) for (AI-based) evolvable and adaptable systems

3.d Engineering support (libraries, platforms, interoperable tools) for the design and operation of Open-World Systems

3.e Engineering support (libraries, platforms, interoperable tools) for the design and operation of cognitive, cooperating systems

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 2: MANAGING COMPLEXITY

1 - SYSTEMS ARCHITECTURE (SYSTEMS AND COMPONENTS, HARDWARE AND SOFTWARE,...)

1.a	Extended methods for architectural design (thousands of components, property metrics, early architectural exploration, ...)
1.b	Design methods and architectural principles, platforms and libraries supporting V&V, Test, and Life-Cycle-Management of complex, networked ECS: Modular Architectures and platforms, support of local-global principles in heterogeneous, distributed systems
1.c	Design methods and architectural principles, platforms and libraries supporting Self Management, Self-Awareness and Self-Healing
1.d	Design methods and architectural principles, platforms and libraries supporting cognitive and adpative systems (Big Data handling, artificial intelligence, machine learning, neuromorphic architecture, ...)
1.e	Model based system architecture, including models representing requirements and specifications in dynamic and executable architectures

2 - SYSTEMS DESIGN

2.a	Hierarchical Concepts and Standards for IP Modelling including coverage and error mode analysis
2.b	Methods and Tools for component based HW/SW Co-Design on all levels of the design hiearchy (from component to system-of-system) for heterogeneous, distributed products in their (possibly unknown) environments
2.c	Methods and Tools for Model Driven Engineering, supporting model creation and transformation (incl model extraction and model learning), model languages (incl. Domain Specific Languages), model management, and scalability of model based approaches
2.d	Methods and Tools for efficient virtual prototyping, (incl. early SW integration and validation, adaptive, re-configurable real-time platforms and cognitive computing, handling of Big Data, support for AI and Deep Learning, usage of Digital Twins, etc.)
2.e	Design and Analysis methods for multi-/many-core systems

3 - METHODS AND TOOLS TO INCREASE DESIGN EFFICIENCY

3.a	Seamless and consistent design tool chain for automated transfer of abstract (system level) descriptions into functional HW/SW blocks
3.b	Strong support of package, board and sensor/MEMS (co-) design including die-embedding and 2.5/3D integration
3.c	New methods and tools to support new design paradigms (e.g., multi-/many-cores, system-of-systems configurations, distributed computing, edge/cloud computing, etc.)
3.d	Support of new technologies: FD-SOI, graphene, nanotubes, ..., <7nm technology
3.e	New approaches to handle analog/mixed signal design

4 - V&V & TEST COMPLEXITY REDUCTION

4.a	V&V methods to prove safeness, soundness and compliance to (certification) standards of real-time complexity reduction in situation representation and situation prediction
4.b	Hierarchical system verification using already verified components and verification process re-use
4.c	Methods and tools to support scenario based V&V and Test, including scenario analysis, scenario selection, combination of formal proof, simulation and test techniques
4.d	Virtual platform in the loop: Enabling the efficient combination of model-based design and virtual platform based verification and simulation
4.e	Methods and tools for V&V and test automation and optimization including test system generation and handling of product variability

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 3: MANAGING DIVERSITY

1 - MULTI-CRITERIA OPITMIZATION OF COMPONENTS AND SYSTEMS

1.a	Integrated development processes for application-spanning product engineering along the value chain
1.b	Consistent and complete Co-Design and integrated simulation of IC, package and board in the application context
1.c	Modular design of 2.5 and 3D integrated systems

2 - MODELLING AND SIMULATION OF HETEROGENEOUS SYSTEMS

2.a	Hierarchical Approaches for Modeling of heterogeneous systems
2.b	Modeling methods to take account of operating conditions, statistical scattering and system changes
2.c	Methods and tools for the modeling and integration of heterogeneous subsystems
2.d	Methods for hardware software co-simulation of heterogeneous systems at different abstraction levels
2.e	Modeling methods and model libraries for learning, adaptive systems
2.f	Models and model libraries for chemical and biological systems

3 - INTEGRATION OF ANALOG AND DIGITAL DESIGN METHODS

3.a	Metrics for testability and diagnostic efficiency (including verification, validation and test), especially for AMS
3.b	Harmonization of methodological approaches and tooling environments for analog, RF and digital design
3.c	Automation of analog and RF design (high-level description, synthesis acceleration and physical design, modularization, use of standardized components)

4. CONNECTING DIGITAL AND PHYSICAL WORLD

4.a	Advanced simulation methods considering the connection of virtual and physical world and its environment
4.b	Novel More than Moore design methods and tools

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

Major Challenge 4: MANAGING MULTIPLE CONSTRAINTS

1 - ULTRA-LOW POWER DESIGN METHODS

1.a Advanced design methods for ultra-low-power design

1.b Design methods for (autonomous) ultra-low-power systems, taking into account application-specific requirements

1.c Method for comprehensive assessment and optimization of power management and power consumption

2 - EFFICIENT MODELLING, TEST, AND ANALYSIS FOR RELIABLE, COMPLEX SYSTEMS CONSIDERING PHYSICAL EFFECTS AND CONSTRAINTS

2.a Hierarchical modeling and early assessment of critical physical effects and properties from SoC up to system level

2.b Design and development of error-robust circuits and systems including adaptation strategies and redundancy concepts

2.c Production-related design techniques

2.d Consistent methods and new approaches for (multi-level) modeling, analysis, verification and formalization of ECS's operational reliability and service life

2.e Consistent design system able to model and optimize variability, operational reliability, yield and system reliability, considering dependencies

2.f Analysis techniques for new circuit concepts and special operating conditions (Voltage Domain Check, especially for Start-Up, Floating Node Analysis, ...)

2.g Advanced test methods, intelligent concepts for test termination, automated metrics/tools for testability and Diagnosis, extraction of diagnostic information

2.h Methods and tools for monitoring, diagnostics and error prediction for ECS (online and real-time monitoring and diagnostics, intelligent self-monitoring of safety-critical components, life expectancy)

3 - SAFE SYSTEMS WITH STRUCTURAL VARIABILITY

3.a Architectures, components and methods for adaptive, expanding systems

3.b Design methods and tools for adaptive, expanding systems

3.c Novel simulation approaches for the rapid evaluation of function, safety and reliability

3.d Security concepts for adaptive, expanding systems

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 5: COMPONENT LEVEL INTEGRATION :

Integrating miniaturised features of various technologies and materials into smart components

1 - FUNCTIONAL FEATURES

- **1.a** Various sensors and systems in package for autonomous cars, industrial robots, smart energy, health, environmental applications, etc.
- **1.b** Selective gas (CO, CO_2, NO_x, VOC, etc.) sensing components
- **1.c** Low power wireless architectures
- **1.d** PMICs with high efficiency at very low power levels and over a wide range of input voltages (AC & DC)
- **1.e** Selective detection of allergens, residues in food/water, atmospheric particles, etc.
- **1.f** Disease monitoring & diagnostics (at home, POC, animal health)
- **1.g** Bio-sensors and bio-actuators
- **1.h** MOEMS and micro-optics
- **1.i** Component-level features for self-diagnosis (PHM detectors)
- **1.j** Harvesters and storage devices (e.g. microbatteries, supercapacitors), including 2D, 3D and solid-state for feeding low or zero power devices
- **1.k** Hardware solutions for security and privacy
- **1.l** IC functionalities for neuromorphic computing
- **1.m** Machine learning and artificial intelligence (including testing of learning components)

2 - MATERIALS

- **2.a** Surface coatings for multi-functionality on the same base structures including self-cleaning materials
- **2.b** High efficiency photonic materials
- **2.c** New / alternative organic and bio-compatible materials
- **2.d** New materials and features for sensing (CNT, graphene, nitrogen voids e.g. in diamond, etc.)
- **2.e** Low quiescent/leakage power material/devices for sensors
- **2.f** Materials for low power, fast responding gas sensors and occupancy sensors
- **2.g** Non-toxic, scalable, high density feature materials for energy harvesting sources and higher performing electrodes and electrolytes
- **2.h** Rare earths replacement, e.g. for magnetics
- **2.i** Heterogeneous integration of new materials, sensors, actuators for miniaturised chips (also for high temperature and photonics applications)
- **2.j** III/V and other wide bandgap semiconductor material (e.g. SiC), integration on silicon and the use for power electronics

3 - INTEGRATION PROCESS TECHNOLOGIES AND MANUFACTURING

- **3.a** 2D and 3D printing technologies (printing, etc.) for heterogeneous system integration and rapid manufacturing
- **3.b** Robust integration of multi-component systems (sensors, actuators, electronics, communication, energy supply (incl. e.g. fluidics and photonics)
- **3.c** Key technology areas (printing, etching, coating, etc.)
- **3.d** Manufacturing & health monitoring tools (including tests, inspection and self-diagnosis) for components
- **3.e** Quantum sensors and associated integration

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 6: BOARD / MODULE LEVEL INTEGRATION:

Effectively integrating modules for highly demanding environments

1 - FUNCTIONAL FEATURES

1.a	Board-level signal processing and control features for self-diagnosis and self-learning
1.b	Smart power (mini-) modules for low-power sensing/actuation and efficient power transfer
1.c	Low-power sensor nodes for real-time data processing (neuronal networks (low TRL), power saving architecutre (mid TRL...)
1.d	High performance signal quality under harsh environmental conditions
1.e	Protective housing and coating features (e.g., against chemicals)
1.f	Photonics features like optical sources, pathes and connectors integrated into PCB
1.g	Advanced and active cooling systems, thermal management
1.h	EMI optimized boards - TRL dependent on switching frequencies, intro of wide band gap materials
1.i	3D board & module design - TRL dependent on materials, components, ...
1.j	Board level high speed communication features (dependent on frequencies, filters, multimode capability, acoustically decoupled FE components ...)

2 - MATERIALS

2.a	Heterogeneous integration of new materials for miniaturised sensor & actuator modules
2.b	Recycling and repair of modules
2.c	Transducer materials (e.g. CMOS compatible piezo, e.g. flexible solar panels) that can be integrated into SiPs
2.d	RF > 10 GHz: CMOS or GaN compatible thin film piezoelectric materials, materials for high efficiencey acoustic transduction, conductive materials
2.e	Materials for flexible devices, flexible "board/stripe", hydrophobic barrieres, agent reservoirs, inks for printing ... lifetime and cost dependent
2.f	Materials for coating, potting, and overmolding (TRL dependent on temperature levels ...)
2.g	New thermal interface materials (depends on temperature capabilities ...)
2.h	New substrate materials on board level - rigid or flexible - TRL dependent on power, frequencies, applications, single-use, multi-use, long lifetime, ...

3 - INTEGRATION PROCESS TECHNOLOGIES AND MANUFACTURING

3.a	Transfer printing of heterogeneous components on various substrates
3.b	Heterogeneous 3D integration of sensors, actuators, electronics, communication, and energy supply features for miniaturised modules
3.c	Highly miniaturised engineering and computer technologies with biochemical processes
3.d	Bio-mimicking (bio-hybrids, fluidics)
3.e	Manufacturing & health monitoring tools (including tests, inspection and self-diagnosis) for components
3.f	Direct manufacturing and rapid prototyping
3.g	Automation and customization ('towards I4.0') in module manufacturing
3.h	Flexible and stretchable devices and substrates, structural electronics
3.i	Chips, passives and packaged components embedded in board
3.j	3D printing of IC components on top of PCBs
3.k	Monolithic/heterogeneous 3D integration of RF FE components, low vertical form factor (<100 μm), minimization of external matching networks by integration

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 7: SYSTEM & APPLICATION LEVEL INTEGRATION:

Increasing compactness and capabilities by functional and physical systems integration

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
	1 - PHYSICAL SYSTEMS INTEGRATION										
1.a	Effective and reliable energy generation, scavenging and transfer	research	research	research	research	development	development	pilot test	pilot test	pilot test	pilot test
1.b	In-situ monitoring in automation, process industry and medical application	research	research	development	development	development	development	development	pilot test	pilot test	pilot test
1.c	Biomedical remote sensing	research	research	research	research	development	development	pilot test	pilot test	pilot test	pilot test
1.d	Low power RF architectures for asset tracking and low data rate communication (e.g. UWB, LoRa)	research	development	development	development	development	development	pilot test	pilot test	pilot test	pilot test
1.e	System integration of wide bandgap semiconductors	research	development	development	development	pilot test	pilot test	pilot test	pilot test	pilot test	pilot test
1.f	Improved signal integrity (EMC)	research	research	development	development	pilot test	pilot test	pilot test	pilot test	pilot test	pilot test
1.g	Modularity and compatibility across development generations (interface definition, standardization)	research	research	development	development	development	development	development	development	pilot test	pilot test
1.h	New materials for improved thermal management	research	research	research	research	development	development	pilot test	pilot test	pilot test	pilot test
1.i	Thermal management on system level	research	development	development	pilot test	pilot test	pilot test	pilot test	pilot test	pilot test	pilot test
1.j	New materials and concepts for humidity transport into and out of the (sensing) systems	research	research	research	research	development	development	development	pilot test	pilot test	pilot test
	2 - FUNCTIONAL SYSTEMS INTEGRATION										
2.a	Recycling and repair of systems	research	research	research	research	development	development	pilot test	pilot test	pilot test	pilot test
2.b	ICT for diverse resources monitoring and prognosis	research	research	research	development	development	development	development	pilot test	pilot test	pilot test
2.c	Efficient computing architectures for real-time data processing in sensor nodes	research	research	research	research	development	development	development	development	pilot test	pilot test
2.d	System health management based on PoF models (and not statistical)	research	research	research	research	research	development	development	pilot test	pilot test	pilot test
2.e	Manufacturing & health monitoring tools (including tests, inspection and self-diagnosis)	research	research	research	development	development	development	pilot test	pilot test	pilot test	pilot test
2.f	Perception techniques	research	research	research	development	development	development	pilot test	pilot test	pilot test	pilot test
2.g	Sensor fusion and cyberphysical systems	research	development	development	development	development	development	pilot test	pilot test	pilot test	pilot test
2.h	Volume reduction (per lot due to customization) in systems manufacturing	research	research	development	development	pilot test	pilot test	pilot test	pilot test	pilot test	pilot test
2.i	Data and system safety, security and privacy	research	research	development	development	development	development	pilot test	pilot test	pilot test	pilot test
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

research or TRL 2-4; *development or TRL 4-6;* *pilot test or TRL 6-8*

Timelines

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6.7.
SYNERGIES WITH OTHER THEMES

For the Architecture, Design and Integration Technologies described in this chapter we expect huge potential for synergies with R&D&I Topics outlined in all other chapters. New and advanced applications described in Chapter 1 to 5 will give rise to further advances in design and integration technologies. We expect most R&D projects based on this SRA to result in innovations in applications as well as in accompanying design and integration technologies.

There is a strong link between the V&V and test methods and tools described here and the techniques described in Chapter 8 on Safe and Secure Systems. Computing and storage nodes (Chapter 9) are essential components in most ECS systems; R&D&I topics to advance these nodes therefore strongly interact with the platform and Systems Design topics here, as well as connectivity and interoperability research (Chapter 7). Last, but not least, the Process, Technology and Materials Chapter 10 is of huge importance here.

The field of Physical and Functional Systems Integration draws upon key enabling technologies (KET) and integrates knowledge from a variety of disciplines. Furthermore, it bridges the gap between components and functional, complex systems. Within the framework of the ECS SRA, the field benefits from links to all other technology chapters. The development of Smart Systems will benefit from progress in nano-electronics, design methods and tool development. Smart Systems are key elements in a wide variety of activities, among others also in the Internet of Things and Services as well as for sensor-based electronic systems for Industry 4.0, Energy in buildings and micro-grids, Environment and Climate Action, Security, eHealth and wearables, transportation, food and water supplies, and natural resources.

7

Connectivity and Interoperability

7.1. EXECUTIVE SUMMARY

Mobility being everywhere, connectivity and interoperability are today key enablers to support the development of innovative applications in various markets (consumer, automotive, digital manufacturing, network infrastructure …). The ubiquitous availability of smart phones and 4G wireless networks is of course a good example (one can have in mind the associated booming development of apps), but the availability of new innovative connectivity technologies (IoT, 5G, car to car, …) enables a wide range of enhanced and new business opportunities for the European industry to be envisioned (smart cities, autonomous driving, …).

To support this vision, interoperable, secure, smart and user-friendly connectivity solutions are necessary to ensure citizen privacy and gain broad acceptance from consumer. Clearly, the main objective of this chapter is to enable the seamless integration of various technologies (hardware and software) in order to develop complex connected System of Systems (SoS) in an effective manner. To do so, semantic, secure and scalable interoperability and heterogeneous integration are key game changers.

7.2. RELEVANCE

7.2.1. Competitive Value

While connectivity is needed today in almost all application fields (consumer market, automotive, health, wellbeing, smart cities …), we can note that European players are stronger in terms of Internet of Things (IoT) and secured solutions (with hardware leaders such as NXP or STMicroelectronics, solution providers such as GEMALTO and service provider such as SIGFOX). On the other hand, mass-market oriented businesses such as the smart phone is today dominated by US (Qualcomm, Avago, etc...) or Asian players (Huawei, Murata, etc…) with European ones 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 Europe 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, in order to bring added value and differentiation in comparison with US and Asian competitors, European industry has to secure the access to any innovative software and hardware technology enabling 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 Artemis Advancy report).

To illustrate the competitive value for Europe of connectivity and interoperability topics, we can quickly review a few 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 is here the deployment of Advanced Driver Assistance Systems (ADAS), which is a key opportunity for European semiconductor companies. While the ADAS market today generates moderate revenue (less than USD 2 billion in 2015), compared with USD 29 billion for automotive electronic systems, this market is expected to grow rapidly. Industry experts expect to see an annual increase of more than 10 per cent from 2015 to 2020. This could make ADAS one of the highest growth rates in the automotive sector and related industries. Moreover, it is likely that regulators will require vehicles to be equipped with certain ADAS applications over the next five years. For example, key automotive markets like Europe, Japan and North America are in the process of introducing legislation to aid the prevention of fatalities of vulnerable road users, with an emphasis on the use of vision systems, a trend that is driving the quick adoption of camera-based ADAS by car makers around the world. This trend will be reinforced by the development of autonomous driving technology (such as Tesla Autopilot technology). Connectivity technology is consequently a major challenge since inter-sensor communication requires high bandwidth, so innovative solutions will be necessary to prevent network overloads. A broadband network with hierarchical architectures will be needed 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. having receivers like actuators, decision makers, sales and customers. Obviously, this will involve a huge number of devices with software systems that are required to 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.

Europe is the leading world region for production and manufacturing automation thanks to companies like Siemens, ABB, Schneider, Metso/Valmet, etc. Industrial control and manufacturing automation is projected to reach USD 153.30 billion by 2022, at a CAGR of 4.88% [Markets and Markets, 2016 [81]]. To this the MES and ERP markets should be added. The cloud ERP market size is estimated to grow from USD 18.52 billion in 2016 to USD 29.84 billion by 2021, at an estimated Compound Annual Growth Rate (CAGR) of 10.0% [Markets and Markets, 2016 [82]]. The Manufacturing Execution System (MES) market was valued at USD 7.63 billion in 2015 and is expected to reach USD 18.22 billion by 2022, at a CAGR of 13.6% [Market and Market 2016]. The factors that are driving the growth of these markets include low cost of deployment, increasing use of industrial automation, adoption of MES and ERP owing to growing benefits, and the importance of regulatory compliance. To this should be added the expected impact of Industry4.0 and its use of IoT and SoS technologies, most likely to occur after 2022. Companies like Cisco and Ericsson forecast that a very high number of IoT devices will be used in the development of digital production. It's clear that software and electronics hardware contributes to this market to a very large extent.

Data Centre: To make 5G a reality, telecommunication operators and big internet companies such as Google, Apple, Facebook or Amazon will have to increase the size of their data centres to cope with user demand for more data. Due to the complexity of the mega data centres deployed today, this creates a huge interconnect challenge. For a data centre such as the Google ones currently deployed, people generally have in mind an optical fibre interconnect solution. Optical fibre is a key technology for high speed links (> 25 Gb/s) but in fact there is a lot of copper cable deployed in data centres these days. "We see copper as maybe not the principal but one of the main interconnects used inside the rack at 100GbE," says Mellanox senior director for marketing, Arlon Martin, who believes an 8m length could be enough to satisfy 98 percent of in-rack cabling requirements. The drawback of this approach is that each copper cable consumes more than 1 W. Having in mind that the biggest data centre currently deployed can has more than 400,000 servers, this means that big data centre may consume 400 kW just to connect the servers to each other. To put this number in perspective, the average power consumption of a house in Europe is 6 kW. Consequently, if we can develop an innovative cost-effective, power-efficient (~100 mW) and high-speed (at least 10 Gb/s) cable technology able to work up to 10 m, we will also open new business opportunities from the telecommunication infrastructure side by enabling greener services.

A critical asset for competitveness is the availability of professionals with the appropriate skills and knowledge in IoT, and particularly SoS connectivity, in terms of their interoperability, security and scalability.

7.2.2. 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 next decades. As it will be illustrated below, the societal benefits associated with connectivity are then key assets in improving the living standard of European citizens and maintaining Europe leadership.

Education improvement: The internet plays a pivotal role in extending access to educational resources and in accelerating knowledge sharing. The internet makes learning resources available to students and teachers; it allows learning and consultation online and can be a valuable complement to the classroom experience. The potential exists for students anywhere to have access to online educational eBooks, tests and courses. These resources can substitute traditional textbooks which may not be readily available or are prohibitively expensive in developing countries. Connectivity has then the potential to significantly extend the impact of the internet in increasing the quality of education (reliable access, improved student experience …) and ultimately academic proficiency, attainment levels and employment outcomes. Improved educational outcomes can have a strong positive impact on individuals' income and health as well as on the economy. Importantly, in addition to these effects, technology can expand opportunities for students to engage in collaborative learning, with great potential for learning and circulating ideas.

Healthcare improvement: Connectivity has the potential to improve medical behaviour for patients and healthcare professionals as well as the delivery of improved medical service. Connected devices can

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81 *see: https://www.marketsandmarkets.com/Market-Reports/enterprise-manufacturing-intelligence-market-32000061.html*

82 *see: https://www.marketsandmarkets.com/Market-Reports/enterprise-manufacturing-intelligence-market-32000061.html*

transform the way healthcare professionals operate by allowing remote diagnosis and more efficient ways of treatment. For example, patient information could be sent to hospitals via mobile and internet applications, thus saving travel time and service costs and 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, monitoring of illnesses can also be enhanced by mobile and internet applications designed to remind patients of their treatments and control the distribution of medicinal stocks.

Energy and environment: One of the projected impacts of digitalisation is better abilities to optimise energy utilisation and minimise environmental footprints. Connectivity and Interoperability are here critical parts of ICT infrastructure that is essential to allow such optimisation and minimisation. Energy efficiency market is estimated to be USD 221 bn in 2015, which is 14% of the global energy supply investments [IEA 2016b [83]] divided between buildings (53%) transport (29%) and industry (18%) [IEA, 2016a [84]].

Improve public services, social cohesion and digital inclusion: ICT technologies have long been recognised for 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 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 they 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: 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.

Europe should recognise the importance of connectivity in complementing the delivery of healthcare, education and other social services and should promote investment in the development of innovative connectivity solution targeting this topics in order to improve the daily lives of European citizens.

OSI MODEL

Layer		Data unit	Funtion
Host layers	7. Application	Data	Network process to application.
	6. Presentation		Data representation, encryption and decryption, convert machine depent 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-poin data connection.
	1. Physical	Bit	A (not necessariliy reliable) direct point-to-point data connection.

F.44 *The focus for connectivity and interoperability R&D&I are related to the OSI model layers 1, 5 and 6*

7.3.
MAJOR CHALLENGES

The connectivity and interoperability technology focus enabling the projected commercial and societal benefits are related to the OSI model layers 1, 5 and 6.

7.3.1. Major Challenge 1: Strengthening the EU position on differentiated technologies and enabling it to capture higher value by moving to system/module level

7.3.1.1. Vision

Targeting system and application, we have to consider the interconnection between sub-systems and should focus on individual component technology development according to needs identified at system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key.

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 sub-system that are integrated into a single system. The operating characteristics should also be taken in its broadest meaning including characteristics such as system level cost-of-ownership.

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

7.3.1.2. Scope and ambition

This major challenge involves the full leveraging of Europe's existing semiconductor manufacturing strength and especially the availability of derivative semiconductor processes (BiCMOS, Si Photonics, RF SOI, FDSOI, GaN ...). The ambition is to develop an innovative connectivity solution (for example, investigating a new frequency band or medium to propagate the signal) and strengthen Europe leadership on 5G and IoT markets.

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[83] *IEA (2016b), Mobility Model, 2016 version (database and simulation model), www.iea.org/etp/etpmodel/transport*

[84] *IEA (2016a), World Energy Investment 2016, OECD/IEA, Paris, http://dx.doi.org/10.1787/9789264262836-en*

An innovative connectivity solution is envisioned that should drive the development in Europe of innovative packaging, MID and printed circuit technologies (by providing system requirements and then facilitating the specification of required technologies) in order to enable the development of differentiated and higher-value connectivity systems leveraging heterogeneous integration schemes.

7.3.1.3. Competitive situation and market changers

While Europe has a very clear technology lead in derivative semiconductor technology, we can note that most of the end users developing the final connectivity system are based either in Asia or in the US. Europe may be strong in RF SOI (STMicroelectronics, SOITEC, etc...) and BiCMOS (Infineon NXP, STMicroelectronics, etc...) but the module makers capturing the main part of the value associated with the 4G Front End Module are based in the US (Avago, Qorvo, Skyworks, etc...) or in Asia (Murata, Huawei, etc...).

In order to enable the emergence of a European champion delivering a connectivity module/solution, the key game changer will comprise enabling the necessary ecosystem required to develop an innovative connectivity system leveraging both heterogeneous integration schemes and derivative semiconductor processes already available in Europe.

7.3.1.4. High priority R&D&I areas

The high priority technical and scientific challenges are:

- Going beyond 5G technologies from IoT to backend (HW, control, envelope tracking, system integration...) to secure European leadership on future 6G R&D investigations.
- Evaluation of a new frequency band with a special focus on an unlicensed band > 200 GHz (for example, targeting the 250 GHz – 325 GHz range promoted by IEEE 802.13.c).
- Evaluation of new medium (RF/mmW signal propagation over plastic, single mode optical waveguide using laminated polymer platform ...).
- Enabling a European ecosystem able to support heterogeneous integration (multi die System in Package, advanced assembly capability, advanced substrate manufacturing ...).

7.3.1.5. Expected achievements

- Innovative connectivity technology working in new frequency band and achieved using Europe-derived technologies (RF SOI, BiCMOS, GaN ...).
- Innovative connectivity solution using new medium.
- Highly integrated connectivity module/system heterogeneously integrating Europe-derived technologies (leveraging both semiconductor and packaging technologies).

7.3.2. Major Challenge 2: Autonomous interoperability translation for communication protocol, data encoding, security and information semantics

7.3.2.1. Vision

To fully leverage this heterogeneous integration at the hardware level, software interoperability is a parallel challenge to provide connectivity that will allow for autonomous System of Systems (SoS) connectivity from IoT to backend 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.

7.3.2.2. Scope and ambition

This grand 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 ambition 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.

7.3.2.3. Competitive situation and market changers

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 is good but fragmented, and secure, evolvable and engineering efficient connectivity is therefore a market cornerstone.

To maintain and strengthen the European lead, advances in autonomous interoperability and associated efficient engineering capability is necessary. The game changers are:

- Autonomous interoperability for SoS integration for efficient engineering at design time and run time.
- Open interoperability frameworks and platforms.

7.3.2.4. High priority R&D&I areas

The high priority technical and scientific challenges in both design time and runtime are:

- Semantics interoperability.
- Autonomous translation of protocols, encodings, security and semantics.
- Evolvable SoS connectivity architectures and technologies over time and technology generations.

7.3.2.5. Expected achievements

- Autonomous semantics translation technologies for a large set of semantics and ontologies.
- Autonomous translation across protocol, encodings, security and semantics.
- Reference translation implementations with performance that meets critical requirements in focused application areas.

7.3.3. Major Challenge 3: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

7.3.3.1. Vision

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 to lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

7.3.3.2. Scope and ambition

The scope is to provide connectivity architecture, reference implementation and associated engineering frameworks spanning technologies from legacy to 5G.

7.3.3.3. Competitive situation and market changers

It's clear that the US is the security leader when it comes to computer connectivity. The big potential game changer is here 5G where Europe 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.

7.3.3.4. High priority R&D&I 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.

7.3.3.5. 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.

7.4.
MAKE IT HAPPEN

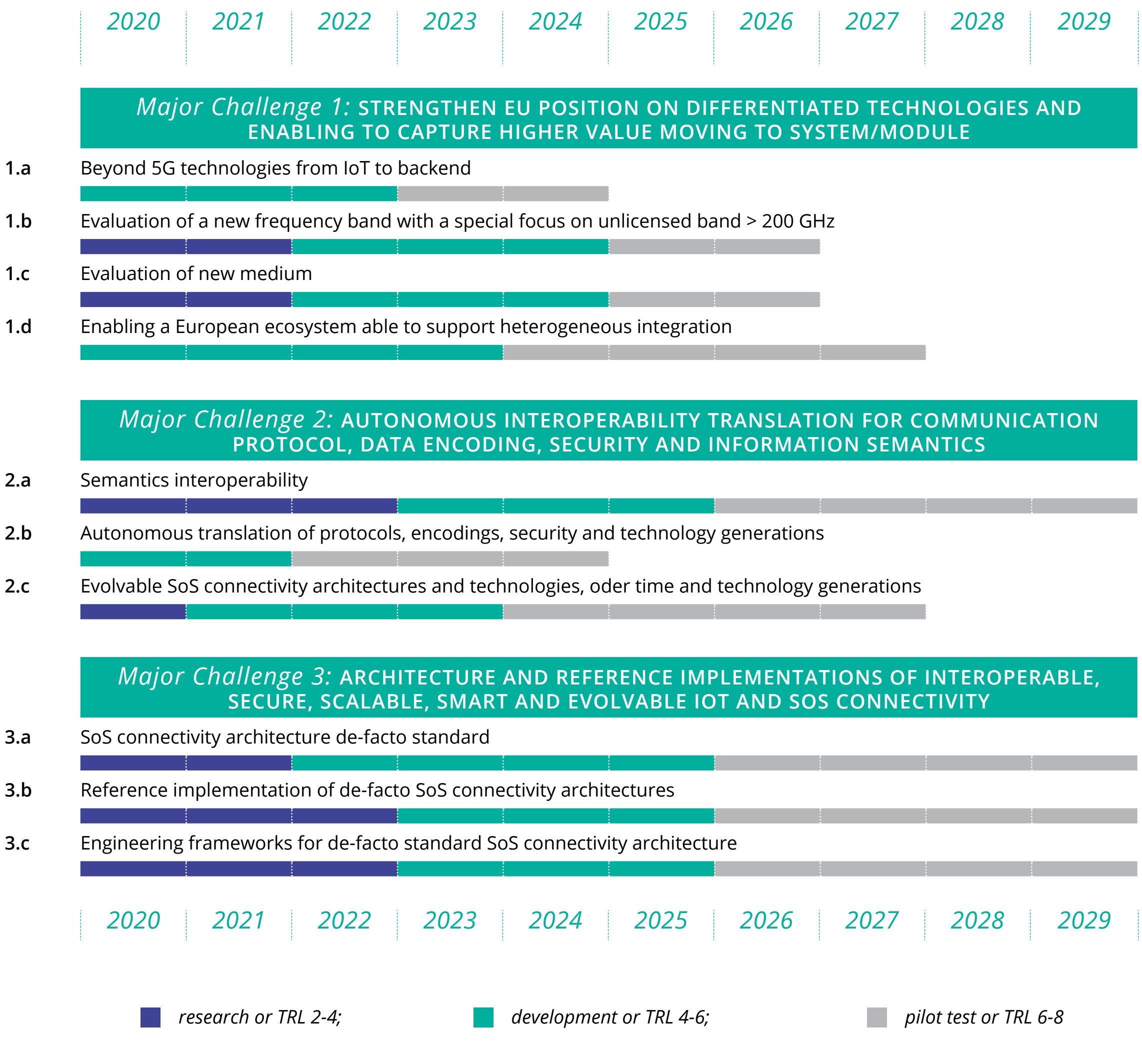
To provide the connectivity and interoperability requested by applications a transition from always best connected to always best integrated is necessary. For the purpose interoperability at all layers in the ISO a communication stack is necessary. For example, at the application level machine understanding of data semantics is vital to reduce engineering costs. At the physical level, hardware supported payload transfer from 5G to Ethernet and vice versa, for example, will enhance security better than software supported transfer.

This requires substantial standardisation efforts both from an international and technology HW/SW perspective.

The availability of engineers having interoperability and dynamic integration competencies is currently limited mainly due to limited academic research and education on SoS problems, so a joint industrial and academic effort is vital to rapidly increase the availability of such competencies.

7.5. TIMEFRAMES

The anticipated time line for finding solutions and mature implementations to the stated major challenges is depicted in the table below.



Connectivity and Interoperability timeline **F.45**

7.6.
SYNERGIES WITH OTHER THEMES

Interoperability and connectivity provide foundation properties for all targeted application areas, covered in chapters 1 to 5. There is also a close relationship with chapter 6 where interoperability and connectivity also provide a foundation for the CPS systems and engineering aspects being described there. The specific problem of security interoperability and coexistence and translation between different security technologies is an area for strong synergies with chapter 8.

8

Safety, Security and Reliability

8.1. EXECUTIVE SUMMARY

Safety, security and reliability are fundamental components of any innovation in the digital economy. Novel products and services such as personal healthcare monitoring, connected cars or smart homes will bring strong benefits to our society only if users are assured that they can depend on and trust them, especially for artificial intelligence (AI) based systems.

Disruptive threats are increasing and machine lear ning is providing real time threat detection and incident response on equipment and in the Cloud. Big data analytics power can conduct to offensive cyber resiliency to prevent massive attacks and identify vulnerabilities. Last but not least Quantum threat is currently driving Standards to develop Quantum resistant algorithm and provide solutions to counter this new phenomenon.

Safety and security, as well as dependability engineering, require the consistent merge of different engineering disciplines, leading to heterogeneous and possibly contradictory requirements. Dependability in its full meaning includes system properties like availability, resilience, survivability, adaptability, maintainability and so forth. This chapter introduces and describes four Major Challenges that have been identified for the European Research and Development community over the next five years in the area of "Dependability and Trustability". It covers all aspects to build trustable technology, either by measures against technical faults (safety, reliability) or with protection against malicious or unintended human intervention (security) and the related use of personal data (privacy).

The Major Challenges in Safety, Security and Reliability are:

1. Safety, security and privacy by design
2. Reliability and Functional Safety
3. Secure, safe and trustable connectivity and infrastructure
4. Privacy, data protection and human interaction.

8.2. RELEVANCE

8.2.1. Competitive Value

Since safety, reliability, privacy and security are mandatory items to be considered in many sectors where Europe has leadership or a significant position, European Industrial competitiveness will be driven by a growth of safety & security revenues in the European market (500 million habitants) but also a re-enforcement of European companies' position and market share in this domain.

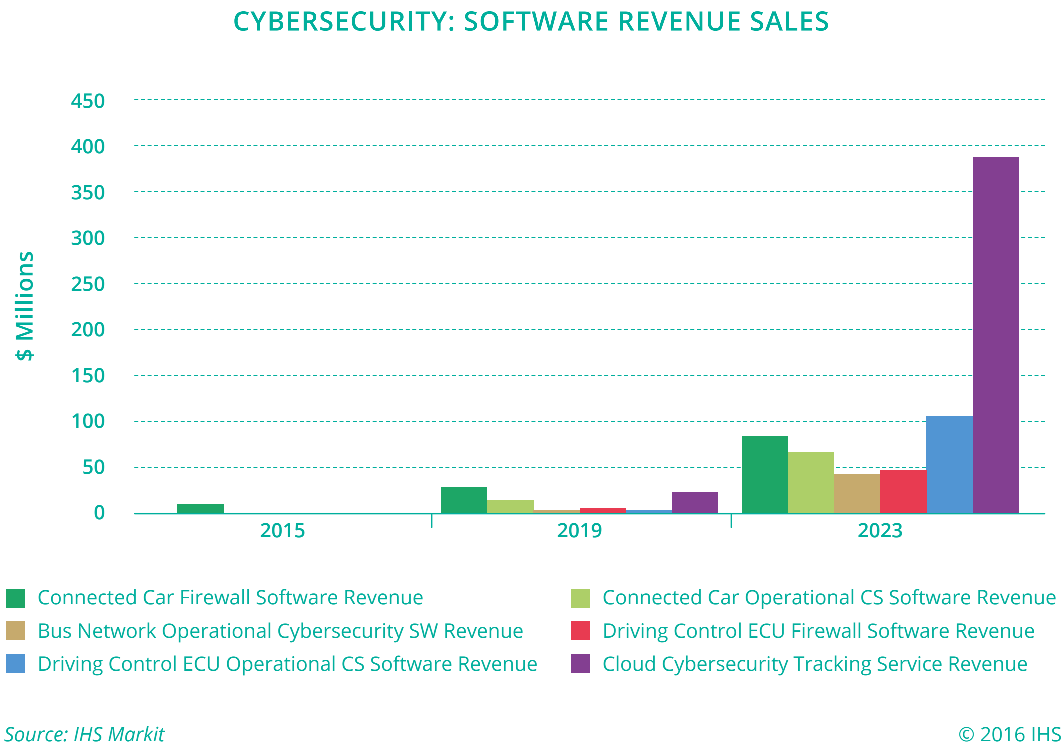
On another hand European actors involved in the domain will have to transform innovations to market products and services through standardisation, assurance and certification. This will permit according to the level of maturity of the different sectors to increase the penetration of safety & security solutions within the applications and supporting infrastructures.

According to Gartner[85], worldwide spending on information security products and services will reach $86.4 billion in 2017, an increase of 7 percent over 2016, with spending expected to grow to $93 billion in 2018. A good example is cybersecurity for automotive. According to [86] this market will reach 753M$ in 2023 with variable growth according to the segment (see Figure 46).

←

8 *Gartner Technology Research, Gartner Says Worldwide Information Security Spending Will Grow 7 Percent to Reach $86.4 Billion in 2017, URL: http://www.gartner.com/newsroom/id/3784965*

86 *IHS Automotive, Automotive Cybersecurity and Connected Car Report, August 2016, URL: http://www.ihssupplierinsight.com/shop/product/5002659/automotive-cybersecurity-and-connected-car-report*



F.46 *Cybersecurity Software Revenue Sales*

8.2.2. Societal Benefits

Dependability and Trustability are fundamental components of any innovation in the digital economy. It is out of question that novel products and services like personal healthcare monitoring, connected cars or smart homes bring strong benefits for the society, provided that dependability and trustability are taken care of. If this cannot be ensured, there is a significant risk that these innovations will not be accepted by society due to missing consumer confidence.

A. Benefits for individuals

Individuals tend to get more and more sceptical towards novel digital innovations due unprecedented worldwide cybersecurity attacks like the attack by the Wannacry ransomware cryptoworm in May 2017 that encrypted 400.000 computers globally and demanded ransom payments in the Bitcoin cryptocurrency, or Safety issues such as the Toyota throttle bug causing the death of one occupant, and having cost more than $1 Billion. In addition, trust of individuals is also massively impacted by privacy concerns, because people don't have any feeling anymore who accesses their private data. According to KPMG survey in 2016 [87], 55% of consumers surveyed globally said they had decided against buying something online due to privacy concerns. Figure 47 also shows these increasing concerns for online activities. Safety aspects have a major impact in case of public knowledge of accidents due to technical failure. Moreover, safety challenges are getting quite tough because of complex functionalities (autonomous car, avionics for dense traffic) and because of security vulnerabilities of interconnected systems.

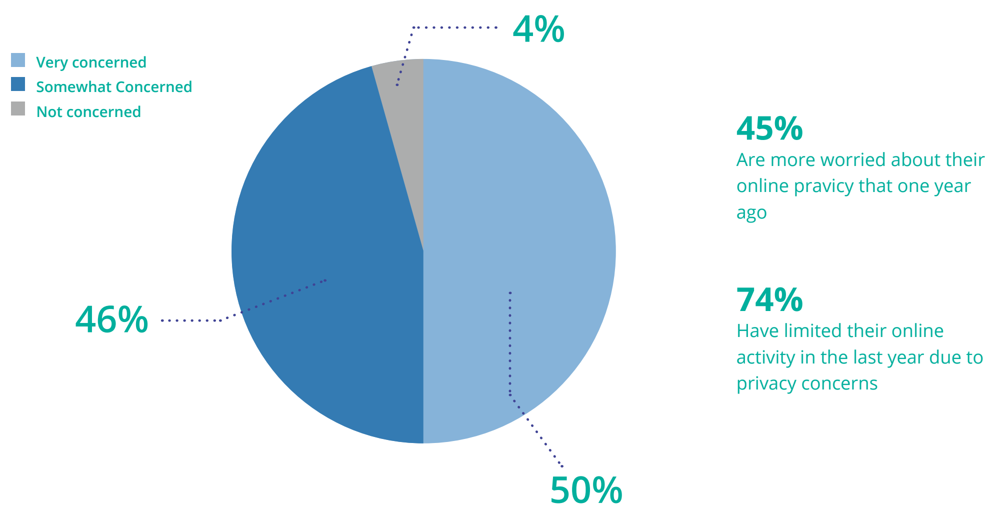
Hence, if European industry manages to create dependable, trustworthy and transparent products and services, a strong benefit for individuals will be seen to regain control over this loss of trust.

[87] *KPMG survey report, "Crossing the line: Staying on the right side of consumer privacy", November 2016, URL: https://home.kpmg.com/sg/en/home/media/press-releases/2016/11/companies-that-fail-to-see-privacy-as-a-business-priority-risk-crossing-the-creepy-line.html Ariel Hochstadt, VPN Mentor Survey, VPN Use and Data Privacy Stats for 2017, URL: https://www.vpnmentor.com/blog/vpn-use-data-privacy-stats/*

[88] *Ariel Hochstadt, VPN Mentor Survey, VPN Use and Data Privacy Stats for 2017, URL: https://www.vpnmentor.com/blog/vpn-use-data-privacy-stats/*

CONSUMER DATA PRIVACY CONCERNS RISING RAPIDLY

How concerned are you about data privacy & how companies use customer data?



Consumer data privacy concerns for online activities [88]

F.47

B. Benefits for organisations and businesses

Businesses will benefit from proactively tackling security and privacy issues in one of several ways: protecting the brand name, offering a competitive advantage from integrating privacy and security features into products and services, and creating new products and services designed to protect personal data. The most important characteristics for businesses in the future will be the aspect that they are perceived as trusted companies. Only as trusted organisations, they can maintain a long-term relationship to their customers. New "trusted products" represent a great opportunity for European companies, for example with the development of a "Trusted IoT" label [89]. Companies do also benefit from safety assessment and certification.

8.3. INTRODUCTION TO MAJOR CHALLENGES

8.3.1. Major Challenge 1: Safety, security and privacy by design

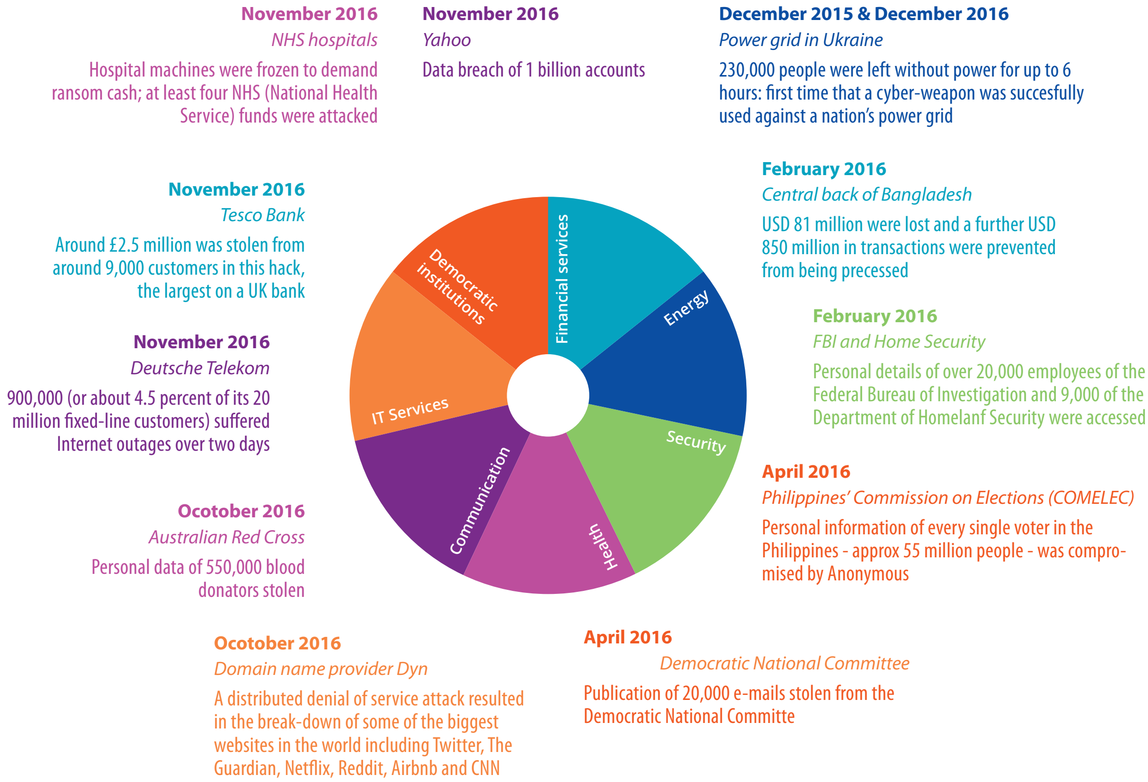
Breaches of sensitive data, mass disinformation campaigns, cyberespionage and attacks on critical infrastructure – these are no longer futuristic threats, but real events that affect individuals, businesses and governments on a daily basis. Yet they remain largely unprosecuted. Increasingly non-conventional threats, using the digital space with complex cyber-attacks, seek to undermine core European values and cohesion. Recent coordinated cyber-attacks across the globe, for which attribution has proved challenging, have demonstrated the vulnerabilities of our societies and institutions.

In this rapidly evolving context, the European Union and its Member States need to anticipate and plan for hitherto unimaginable scenarios in which they would be put under severe attack. Given the non-territorial nature of cyber threats and their increasingly disruptive effect, it is urgent to build up cyber capabilities at all levels – from basic cyber hygiene to advanced cyber intelligence, cyber defence and cyber resilience – in each Member State and scale up European cooperation.

8.3.1.1. Vision

Although the shift towards a digital world offers huge opportunities, it also comes with new types of risks and threats. As all sectors of our lives increasingly depend on cyber activity, any one of them could be targeted by a cyberattack.

These attacks can be carried out at the micro level, targeting individual citizens and businesses, or – as is increasingly the case – at the macro level, with a view to destabilising governmental institutions and state security, public policies and entire economies [90].



No critical sector escapes the cyber threat. This figure features only a small selection of incidents that took place in 2016. Many more attacks occur every day all over the world. **F.48**

Apart from the indirect transversal destabilising impact, the sheer economic value of these breaches is huge. Restricting the outlook just in the European Union, the average cost of a breach in 2017 fluctuates from $2.8m to $4.6m, being then a large loss factor for the targeted organisation [91].

The landscape described till now – in which we move, live, create trust and produce sensitive data, and in which our systems, hardware and software have to reside for way longer than 1.5 years, whereas for some sector like railway, or automotive, ten times that – is much wilder and more balkanised than we would like to think. The recent discovery of Spectre and Meltdown has shown the exploitation of processor common architectural patterns, targeting at the same time, multiple families of processors. New architectural processor pattern must be introduced addressing at the same time performance and security. This is the very reason why security, safety and privacy cannot be plugged in any system or software "at a later stage". Instead, they have to be rooted in the foundations, supporting and being integrated in hardware and software definition, design, development and deployment, and during operation and optimisation.

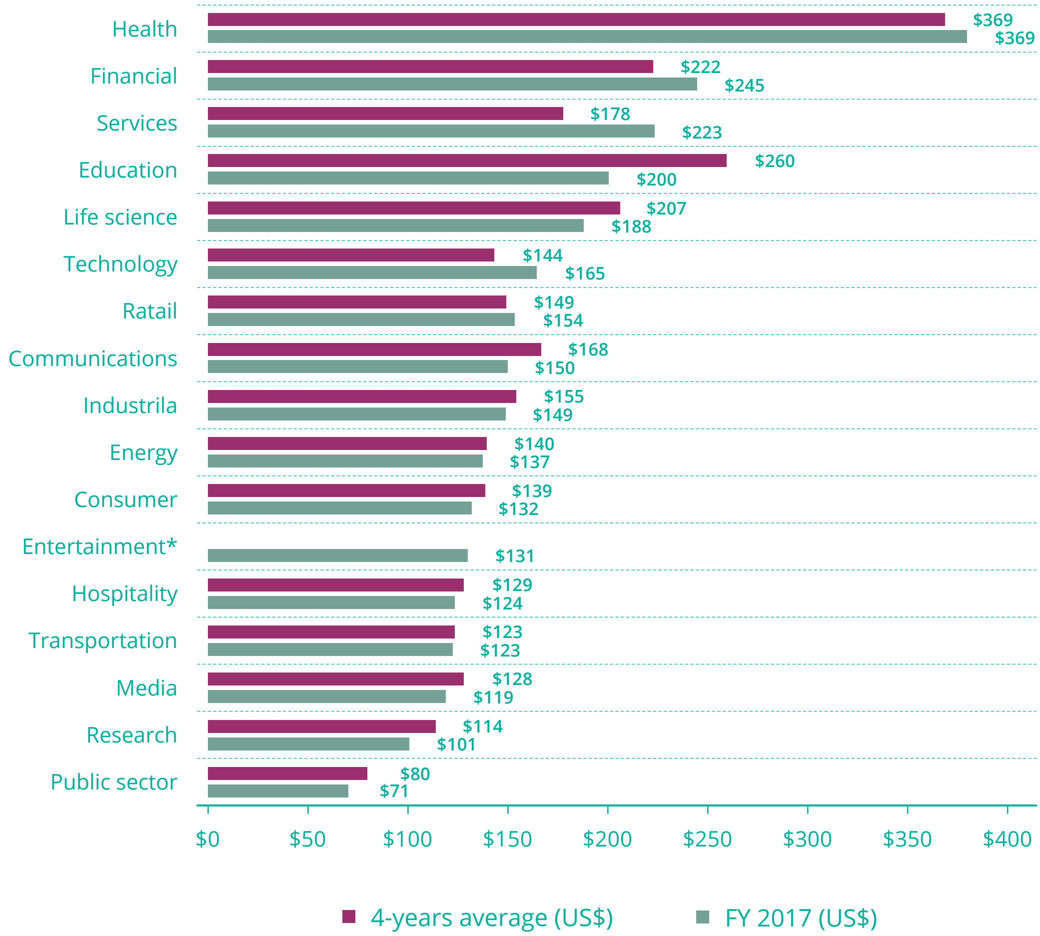
←

[89] *European Commission, ICT Standardisation Priorities for the Digital Single Market, April 2016, URL: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=15265*

[90] *European Political Strategy Centre, Building an Effective European Cyber Shield. EPSC Strategic Notes, Issue 24, 8 May 2017*

→

[91] *Ponemon Institute, 2017 Cost of Data Breach Study. Global Overview. June 2017*



F.49 *Per capita cost by industry classification. *Historical data are not available for all years. Measured in US$.*

8.3.1.2. Scope and ambition

The scope of this Major Challenge covers dependability and trustability from design to deployment, with a further glance to the hardware and software life cycle. It covers the enablers to be as future-proof as industrially imaginable today, so to be reliable and resistant to attack techniques envisionable 5-7 years from now. It covers centralised, cloud-based and edge paradigm as well as both industrial and consumer worlds, striving to cover the short-life and extremely manifold consumer scenario and the long-life, reliability-centric industrial one.

The ambition is to facilitate the worldwide uptake of “European Technology” and infrastructure with the goal to earn international reputation for secure, safe, dependable and trustable hardware, software and hybrid definition, design, development and deployment.

8.3.1.3. High priority R&D&I areas

Activity field 1: **Reinforce the Design**

- Strengthened methods for risk management, specifications, architecture and development, development, integration, verification and validation
- New methods and tools for formal verification of specifications, designs and implementations (model level proofs, source code analysis, binary analysis, hardware analysis, etc)
- New design tools Safety/security engineering
- Delivering high-assurance proofs over the whole life cycle
- Design to fail securely – Cyber threat analysis, susceptibility, assessment, drive pattern of failure
- Multi-level security assessment tools (may they be for security certifications or the security characterisations)
- Certification and standardisation of the complete life cycle of hardware and software (by components and by relations with other components)
- End-to-End Security of the supply chain in order to build trustable systems from the manufacturing into the foundry up to the Cloud processing
- Combined safety and security certification
- Support the evaluation of the systems examined within the safety/security assessment process
- Hardware/Software and hybrid track record
- Security and safety for hardware and software throughout the whole lifecycle
- Real-time safe high-performance computing
- Modelling of safety and security requirements in early design steps to get certification approval and enable incremental certification
- Design methods and tools for Safety and Security Co-Engineering (Modelling, Dependencies, Analysis)
- Rethink Architectures principles with respect to security
- Build new architectures principles encompassing security resiliency (such as DARPA Morpheus and MITRE's Cyber Security Resiliency Engineering Framework)
- Architectural principles to support dynamic safety evaluation and assurance (runtime certification/validation)
- Architecture principles supporting compositional safety and security proofs

Activity field 2: **Harden the Edge**

- On-Chip Encryption
- Integrated security, privacy, trust and data protection solutions or smart systems
- Addition of security capabilities to non-secure legacy technologies
- Integration of hardware and software
- Safe & Secure execution platform
- Safe and Secure certifiable software infrastructures
- Power efficient security features
- Secured devices – Trusted boot, trusted execution, authentication, anti-counterfeiting mechanisms
- Resistance to eavesdropping & injection attacks
- Cyber-security to make products tamper-proof in attacks from hackers
- Tamper Proof technologies
- Segregation and isolation of functional layers of components communication architecture
- Secure real-time systems, protocols, packaging, chip architecture
- Mitigate processor performance variability
- Secure sensor data storage in a standardised way

- (Secure) HW Upgrades and SW Updates
- Multi-tenancy in embedded hardware infrastructures
- Virtualisation and hypervisoring

Activity field 3: **Protect the Reach**

- Standards, information models and interoperability for smart systems integration
- Secured device management
- Certification of safe and secure products (certification standards, design rules, testing and inspection methods, certification scheme for third party evaluation)
- Modular certification
- Certificate management and distribution including certificate revocation lists
- Secured availability and maintainability within product lifecycle
- Quantum Computing exploitation and/or attack hardness
- Risk Management concepts and methods. (applicable to dynamic adaptation and configuration)

8.3.1.4. Competitive situation

Speaking of information technology, there is little excellence that is entirely born and raised in the EU, as base industrial technologies are dominated by giants like Intel, CISCO, Microsoft and the US in general. At the same time, European framework programmes are fostering basic STEM research and capabilities we need to look upon for our challenge, like the Quantum Flagship [92].

In the domain of engineering theory, methods, languages and tools, the European ecosystem has been a significant contributor over the past decades, both in the formal and the semi-formal design areas. Further developing these methods for effective applicability to complex systems in industry remains a challenge, where supporting a good combination of European academics, tool vendors and industry will be instrumental.

From an industrial point of view, the European ecosystem possesses a huge potential in the research and design through the leadership in embedded systems and semiconductors. When utilising this advantage, European industry has a strong chance to increase market shares for safe, secure, and privacy-preserving systems.

8.3.1.5. Expected achievements

Expected achievements are secure, safe, dependable and trustable design methodologies, practices, and standards for products and infrastructure that customers can rely on.

←

[92] *Digital Single Market news, "European Commission will launch €1 billion quantum technologies flagship". From https://ec.europa.eu/digital-single-market/en/news/european-commission-will-launch-eu1-billion-quantum-technologies-flagship, May 17th, 2016. Retrieved Aug 14th, 2017*

8.3.2. Major Challenge 2: Reliability and Functional Safety

8.3.2.1. Vision

The vision of the Major Challenge 2 is to provide all means and methods needed for the new ECS solutions to meet the reliability and functional safety targets and achieve resilience of ECS systems. Upcoming AI technologies used in safety critical design (Such as autonomous driving) introduce the need for Explainable AI. Current designs are unable to explain the reasoning, preventing the building of trust and safety on top of it. This shall even be achieved under the following conditions, which actually rather increase the risks of early and wear-out failures or software defects and worsen the severity of their consequences:

- Continuous growth in number, complexity, and diversity of the functional features, of the devices and components integrated as well as of the technologies and the materials involved in each product
- Increase in reliability and safety level to be achieved by the products, which will simultaneously and more frequently be deployed to ever harsher environments
- Decrease in time-to-market and cost per product due to the stronger global competition
- Higher complexity and depth of the supply chain raises the risk of hidden quality issues

8.3.2.2. Scope and ambition

When creating new functionalities and/or increasing the performance of ECS, the concerns of reliability and functional safety shall be accounted for right from the start of the development. This avoids wrong choices, which otherwise, may lead to costly and time-consuming repetitions of several development steps or even major parts of the development. In worst case, unreliable products could enter the market with dramatic consequences for customers and supplier. The improvements in reliability and safety methodology methodologies as well as their prompt implementation in transfer into industrial practice by R&D&I actions strictly aim at enabling the new European ECS products to enter the world market fast, to gain market shares rapidly, and to keep leadership positions sustainably in order to secure jobs and wealth in Europe:

- Determination of the 'Physics of Failure' **(PoF)** for all key failure modes and interactions
- Development of fast and comprehensive technology / product **qualification** schemes
- Creation of commonly accepted PoF based design for reliability, testing, manufacturing, … **(DfX)** methods based on calibrated models and validated numerical simulations and/or formal approaches
- Strategies for field data collection, prognostic health management **(PHM)** and autonomic development of ECS

8.3.2.3. High priority R&D&I areas

Activity field 1: **Experimental techniques for PoF assessment, analytics, and testing**

- Physical failure analysis techniques
- Realistic material and interface characterisation depending on actual dimensions, fabrication process conditions, ageing effects etc. covering all critical structures
- Tamper-resistant design, manufacturing & packaging of integrated circuits
- Comprehensive understanding of failure mechanisms, lifetime prediction models
- Methods and equipment for dedicated 3rd level reliability assessments (1st level: component, 2nd level: board, 3rd level: system with its housing, e.g. massive metal box) also accounting for the interactions between the hierarchy levels (device - component - module - system)
- Integrated mission profile sensors in field products avoiding security or privacy threats
- Wafer fab in-line and off-line tests for electronics, sensors, and actuators, and complex hardware

(e.g., multicore, GPU) also covering interaction effects such as, heterogeneous 3D integration, packaging approaches for advanced nodes technologies
- Accelerated testing methods (e.g., high temperature, high power application) based on mission profiles and failure data (from field use and from tests)
- Multi-mode loading based on mission profile

Activity field 2: **Pro-active DfX strategies based on virtual techniques**
- Virtual testing – design of very harsh tests for component (and system) characterisation
- Mathematical reliability models also accounting for the interdependencies between the hierarchy levels: device – component – module – system
- Mathematical modelling of competing and/or super-imposed failure modes
- Failure prevention and avoidance strategies based on a hierarchical reliability approach
- Virtual prototyping – DfX – building blocks
- Standardisation of the simulation driven DfX
- Automation of reliability assessment based on electronic design input
- Coordination action: Providing room for companies and research institutes to exchange expertise on reliability issues for advanced technologies
- European portal for DfR service provided by institutes and SMEs (provides access to DfR service at reduced cost - similar to 'Europractice' for wafer processing service)

Activity field 3: **Functional safety – Prognostic Health Management (PHM)**
- Self-diagnostic tools and robust control algorithms, validated by physical fault-injection techniques (e.g., by using end-of-life components)
- Hierarchical and scalable health management architectures, integrating diagnostic and prognostic capabilities from components to complete systems
- Monitoring test structures and/or monitor procedures on component and module level for monitoring temperatures, operating modes, parameter drifts, interconnect degradation etc.
- Identification of early warning failure indicators and development of methods for predicting the remaining useful life of the concrete system in its use conditions
- Functional safety aspects for autonomous systems including self-diagnostic and self-repair capabilities
- Development of schemes and tools using machine learning technique and AI for PHM
- Big sensor data management (data fusion, find correlations, secure communication)
- Safety certification on key domains like automotive, railway, industrial machinery and avionics

Activity field 4: **Dynamic adaptation and configuration, self-repair capabilities, resilience of complex systems**
- Self-diagnostic architecture principles and robust control algorithms that ensure adaptability and survivability in the presence of security attacks, random faults, unpredictable events, uncertain information, and so-called sensor false positives.
- Architectures, which support distribution, modularity, and fault containment units in order to isolate faults.
- Develop explainable AI models for both human interaction and system interaction,
- Identify and address safety related issues introduced by AI applications,
- Support for dependable dynamic configuration and adaptation/maintenance: as to cope with components to appear and to disappear, as ECS devices to connect/disconnect, and communication links are to be established / released depending on the actual availability of network connectivity; this includes e.g. patching, to adapt to security countermeasures.
- Concepts for run-time or dynamic certification/qualification, like run-time or dynamic safety contracts, to ensure continuing trust in dynamic adaptive systems in changing environments.

- Concepts for SoS integration including the issue of legacy system integration.
- Concepts and architecture principles for trustable integration and verification & validation of intelligent functions in systems / products: dedicated uncertainty management models and mechanisms (monitoring and issue detection) for automated or human-in-the loop online risk management. This includes machine-interpretation of situations (situational awareness) and machine-learning, for handling SotiF (Safety of the intended Functionality) and fail-operational issues, decision taking, prediction and planning.

8.3.2.4. Competitive situation

The current reliability and safety assessment practice shows the following shortcomings:

- **PoF & Qualification:** Predefined qualification plans are applied based on inherited standards often without adaption to the specific new PoF situation.
- **DfX:** While virtual schemes based on numerical simulation are widely used for functional design, they lack a systematic approach for reliability assessments.
- **Lifetime prediction:** System-level lifetime predictions are still based on MIL standards (FIDES, Telcordia etc.) with a constant failure rate statistics.
- **PHM:** Rarely any solutions on component or system level are available except from high-end products (e.g., in avionics and energy infrastructure). Search for early warning failure indicators is still at basic research stage.
- **Dynamic adaptation:** Highly dynamic architectures are pushed by data center providers to provide resilience and adaptability such as RackScale architecture, but they are not designed with safety in mind.

Intense research in the U.S and Asia tackles these shortcomings. Local conferences disseminate the results. Europe contributes details but does not set the standards.

8.3.2.5. Expected achievements

Public authorities and customers will accept innovative products only with all reliability and safety requirements fully met besides all the new functional features offered. Hence, this transversal topic is most essential for paving the way to the market for the new ECS products. Moreover, reliability and safety are concerns with great influence on customer satisfaction and trust. They enable generating a positive attitude of easy acceptance that helps unleashing the great potential of ECS technologies for creating products that benefit the public health, help the ecology, and create economic growth at the same time.

8.3.3. Major Challenge 3: Secure, safe and trustable connectivity and infrastructure

8.3.3.1. Vision

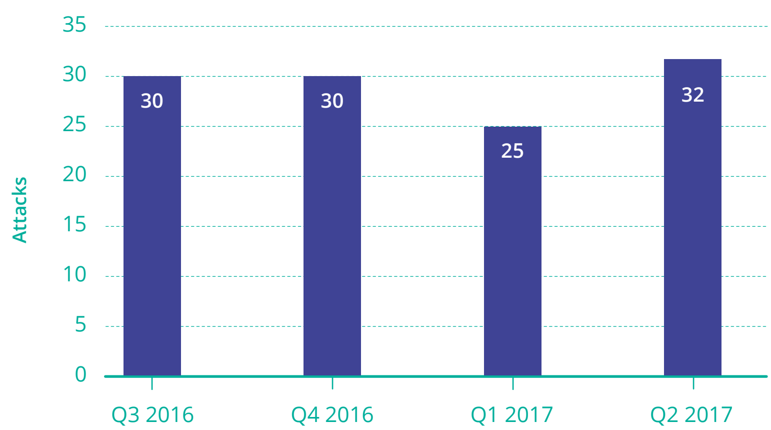
More and more Internet-connected devices find their way into homes and businesses. According to Gartner[93], there will be 20 billion Internet-connected devices by 2020. However, insecure IoT devices pose an increasing risk to both consumers and the basic functionality of the Internet. Insecure devices serve as building blocks for botnets, which in turn provide attackers access to compromised devices, perform DDoS attacks, send spam as well as steal personal and sensitive data.

The sheer number and volume of attacks rendered possible by the IoT explosion makes very clear the paramount importance of having a sound secure and trustable infrastructure. Globally, we witnessed the three largest attacks in history, aimed at assessing the capabilities to literally bring down the internet. Security personnel are concerned that the use of DDoS attacks could cause wide scale interruptions to our critical infrastructure, including public health and safety services. These high numbers of sources are most probably driven by attacks from Mirai botnets. Mirai is a malware that turns networked devices into remotely controlled "bots" that can be used as part of a botnet in large-scale network attacks. It primarily targets online consumer devices such as IP cameras and home routers[94].

93 *Gartner Technology Research, Gartner Says 6.4 Billion Connected "Things" Will Be in Use in 2016, Up 30 Percent From 2015, URL: http://www.gartner.com/newsroom/id/3165317, Nov. 10, 2015*

94 *Biggs, John (Oct 10, 2016). "Hackers release source code for a powerful DDoS app called Mirai". https://techcrunch.com/2016/10/10/hackers-release-source-code-for-a-powerful-ddos-app-called-mirai/, TechCrunch. Retrieved 12 December 2019.*

AVERAGE NUMBER OF DDOS ATTACKS PER TARGET, Q3 2016-Q2 2017



Top target organization DDoS attack count Q2 2017: **558**

F.50 *Sustained attack campaigns are constantly hitting companies*

Without a significant change in how the IoT industry approaches security, the explosion of IoT devices increases the risk to consumers and the whole industry. Therefore, industry must work to develop and adopt the necessary standards to ensure connected devices with sufficient incorporated security. This required change is addressed by the vision of secure and trustable connected devices that are robust, use broadly adopted security standards and have strong certification testing and enforcement mechanisms. Involved infrastructure like networks and cloud computing systems must be capable of detecting and containing potential security incidents.

8.3.3.2. Scope and ambition

The scope of this Major Challenge covers security and trustability for devices with communication capabilities, either via Internet connectivity or locally towards other nodes. Safety is also covered in case safety functions are realised via connected devices. This includes IoT nodes like networked sensors and actuators, fixed and wireless networks as well as centralised (cloud computing systems) and non-centralised (fog and edge computing) processing elements. It also covers security for communication protocols on different layers.

The ambition is to facilitate the worldwide uptake of “European Technology” and infrastructure with the goal to earn international reputation for secure, safe and trustable networking elements, in particular for industrial applications.

8.3.3.3. High priority R&D&I areas

Activity field 1: **Secure IoT devices**

- Processes for adding new devices/capabilities to the network (“onboarding”)
- Strong security with immutable, attestable and unique device identifiers
- Onboarding “weak” AI at the edge, safe and secure
- Authentication, Authorization, Revokability and Accountability
- Hardened devices with high integrity, confidentiality and availability
- Inherently trusted processor that would, by design, ensure security properties
- Lifecycle management
- Standardized, safe and secure “over the air” SW updates
- End-of-life (EOL) / End-of-Support (EOS) functionality
- Upgradable security for devices with long service life
- Secure components and secured ownership within an insecure environment
- Certification processes, testing and enforcement
- Components enabling integrity and confidentiality of the embedded SW and firmware

Activity field 2: **Secure communication protocols**

- Ensuring high standards for secured communication
- Secure interoperability of protocols, components and communications
- Monitoring, detection and mitigation of security issues on communication protocols
- Quantum key distribution (aka “Quantum Cryptography”)
- Formal verification of protocols and mechanisms
- Production of verified reference implementations of standard protocols and the guidelines to securely deploy them

Activity field 3: **Secure IT infrastructure**

- Infrastructure resilience and adaptability to new threats
- Continuous' secure end-to-end systems
- Secure cloud solutions
- Secure edge/fog computing
- Secure wireless and wired networks
- Low-power wide area networks
- 5G-related aspects of softwarisation, SDN and security of professional communications
- Artificial Intelligence for networks and components autonomy, network behaviour and self-adaptivity

8.3.3.4. Competitive situation

When looking at IoT technology, the worldwide market is dominated by US companies like Apple, Amazon, Microsoft or Google. These companies act worldwide and provide cloud computing platforms and data centers in many countries close to their customers. Wireless technology on the other hand is traditionally strong in Europe, originating from the success of the GSM technology up to ongoing development for 5G systems. Europe has several renowned, internationally acting mobile network equipment suppliers. However, recently competition from Chinese companies in this field has significantly increased.

From an industrial point of view, European companies possess a huge potential in the IoT market through the leadership in embedded systems and semiconductors, particularly in automotive industry. When utilising this advantage, European industry has a strong chance to increase market shares for secure connectivity and infrastructure.

8.3.3.5. Expected achievements

Expected achievements are secure, safe and trustable connected products and infrastructure that customers can rely on. This will be achieved with certified products according to a comprehensive security standard consisting of elements from the described high priority R&D&I areas above.

8.3.4. Major Challenge 4: Privacy, data protection and human interaction

8.3.4.1. Vision

More and more Internet-connected devices find their way into homes and businesses. According to Gartner there will be 20 billion Internet-connected devices by 2020. As of today, the IoT already generates a vast amount of information about our activities. This data can be used to create unexpected and undesirable influence to people. For example, some rental car companies include sensors in vehicles to warn drivers if they drive too recklessly. If such kind of data is given to car insurance

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[95] *REGULATION (EU) 2016/679 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation), http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679&qid=1490179745294&from=en*

[96] *DIRECTIVE (EU) 2016/1148 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union, URL: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L1148&from=EN*

[97] *European Commission, ICT Standardisation Priorities for the Digital Single Market, April 2016, URL: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=15265*

companies, insurances may deny users without transparently providing reasons to users. There are many similar examples that make people nervous about the use of big data technology.

Several measures have already been taken by the European Parliament and its national counterparts which aim to strengthen Europe's resilience. Two of these are the EU General Data Protection Regulation (GDPR) (Regulation (EU) 2016/679)[95] and the EU Directive on security of network and information systems (EU Directive 2016/1148)[96] as well as corresponding national laws in many EU Member States. The EU Directive 2016/1148 (better known as NIS directive) states that every operator of critical infrastructure and digital service providers must cooperate by exchanging security relevant information and are liable to maintain a certain level of security.

The acceptability of novel innovations with regard to privacy also involves strong human interaction including non-technical factors like psychological, social and work contextual factors. Therefore, people must be able to transparently see, how much and to what extend data about themselves is being shared in products and services, e.g. with the vision of using a "Trusted IoT label" as identified by the European Commission[97].

8.3.4.2. Scope and ambition

The scope of this Major Challenge is to develop methods and framework enabling the deployment of privacy, data protection and human interaction for different market without impacting customer acceptance. Hence, different competing requirements shall be satisfied:

- Limited computing resources vs. appropriate security level and real-time requirements
- Consistent (interoperable) Integration in different application domains having heterogeneous technical and market constraints
- Agility for new product development and optimised time to market while integrating and validating appropriate privacy framework
- High degree of product customisation and validation of privacy attributes
- Fulfilment of European directives and national regulations
- Data management and ownership in multi-stakeholder (multi-sided) market

8.3.4.3. High priority R&D&I areas

Activity field 1: **(Local) Technical solutions for privacy and data management**

- Security for privacy and personal data protection
- Identity, access management and authentication mechanisms
- Trusted devices based on block chain
- Secure aware data processing and storage
- Biometric technologies

Activity field 2: **(Global) Data management for privacy and protection**

- Data privacy & data ownership (use of enormous amount of data respecting privacy concerns)
- Data Protection, data standards
- Data pedigree
- Definition of models for data governance
- Supply chain security and zero-trust supply chain
- IoT Forensic capability for insurance & investigation purposes

Activity field 3: **Human interaction**

- Evaluation and experimentation for ECS platforms directly interfacing human decisions
- Establish a consensus for societal expectations for safety margin, ethic and mobility issues
- User acceptability and usability of secure solutions
- Design of trusted systems considering non-technical factors including psychological, social and work contextual factors
- Evaluation and experimentation using extended simulation and test-bed infrastructures for an integration of Cyber-Physical Systems Platforms that directly interfaces with human decisions.

8.3.4.4. Competitive situation

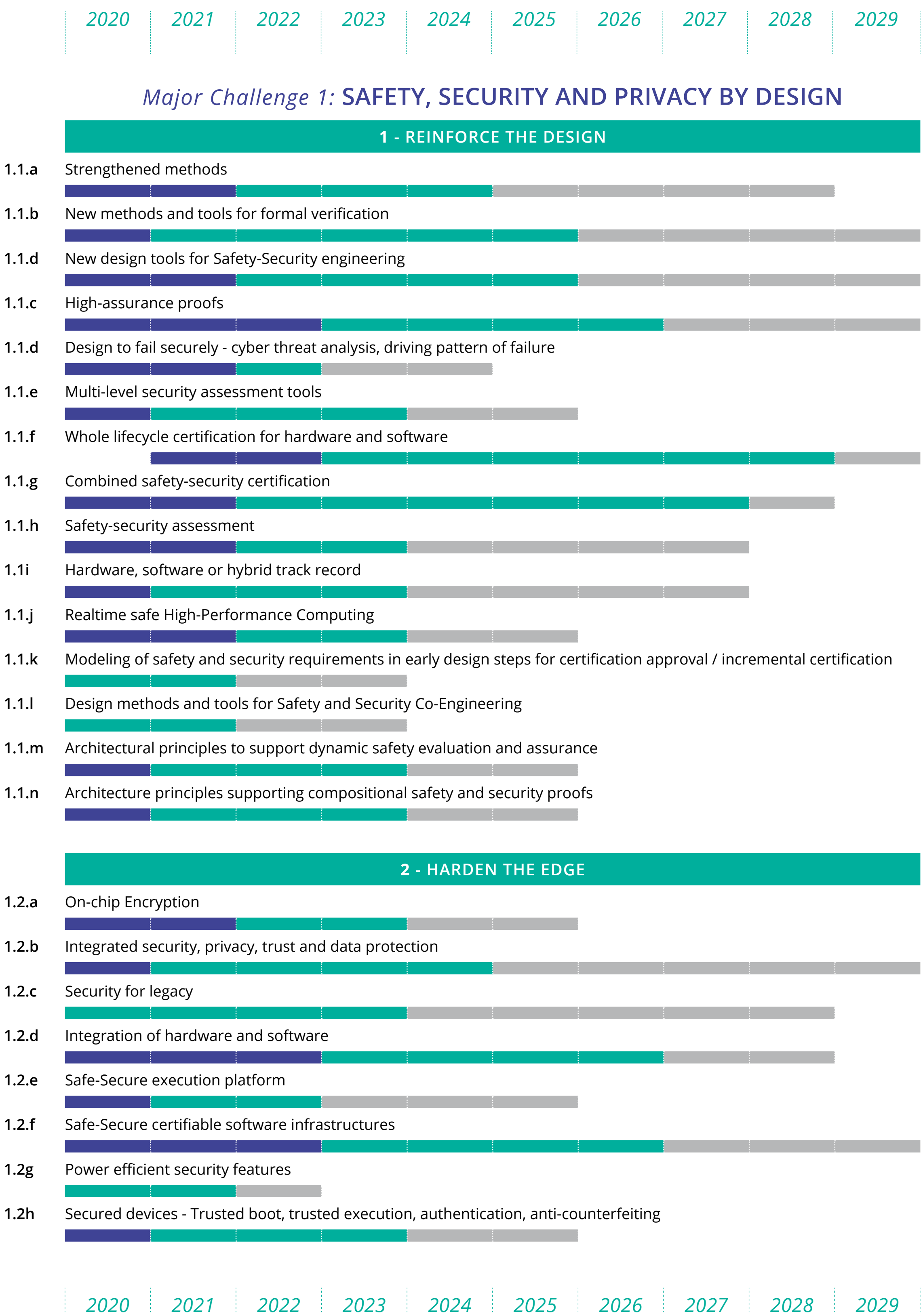
The European General Data Protection Regulation (GDPR) has a global impact after it goes into effect on May 25, 2018, because it not only affects EU companies, but also any company that does business with the EU. Hence, this stringent data privacy regulation already creates a leading role for Europe since other countries implement and follow it even for their own markets.

From an application point of view, European companies have a leading edge in different markets such as automotive and semiconductors or advanced production. Exactly the mix between domain-specific knowledge (subject matters) and connectivity technology will be required to create the added value at the end customer market.

8.3.4.5. Expected achievements

The expected achievements are a set of frameworks to facilitate the uptake of connected services and products for all industry sectors, while ensuring fulfilment of European directives and national regulation. The development of these methods is mandatory to ensure the success and security of our future smart environments, for the customer trust and acceptance and, therefore, is necessary to maintain the European society and its position in a global competition on economic markets.

8.4. TIMEFRAMES



2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

1.2i Resistance to eavesdropping & injection attacks

1.2j Tamper-proof technologies

1.2k Segregated Architecture - Enclaving communications

1.2l Secure realtime systems

1.2m Mitigate processor performance variability

1.2n Secure standardised sensor data storage

1.2o Secure upgrading

1.2p Multi-tenancy in embedded hardware infrastructures

1.2q Virtualisation and hypervisoring

3 - PROTECT THE REACH

1.3.a Standards and interoperability

1.3.b Secured device management

1.3.c Safe-Secure Certification schemes

1.3.d Modular certification

1.3.e Certificate management and revocation

1.3f Secured availability and maintenability

1.3g Quantum computing exploitation and hardening

1.3h Risk management

Major Challenge 2: RELIABILITY AND FUNCTIONAL SAFETY

1 - EXPERIMENTAL TECHNIQUES FOR POF ASSESSMENT, ANALYTICS, AND TESTING

2.1.a Physical failure analysis techniques

2.1.b Material and interface characterization

2.1.c Tamper-resistant design, manufacturing & packaging of integrated circuits

2.1.d Understanding of failure mechanisms, lifetime prediction models

2.1 e Methods and equipment for dedicated 3rd level reliability assessments

2.1.f Integrated mission profile sensors in field products avoiding security or privacy threats

2.1.g Wafer fab in-line and off-line tests for electronics, sensors, and actuators, and complex hardware

2.1.h Accelerated testing methods

2.1.i Multi-mode loading based on mission profile

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2 - PRO-ACTIVE DFX STRATEGIES BASED ON VIRTUAL TECHNIQUES

2.2.a Validated virtual testing methods

2.2.b Mathematical reliability models also accounting for the interdependencies between the hierarchy levels: device – component – system

2.2.c Mathematical modelling of competing and/or super-imposed failure modes

2.2.d Failure prevention and avoidance strategies based on a hierarchical reliability approach

2.2.e Virtual prototyping – DfX – building blocks

2.2.f Standardisation of the simulation driven DfX

2.2.g Automation of reliability assessment

2.2.h Providing room for companies and research institutes to exchange expertise on reliability issues for advanced technologies

2.2.i European portal for DfR service provided by institutes and SMEs

3 - FUNCTIONAL SAFETY – PROGNOSTIC HEALTH MANAGEMENT (PHM)

2.3.a Self-diagnostic tools and robust control algorithms

2.3.b Hierarchical and scalable health management architectures, integrating diagnostic and prognostic capabilities

2.3.c Monitoring test structures and/or monitor procedures

2.3.d Identification of early warning failure indicators and development of methods for predicting the remaining useful life

2.3.e Functional safety aspects for autonomous systems including self-diagnostic and self-repair capabilities

2.3.f Development of schemes and tools using machine learning technique and AI for PHM

2.3.g Big sensor data management

2.3.h Safety certification on key domains such as automotive, railway, industrial machinery, and avionics

4 - DYNAMIC ADAPTATION AND CONFIGURATION, SELF-REPAIR CAPABILITIES, RESILIENCE OF COMPLEX SYSTEMS

2.4.a Self-diagnostic architecture principles and robust control algorithms

2.4.b Architectures supporting distribution, modularity, and fault containment units

2.4.c Support for dependable dynamic configuration and adaptation/maintenance

2.4.d Concepts for run-time or dynamic certification/qualification

2.4.e Concepts for SoS (Systems-of-systems) integration including the issue of legacy systems integration

2.4.f Concepts and architecture principles for trustable integration of intelligent functions in systems / products

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 3: SECURE, SAFE AND TRUSTABLE CONNECTIVITY AND INFRASTRUCTURE

1 - SECURE IOT DEVICES

3.1.a Processes for adding new devices/capabilities to the network ("onboarding")

3.1.b Strong security with immutable, attestable and unique device identifiers

3.1.c Onboarding "weak" AI at the edge

3.1.d Authentication, Authorization, Revokability and Accountability

3.1.e Hardened devices with high integrity, confidentiality and availability

3.1.f Inherently trusted processor

3.1.g Lifecycle management

3.1.h Standardized, safe and secure "over the air" SW updates

3.1.i End-of-life (EOL) / End-of-Support (EOS) functionality

3.1.j Upgradable security for devices with long service life

3.1.k Secure components and secured ownership within an insecure environment

3.1.l Certification processes, testing and enforcement

2 - SECURE COMMUNICATION PROTOCOLS

3.2.a Ensuring high standards for secured communication

3.2.b Secure interoperability of protocols, components and communications

3.2.c Monitoring, detection and mitigation of security issues on comm. protocols that occur due to external, malicious activities

3.2.d Quantum key distribution (aka "Quantum Cryptography")

3.2.e Formal verification of protocols and mechanisms

3.2.f Production of verified reference implementations of standard protocols and the guidelines to securely deploy them

3 - SECURE IT INFRASTRUCTURE

3.3.a Infrastructure resilience and adaptability to new threats

3.3.b Continuous' secure end-to-end systems

3.3.c Secure cloud solutions

3.3.d Secure edge/fog computing

3.3.e Secure wireless and wired networks

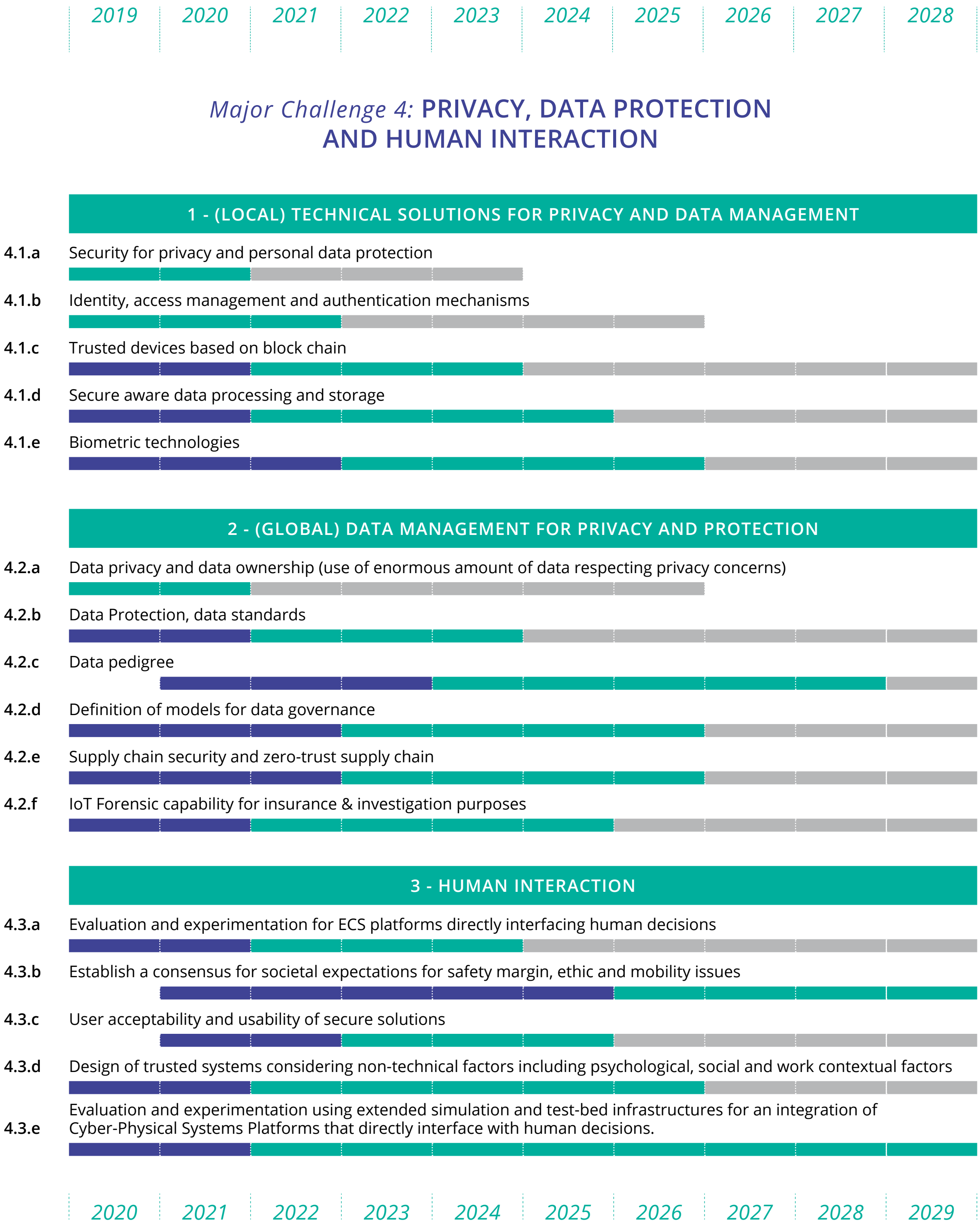
3.3.f Low-power wide area networks

3.3.g 5G-related aspects of softwarisation, SDN and security of professional communications

3.3.h Artificial Intelligence for networks and components autonomy, network behaviour and self-adaptivity

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Major Challenge 4: PRIVACY, DATA PROTECTION AND HUMAN INTERACTION



research or TRL 2-4; *development or TRL 4-6;* *pilot test or TRL 6-8*

Safety, Security and Reliability timelines **F.51**

8.5.
SYNERGIES WITH OTHER THEMES

	MC1: SAFETY, SECURITY AND PRIVACY BY DESIGN			MC2: RELIABILITY AND FUNCTIONAL SAFETY			
	Secure the Design	*Harden the Edge*	*Protect the Reach*	*PoF assessment & analytics, PoF-based testing*	*Pro-active DfX based on virtual techniques*	*Functional safety by PHM*	*Dynamic adaptation and configuration, self-repair capabilities, resilience of complex systems*
Transport	x	x	x	x	x	x	x
Health	x	x	x	x	x	x	x
Energy	x	x	x	x	x	X	x
Industry	x	x	x	x	x	x	x
Life	x	x	x	x	x		x
Architecture, Design, and Systems Integration Technology	x	x	x	x	x	x	x
Connectivity	x	x	x	x			x
Computing & Storage	x	x	x	x	x	x	x
Process Technology, Equip, Mat & ECS Manuf	x	x	x	x	x	x	

F.52 *Synergies with other chapters*

MC3: SECURE, SAFE AND TRUSTABLE CONNECTIVITY AND INFRASTRUCTURE			MC4: PRIVACY, DATA PROTECTION AND HUMAN INTERACTION		
Secure IoT devices	*Secure communication protocols*	*Secure IT infrastructure*	*Technical solutions for privacy and data management*	*Data management for privacy and protection*	*Human interaction*
x	x	x	x	x	x
x	x	x	x	x	x
x	x	x	x	x	
x	x	x	x	x	x
x	x	x	x	x	x
x	x		x		
x	x	x	x	x	x
x	x	x	x	x	
x	x		x	x	

9

Computing and Storage

9.1. EXECUTIVE SUMMARY

Computing and storage are the fuel of the digital revolution in providing ever increasing performance for existing and new applications at a constant or decreasing cost.

As the Moore's Law started to break down with the size of transistor shrinking to near atomic scale, chipmakers increasingly face issues trying to pack more and more transistors onto a chip and hence computing turns towards alternative ways to get more computing power including massively parallel, heterogeneous, distributed designs of processors and accelerators. But it has a drastic impact on programming and on the efficient management of the ever-increasing complexity of computing and storage systems. Energy becomes more and more critical both for high end and embedded systems. Performance is also shifting from an absolute number of operations per second to operations per second and per watt for all domains of computing. To manage the increasing intrinsic complexity of computing systems, solutions relying on intelligence of men and machine are more and more crucial.

Investigations of new technologies from neuromorphic computing, spintronic, optical to quantum for the long term open the way to new computing paradigms with new Cyber-Physical Systems and Artificial Intelligence driven applications.

Computing and storage now tend to form a continuum between extreme edge devices, edge devices, IoT, Fog, Cloud and HPC. Applications are increasingly distributed, and computing and storage have to be where they are most efficient. This trend is observed through the edge intelligence (aka Cognitive CPS, Intelligent Embedded Systems, Autonomous CPS) where data is transformed into information as early as possible to ensure privacy, efficiency and safety requirements. Having intelligent processing at the edge has pushed forward the requirement for computing and storage to be even more energy efficient and affordable.

This trend leads to the following major challenges for computing technologies:

- Increasing performance (including efficiency) at acceptable costs
  - For High Performance Computing (HPC) and servers,
  - For Data Analytics (data-intensive systems) and High-Throughput Systems (HTC),
  - And especially for low power and ultra-low power intelligent computing (edge and deep edge computing),
    - Which leads to the development of domain-aware accelerators and associated software environment,
    - And promotes in-memory or near memory computing, avoiding having to move data as much as possible.
- Creating a hardware and software continuum so that data are transformed into information in an optimal way in the optimal location,
- Making computing systems more integrated with the real world and
- Making "intelligent" machines.
- New computing paradigms require novel tools to facilitate the realisation of complex systems.
- New disruptive technologies should be analysed and further considered in order to support computing and storage in the future: Quantum technologies, neuromorphic computing, spintronic and optical Computing for example.

- Favoring reuse, open-source and legal enforcement (such as the GDPR) to sustain European sovereignty in front of GAFA and BATX.

In terms of the business direction, we also see a shift from "historic" hardware and software companies (such as IBM, Intel, ARM) to GAFA and BATX, which are increasingly vertical and are now developing their own hardware to sit beside their software ecosystem. Europe should react so that its sovereignty in hardware and software is not lost. This can be achieved by favouring reuse, open-source and legal enforcement (such as the GDPR).

9.2. **RELEVANCE**

9.2.1. Competitive Value

The key ingredient to the digital world is the availability of affordable computing and storage resources. From deeply embedded microcontrollers to supercomputers, our modern civilisation demands even more on computing and storage to enable new applications and change our way of life. In less than 10 years, mobile computing, a.k.a smartphones linked by Internet to data centres, have changed the way we see, interact and understand the world. Even in less developed countries, having a smartphone is nearly as vital as food. Computing and storage systems are morphing from classical computers with a screen and a keyboard to smart phones and to deeply embedded systems in the fabric of things. This revolution on how we now interact with machines is mainly due to the advance in artificial intelligence, more precisely of machine learning (deep learning) that allows machine to better comprehend the world by vision, audio and various signal analysis. This advance in AI is also due to the progress in computing and storage that allows the processing of more and more data, so that it is possible to "train" the artificial Intelligence algorithms on a greater amount of data.

Computing and storage should also enable more products (diversification) at affordable prices.

This should cover the complete spectrum, from ultra-low power wearable devices to Exascale systems.

While Europe is recognised for its knowhow in software and especially in embedded systems architecture and software, it should continue to invest in this domain to continue to be at the top, despite fierce competition from countries like China, India, etc.

European companies are also in the leading pack for embedded microcontrollers. Automotive, IoT and all embedded systems consume a large number of low-cost microcontrollers, integrating a complete system, computing, memory and various peripherals in a single die. Again, a pro-active innovation is necessary to cope with the new applications and constraints, like for Cyber-Physical Systems and Edge computing, especially when local AI is required. All the new applications require more processing power, requiring more efficient and powerful processors and microcontrollers, a domain that Europe left some time ago.

Europe no longer has a presence in "classical" computing such as processors for laptops and desktop, servers and HPC, but the new 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 for example*" could reactivate an active presence of Europe in that field. The ECS SRA recognises that this initiative is important for Europe and it has led to the launch of the "European Processor Initiative – EPI[98]".

Europe has also a very weak presence in storage: volatile memories, but also non-volatile memories (Flash) and magnetic storage are mainly developed outside of Europe.

Coprocessors, GPU and Deep Learning accelerators (and other accelerators) are also becoming more and more important. European solutions exist, but the companies are often bought by foreign companies. A rising approach to change this situation and prevent dependence on foreign closed processing technologies, relies on Open Hardware initiatives (Open Compute Project, RISC-V, OpenCores, OpenCAPI, etc.). The adoption of an open ecosystem approach, with a globally and incrementally built know-how by multiple actors, prevents that a single entity can be purchased or cease to exist for other reasons. The very low up-front cost of open hardware/silicon IP lowers the barrier of innovation for small players to create, customise, integrate or improve Open IP to their specific needs. Thanks to Open Hardware freely shared, and to existing manufacturing capabilities that still exist in Europe[99], prototyping facilities and the related know how, a new wave of European startups could come to existence building on top of existing designs and creating significant value by adding the customisation needed for industries such as HPC, automotive, energy, manufacturing or medicine.

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

9.2.2. Societal benefits

Computing is at the heart of a wide range of fields by powering most of the systems with which humans interact. It enables Transformational Science (Climate, Combustion, Biology, Astrophysics, etc…), Scientific Discovery and Data Analytics. The advent of complete or partial autonomous system, in addition to CPS, requires tremendous improvement in the computing fabric. Even if deeply hidden, these computing fabrics directly or indirectly impact our ways of life: Autonomous systems (car, aircraft, train, etc.), Quality of life (healthcare, transportation, energy, etc.), Communication (Satellite, 5G, etc.).

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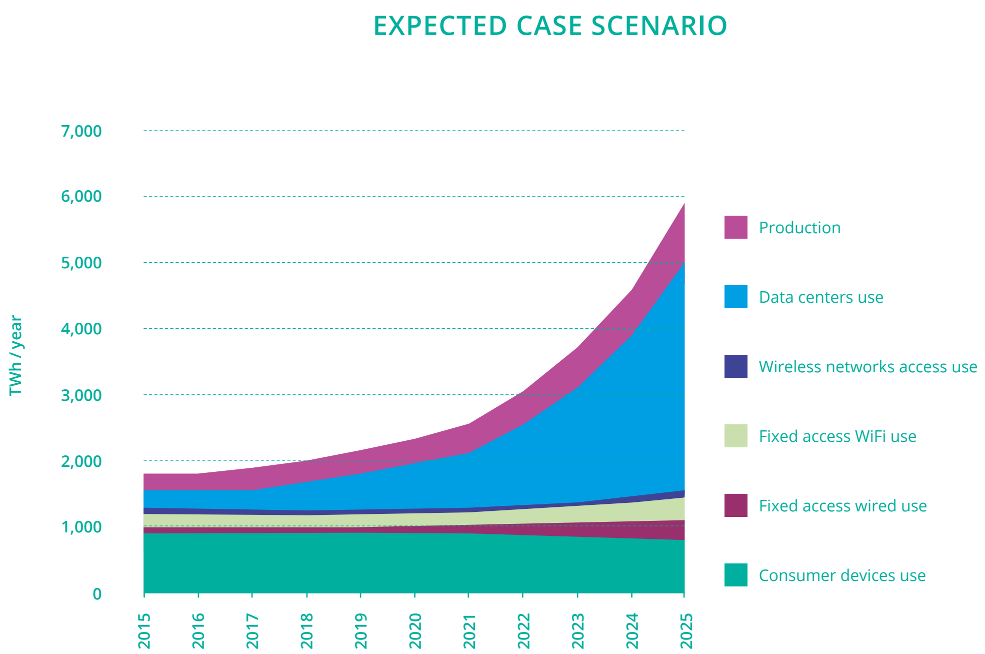
[98] *https://ec.europa.eu/digital-single-market/en/news/european-processor-initiative-consortium-develop-europes-microprocessors-future-supercomputers*

[99] *mainly for applications requiring a good energy efficiency and low cost, and not so much focused on ultimate processing speed.*

For example, computing and storage are key to solving societal challenges listed in the previous chapters, like monitoring and using the right amount of material and energy to save goods and energy. They will allow industrial processes to be optimised and thus save money. They enable cheaper products because they allow more efficient solutions to be built. In the medical domain, for example, they will allow healthcare to be delocalised (for example in the countryside, where no specialists are available). There will be synergies between domains: the developments on computing and storage for self-driving vehicles with higher reliability and predictability will directly benefit medical systems, for example. New applications, relying on complex computing and storage systems, allows you to monitor your health thanks to smart bracelets or smart watches, and could reduce the impact of a heart attack or other health problems. Cars will send their location and call for help after an accident. Intelligent applications helping the driver will reduce the number of accidents by monitoring the environment and warning the driver. Surveillance systems will allow security to be improved in various locations.

According to a forecast made by Dr Anders S.G. Andrae [100] (see Figure 53), the power usage of the data centres will multiply by seven between 2019 and 2025. Environmentally friendly data centres should be promoted to avoid this. We should ensure that the societal benefits induced by data centres will not be outweighed by their (not green) energy consumption. Energy efficiency of data centres is becoming increasingly crucial, as it is expected that the digital economy (internet, devices, networks, data centres and storage) will consume 20% of global electricity by around 2020. If the internet was a country, it would be ranked third (after China and USA) in electricity consumption with 1,500 TWh.



F.53 *Exponential energy consumption of data centres, from "Total Consumer Power Consumption Forecast", Anders S.G. Andrae, October 2017*

9.3. MAJOR CHALLENGES

9.3.1. Increasing performance at acceptable costs

Efficient systems and management of complexity

9.3.1.1. Vision

This major challenge addresses the course of computing technology and determines whether or not it would allow a 50× increase in peak performance in viable operating costs (i.e. energy, financial cost, reliability, size, etc.) by 2022 and to continue such progression beyond. The focus will be put on the main technological challenges that might prevent such an objective from being reached: energy consumption increase, memory and storage limitation, increasing complexity of applications *versus* achievable parallelism and resilience.

9.3.1.2. Scope and ambition

Computing solutions need to cover the whole range of applications, going from low-end IoT devices up to Exascale Computing. The expectation is not just to get more processing power, but at affordable cost in terms of power, size, price, cyber security. It is a shift from absolute number of operations per second to systems with a high efficiency.

An ambitious goal the High-Performance Computing community has set for itself is Exascale Computing as the next major step in computer engineering. The unprecedented level of computing power offered by Exascale is expected to significantly enhance our knowledge for the benefit of a large spectrum of industries including Energy, Bioinformatics and Medical Systems, Materials Science, Transportation, Entertainment and many others. The HPC community also sees for the future a change in the nature of the loads: although simulations will remain mainstream, applications related to big data processing (data analytics) and Artificial intelligence loads will be mixed with simulations (digital twins, etc). There will be a shift from single, double and quadruple precision floating-point type operations to more flexible data representations. The ETP4HPC, HiPEAC and BDVA are working together in order to precise the future requirements for post exascale machines[101].

The autonomous systems (such as automotive, train, aircraft) require embedded vision, complex decision-making and sensor processing (Radar, Lidar, Positioning, etc.) that were only possible with HPC systems a few years ago, but need now to be realised with cost and energy effective systems that don't have to be installed in dedicated rooms.

←

[10] *"Total Consumer Power Consumption Forecast", Anders S.G. Andrae, October 2017*

→

[101] *https://www.etp4hpc.eu/hpc-vision-018.html, document available at https://www.etp4hpc.eu/pujades/files/Blueprint%20 document_20190429.pdf*

9.3.1.3. Competitive situation and game changers

The major consolidation of the semi-conductor market observed in 2015 is continued with new mergers still on-going. The top ten players have gained an aggregated market share of almost 60%.

This creates a situation where few major companies are providing computing solutions, notably for the high-end, for the world. According to the 2017 McLean report, in the top 10 Worlwide Semiconductor Sales leaders, only 2 companies are still Europea [102], putting at risk the capability of Europeans to make their own decisions. For sovereign domains, but with small volumes, such as HPC, space, aeronautic, military, it may be difficult in 10-15 years to get access to some technologies.

Maintaining European knowhow on these technologies is required to meet the challenges at all stages of the data-processing chain and to ensure our sovereignty. Indeed, the intelligence of today's systems is not coming from a single element but from a tight collaboration between distributed elements like Smart Sensors (deep edge), CPS, Iot, Edge, Cloud and HPC. At each level, the large amount of data (*"data deluge"*), resilience, confidentiality and autonomy require new innovative computing solutions to satisfy emerging needs that are not satisfied anymore with the "ever-shrinking technology nodes" as highlighted in the HiPEAC vision document (http://www.hipeac.net/roadmap). The industrial and research computing community must support these evolutions by aiming at providing from 1 ExaFlops/s for HPC down to 1 TeraFlops/s/Watt for embedded CPS in 2020.

European innovation is required and processing cores that are accessible, either under licensing (such as ARM cores) or open source (such as RISC V), are possibilities for European research and industry to develop innovative and legally safe solutions while benefiting from established ecosystems. Although the USA is currently the technological leader in RISC-V, China and India have recently adopted it at the national level to foster technological independence in the area of processing technologies. Some European companies are also starting to develop RISC-V solutions. With this Open Source ISA and its many implementations, Europe could ensure its independence and emerge as a leader in the broadly understood open hardware movement given its rich tradition of open technologies, a diverse ecosystem and a strong industry – like e.g. automotive, which could be a major customer. Europe has a long tradition of leading the open source / open hardware movements, as evidenced by OpenRISC predating RISC-V, and the LEON CPU widely used in space domain. The too narrow application fields of these initiatives are now extended to a broader market by RISC-V, drawing on the experiences of those earlier efforts.

←

[102] *Finally, NXP will remain European for now, one reason being the delay of an answer from the Chinese regulators.*

On the other hand, the industrial and automotive sectors are seen as having growth potential in which European actors are well positioned. In addition to this good positioning, the forecast for annual growth rates in Europe will be higher than in other regions.

The European positioning in these innovative fields must be maintained and leveraged to achieve gains in others sectors. The industrial applications (such as Industry 4.0) and automotive (such as autonomous car) are launch pads for new technologies trying to cope with the challenges that are shared by embedded, mobile, server and HPC domains: **energy and power dissipation, and complexity management.** The safety requirements, applicable even in loss of connec tivity, prevents Cloud-only based solutions for Artificial Intelligence, Image processing, Complex decision-making (including preserving human life) with strong real-time constraints.

CPS used in harsh environments (high temperature, radiation, vibration, etc.) requires either dedicated or finely tuned architecture to run critical and highly intensive application: on-board satellite data processing, aircraft or cars self-monitoring.

9.3.1.4. High priority R&D&I areas

The hardware and architecture challenges

Next generation hardware[103] faces a huge challenge: an increase by a factor of at least 50 in performance to be combined with technology breakthroughs to reduce the power consumption by a factor of 100 (e.g. an extrapolation of the power load using current technology will require over a gigawatt for future exascale systems). The technical axes of exploration for power reduction in hardware design include: energy efficient building blocks (CPU, memory, reducing length of interconnects) possibly based on 3D silicon technologies, extensive usage of accelerated computing technologies (e.g. GPU, FPGA, neuronal accelerators) to complement general-purpose processor, reducing the communication cost between storage and computing (computing near memory, if not in memory), domain specific integration (System in Package, System on Chip), domain specific customised accelerators (e.g. for deep-learning, cryptography, variable-precision floating-point ...), integrated photonic backplane, cooling and packaging technologies, etc. This challenge is recognised by Europe that launched a “Framework Partnership Agreement in European low-power microprocessor technologies” (call ICT-42-2017 closed on September 26, 2017), but the effort needs to continue.

The challenge is not only at the component level, but also at the system and even infrastructure level: for example, the Open Compute Project was started by Facebook with the idea of delivering the most efficient designs for scalable computing through an open source hardware

→

[103] *The state-of-the-art is illustrated in the following respective references:*
CPU: http://wccftech.com/intel-skylake-cpu-10-20-performance-boost-faster-igpu-ddr4-overclocked/
Memory: https://www.intel.com/content/www/us/en/architecture-and-technology/intel-optane-technology.html
Interconnect: http://www.infinibandta.org/content/pages.php?pg=technology_overview
Storage: http://www.zdnet.com/article/ibms-world-record-330tb-uncompressed-data-on-a-palm-sized-tape-cartridge/

community. According to OCP, designs are more efficient at the ingredient level (server, storage, networking) compared to traditional gear yielding energy savings of 15% + and reduced service costs of ≈ 50%. Also, data centres achieve PUE's[104] better than 1.1.

Progress on ultra-low power hardware, generally powered by energy harvesting or capacitor, is needed to support the integration of intelligence into very small devices: biological implants, smart tattoos, RFC/RFID type solutions, home automation, food and goods tracking, in-material health monitoring.

In addition to the critical power issue, comes the *memory wall*. Today limitation is not coming from the pure processing power of systems but more from the capacity to bring data to the computing nodes within a reasonable power budget. As the memory dictates the size of the problem that can be solved, the need to scale the application to the computing power requires a huge improvement in memory access time and this issue gets worse due to the fact that memory access time (typically a doubling of the bandwidth every 3 years) is lagging behind the progress made in CPU cycle time. Furthermore, the system memory challenge is only part of a broader **Data Movement challenge** which requires significant progress in the data access/storage hierarchy from registers, main memory (e.g. progress of NVM technology, such as the Intel's 3D-xpoint, etc.), to external mass storage devices (e.g. progress in 3D-nand flash, SCM derived from NVM, etc.). In a modern system, the major part of the energy is dissipated in moving data from one place to another: computing in memory, or decreasing the communication cost between the storage and where the data are processed, is crucial. Another important point is the emerging of new memory technologies (PCM, CBRAM, MRAM, ReRAM, …) with access performances that are much better than standard flash memories but not yet at the level of DDR. This allows new application partitioning between volatile and non-volatile memory and more generally a complete review of the system memory hierarchy. This is very important especially regarding energy-saving policies. One of the main interests is the capacity to change from one operating point to another very rapidly, in any case much faster than saving an execution context from DDR to Flash as is the case today. This opens a path to very aggressive energy-saving policies as both the latency and the switch from one mode to another can be extremely short. As a consequence, it drives needs in the Application frameworks to integrate these new capabilities in order to give application developers the capacity to use these new features. The usage of a 64-bit, or even 128-bit, addressing scheme and large (non-volatile) memories could also have a drastic impact on what is one of the bases of most current computing system: the notion of file system. Objects can be directly addressed and mapped in the memory space. The use of the "key data" addressing scheme (for example, in the DAOS[105] file system that will be used in the exaFLOP range computer Aurora) is a first step in this direction.

←

[104] *https://en.wikipedia.org/wiki/Power_usage_effectiveness*

[105] *https://github.com/daos-stack*

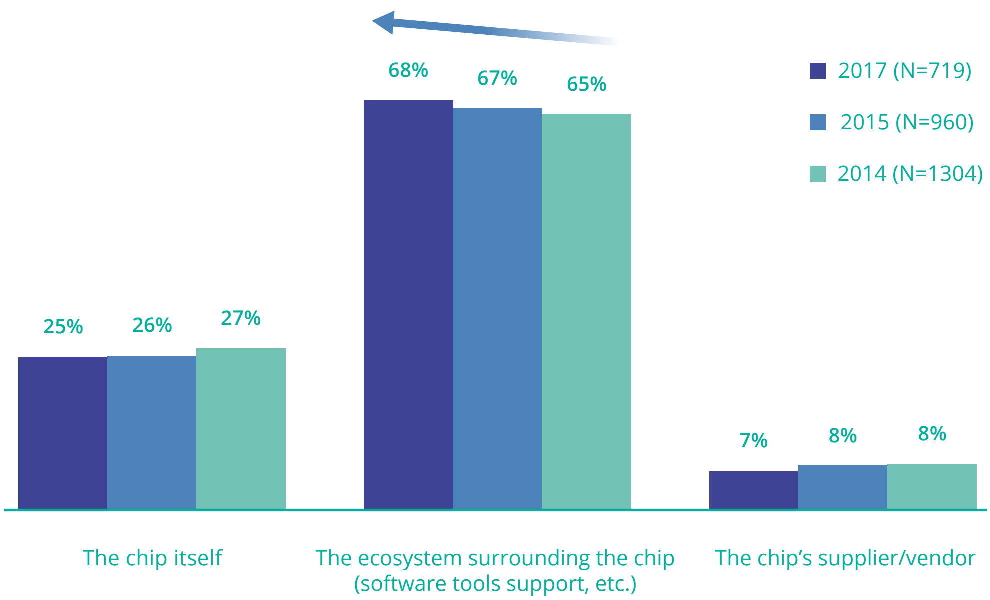
Energy of communication is not only at the chip/board and system levels: it is also between systems. The emergence of 5G will also have an impact on computing systems, both on how they are distributed, but also in the design of the computing elements required to ensure efficient 5G systems and infrastructure.

Finally, the increasing size and complexity of such system architectures is challenging their design and development, implying in turn the revision of their *design methodology* (see chapter 6 for more details).

The software challenges

The choice of a computing solution is not driven mainly by its intrinsic performances but by the software ecosystem. With the ever-increasing complexity of processors, more advanced software infrastructure has to be developed.

WHAT'S MOST IMPORTANT WHEN CHOOSING A MICROPROCESSOR?



Source: AspenCore 2017 Embedded Markets Study

F.54

It is well known that the gap between hardware and software capabilities is widening in high-performance systems. While a single processor chip can provide from several up to thousands of processing cores, many applications still (sometimes poorly) exploit only few cores in parallel. Safety Critical applications hardly start to use multi-core processors. Therefore, there is an urgent need to upgrade the software to the hardware capacity through the following potential actions:

- Middleware/Software: the data movement constraints (streamed, stored and even replayed from stream) must be used to dynamically or statically schedule massively parallel tasks in order to optimise the core's usage. These scheduling strategies must not only optimise processor usage but also prevent any data loss and decrease processing latencies. Guaranteeing both real-time and safety properties will come from a close collaboration between hardware and software, where time is frequently absent from the underlying programming language. For HPC, coordinated and hierarchical checkpoint/restart, new strategies become mandatory to unload this burden from application level to system level and to manage heterogeneity optimally.

- Programming Models and Methods: *Massively and Hybrid Parallel Computing* requires new programming models suitable to support scalability and a large range of heterogeneous computing, such as for vector accelerators. The main challenge is to have programming models integrating multi-dimensional constraints. Up to now the programming models have been mainly based on maximising the efficiency of the computing system regarding the type of data and their type of use case. Now things are different as this optimisation still needs to happen but other aspects such as power consumption, scalability security, and dependability have to be managed simultaneously. This is even more important for the IoT system where resources are very scarce and for which efficient resource management is a highly differentiating factor. One of the challenges is to provide application designers with the right knobs in order to make the best trade-off. There is a strong need for new languages or programming framework where this security, dependability and power consumption are built-in features whereby adequate control is given to the programmer to ensure the most optimal solution in terms of design decisions. It is mandatory to offer the best expertise in every domain even for developers who are not the best experts in all facets of today's systems: the underlying complexity increase should be hidden to the programmers. This type of requirement ranges from very small IoT devices up to very large computing systems.
- This requirement necessitates, in turn, the definition of common communication protocols (e.g. CCIX, Gen-Z, OpenCAPI) and the improvement of existing standards (e.g. PThreads/OpenMP, OpenCL, OpenACC, CUDA, HLS, MPI, auto-vectorisation, etc.) to provide better support for both precision and coarse parallelism, interoperability, scalability, portability, latency awareness.
- The application complexity is increasing dramatically and optimised code production represents a challenge. Improvement of existing codes is just impossible, which implies the need to invent new parallelisation strategies. The development of such massively parallel applications also requires new code production tools to support the debugging, validation and certification tasks. As an example, Open Hardware initiatives unleashed low-level software by giving direct access to hardware: LinuxBoot[106], open embedded software and open networking software such as SONiC[107], ONIE[108] and Switch Abstraction Interface (SAI)[109].
- The ever-increasing size and complexity of software itself is becoming more challenging. The costs and effort to understand and maintain the existing software stacks is exploding. The development of model-driven software techniques, DSLs, etc, partly alleviate this issue, but creates new problems with respect to the evolution of languages and models, tool creation and tool integration.
- In addition, the software should also contribute to the solution of hardware-critical challenges by providing robust, energy-aware and fault-tolerant self-healing applications.

System challenges and applications/architecture co-design

Emerging computing systems (IoT, CPS, HPC, etc.) cannot be a mere assembly of disparate improvements issued from the previous steps but a smart combination of them to provide efficient solutions. That leads to the concept of software/hardware *co-design* challenge which can be defined as the simultaneous design/development of both hardware and software to be optimally implemented in a desired function. The high-level approaches are shown in chapter 6, but the complexity of co-design of computing and storage stems from the combination of the following themes of work:

- Reconsideration of basic mathematical models and reworking of algorithms (e.g. massively parallel algorithms, genetic programming, Deep-Learning, etc.); they have to remain platform-independent to suit any future candidate targets. Algorithms that *a priori* include sequential sections have to be restructured to open ways to extract as much inherent parallelism as possible through suited state-of the-art tools to cope with the capabilities of the computing fabric.

- Scalable implementation on large and heterogeneous platforms (different computing architectures, accelerators, etc) using new interoperable and composable programming paradigms (energy-aware static/dynamic placement, scheduling, communication, etc.) that can be transparent to the user. All these challenges should be addressed in an integrated manner, in connection within a 'Grand Mission' addressing the need for a versatile European hardware platform for a new generation of computing.
- Optimal composition of hardware and of the constraints of users according to many variable criteria including computing technologies, use of reconfigurable logic, memory access and interconnection and I/O (e.g. combination of communication protocols, support of data coherence/consistency models, memory and network contention etc.). It yields a design space exploration problem that we are able to face with appropriate tools, possibly using Artificial Intelligence related techniques. This huge complexity will be managed by selecting only some relevant solutions that match the user multi-criteria. This kind of tooled-up approach enables future products to be properly sized.

9.3.1.5. Expected achievements

HPC and related application domains

As stated in previous sections, HPC has become indispensable to all branches of government, education and all fields of industry and thus it impacts almost every aspect of daily life. To date, progress towards petascale computing has been achieved mainly through an evolutionary enhancement of microprocessor technology but the transformation towards the next step of exascale computing represents a challenging venture: an in-depth reworking of application codes in conjunction with radical changes in hardware to optimally exploit high levels of parallelism in solving ever-increasing complex problems.

HPC technology will in turn extend itself into a set of immediate application areas including Data Centre and Cloud Computing, and offers a convergence with Big Data to form the new *HPDA* ("high-performance data analytics") discipline.

The technologies developed for HPC generally become mainstream a few years after – for instance, self-driving cars required the processing power of super-computers only of few years ago, such is the "ripple effect".

←

[106] *https://opensource.com/article/17/2/linux-boot-and-startup*

[107] *https://azure.microsoft.com/en-us/blog/sonic-the-networking-switch-software-that-powers-the-microsoft-global-cloud/*

[108] *http://onie.org/*

[109] *https://azure.microsoft.com/en-us/blog/switch-abstraction-interface-sai-officially-accepted-by-the-open-compute-project-ocp/*

CPS domain

More and more heterogeneity is the way to reach the performance expected from CPS with always more energy efficiency. Considering that the use of multi-core processors is not yet fully managed for safety critical applications for which determinism is mandatory, adding heterogeneity is just moving to another order of complexity. Current programming solutions for dedicated accelerators, even if promising, such as High Level Synthesis for FPGA, rely too heavily on the programmer being able to understand the underlying architectures. The advent of FPGA as part of Cloud building blocks, such as F1 Amazon EC2, and Microsoft Brainwave dedicated to Deep Learning, will accelerate the development of scalable, hardware-agnostic and energy-efficient programming solutions. Such solutions must encompass FPGA, DSP, GPU, CNN/DNN accelerators, or even more innovative hardware.

Distributed intelligent platforms will be part of the landscape of everyday life activities (healthcare, transportation, education, business, etc.) to reduce the event-response latency by providing real-time decisions, capturing live data streams, building complex decision logic and enabling real-time monitoring, predictive alerts and guided interactions. The introduction of 5G with its guarantees of low latency and Quality of Service will also unlock more reliable distributed systems.

Extreme low power and IoT

Extreme low-power computing is necessary in many advanced systems based on pervasive computing, including sometimes devices where computing is necessary but no battery is available. Beyond the challenge of harvesting energy, there is a pressing need for architectures that fully optimise the energy consumption with dedicated processing cores, accelerators and energy management systems.

9.3.2. Making computing systems more integrated with the real world

Dependability and real time

9.3.2.1. Vision

Computing systems are more and more pervasive and they are present in almost all objects of current life (wearable objects, home appliances, retail and home automation, etc.). These systems bring intelligence everywhere (Smart Anything Everywhere) and are usually referred to as Cyber-Physical Systems, and they will evolve towards Autonomous Cyber-Physical Systems (ACPS) or Cognitive Cyber-Physical Systems or Intelligent Embedded Systems (depending on the source of the term). Their role in complex systems is becoming increasingly necessary (in cars, trains, airplanes, health equipment, etc.) because of the new functionalities they provide (including safety, security, autonomy). They are also required for the interconnection and interoperability of systems of systems (smart cities, air traffic management, etc.).

Because of their close integration with the real world, the systems have to take into account the dynamic and evolving aspect of their environment, to provide altogether deterministic, high-performance and low-power computing as well as efficient processing of deep-learning algorithms.

Finally, because of their usage in dependable systems they have to follow certification / qualification processes imposing guarantees regarding their functional and non-functional specifications.

9.3.2.2. Scope and ambition

The ambition for computing systems when they need to be integrated in the real world is the realisation of systems offering altogether a large computing local performance (since they need to be smart), a good level of performance predictability (implying deterministic architecture suited to certification/qualification processes) and efficient interconnection capabilities (distributed systems and systems of systems).

To interface with the physical world, these CPS require a fine, fast and dynamic understanding of their environment through real-time analysis based on AI technologies.

Their natural interconnectivity requires the establishing of connections to the external world with high levels of safety, privacy and security as described in chapter 8. Moreover, the realisation of trustable computing systems ensuring reliability, predictability, safety, security and privacy is generally necessary, even when connected to systems and networks that have low security, safety or reliability levels.

Engineering methods (including analysis, verification and validation to ensure properties such as security) scaled to the complexity and high-level non-functional requirements of CPS are necessary especially in the case of adaptive systems. They must satisfy the multidisciplinary challenge of designing CPS with numerous constraints, objectives and functional or non-functional requirements which are often contradictory (response time, safety, trust, security, performance, QoS, energy efficiency, size, reliability, cost).

9.3.2.3. Competitive situation and game changers

Europe has a good position in smart systems connected to the real world. This strong position is confirmed at product level (cars, planes, industry, robots, etc) as well as scientific level (formal methods, time analysis, design methodology) and general knowhow in embedded systems.

However, as this domain is undergoing tremendous changes (due to the increased need for more computational resources), it remains a great opportunity for future developments. The good technological level of Europe must be maintained and improved.

9.3.2.4. High priority R&D&I areas

System challenges and applications/architecture co-design

As explained in the previous challenge, computing in embedded systems faces fundamental challenges of power, bandwidth, and synchronisation.

But **dependability** is a key for these embedded systems, which are the heart of systems used by people (planes, self-driving cars, etc). Knowing how to correct errors on these more and more complex systems is a challenge to making them reliable and resilient. Knowing how to ensure that time constraints (response time, etc) are met is a challenge to making them predictable, and thus safe. Security techniques (secure access mechanisms, blockchains, etc) have to be adapted to make CPS able to satisfy the privacy of their users. For example, blockchains that can be used in IoT and smart sensors powered by battery or harvesting energy require a large improvement in the efficiency of computing elements.

Because of their interaction with the physical world, CPS have extremely dynamic properties with numerous parameters possibly changing at runtime, sometimes discontinuously. The subsequently high number of scenarios makes modelling, simulating and implementing them really challenging.

CPS tend to offer increased autonomy – ACPS for Autonomous CPS - (autonomous cars, robots, home automation, etc.), which implies complex decision-making based on AI combined with high timing constraints as well as reliability, safety and security constraints.

This challenge of dependability is also present for HPC and server systems: as the number of components increases faster than their reliability, *system resilience* becomes the third challenge pole in Exascale system design: SMTBF is decreasing towards the range of 1h-10h and thus requires more efficient checkpoint/restart mechanisms together with Algorithm-Based Fault Tolerance, redundancy strategy, enforcement of real-time constraints for application reconfigured at runtime, real-time vote with no single point of failure. Technical improvements on this topic are expected to be manifold to include enhancement of both hardware and software reliability but also the development of fault resilient algorithms.

Multi-domain/multi-paradigm design and analysis are also major system challenges. The key point of CPS is that the embedded hardware and software can no longer be designed and analysed without integrally considering the encompassing system and context, typically involving mechanical and physical aspects and processes. Therefore, holistic approaches, implying multi-disciplinary techniques and teams, will be required to meet all the CPS requirements (dependability, efficiency, etc).

The hardware challenges

Today's distributed embedded systems (as exemplified by CPS) are built on a large number of distributed computational platforms that communicate with each other via a [wireless] network fabric and interact with the physical world via a set of sensors and actuators. To meet the increasing performance and flexibility demands, embedded systems leverage heterogeneous multi/many-core architectures optionally enhanced with hardware accelerators (e.g. GPU) to replace more and more µcontrollers and DSPs, to ensure real-time behaviour with partitioning and virtualisation technologies and to handle critical systems (e.g. independent certification of safety-critical components, separation of safety-relevant subsystem on the same processor, etc.).

Determining statically the Worst-Case Execution Time of such a complex system is an intractable challenge, and new (possibly dynamic or statistical) approaches are required to ensure that the system will fulfil its mission in due time. Processing time determinism is indeed often required in applications with safety-critical or hard real-time constraints. The solution can also be found with the design of dedicated architectures. When this is affordable, specific interconnection systems for multi/many-core processors can, for instance, be more effective and easier to implement than software approaches.

For the security aspect, trustable secure zones, enclaves, isolation techniques, specific modules for protection, cryptoprocessors, homomorphic computing etc, have to be considered. The Open Source hardware (RISC-V, OpenPower, etc) will allow white box design and the exploration of processor architectures by the community. Specification of many parts of the systems are generally not completely known or disclosed. This leads to black or grey boxes which have to be specifically considered. With most recent technologies, components reliability or performance variation may also require a specific approach to ensure good characteristics at upper layers. Edge systems are already made of small processing units (such as µcontroller) cooperating altogether (e.g. watch, phone, shoes). The battery requirement limits the possibility of integration. With the advent of autonomous energy sources, such as ambient RF energy harvesting, the design of ultra-low power and energy-aware processors for computation and communication may greatly improve this integration.

The software challenges

Software components are distributed throughout an embedded system and interact with one another across well-defined interfaces. At a feature level, they also collaborate via their shared interaction with the physical world. Three specific challenges are particular to collaborating embedded systems:

- **Virtual System Integration:** From a design perspective, challenges arise in the modelling (integration of models representing different formalisms, communication among hardware/software sub-models, etc) and analysis of the design.

- **Runtime System Adaptation:** Reasoning and planning adaptation of a set of sub-systems via the maintenance of consistent information and management of inconsistencies and the usage of online model calibration.
- **Model management:** How to deal with heterogeneous models that together describe a component, physically as well as its behaviour. There are dependencies involved, and ensuring the consistency of these dependencies is of paramount importance.

Getting computers to work together with physical processes requires technically intricate, low-level design: embedded software designers are forced to deal with interrupt controllers, memory architectures, assembly-level programming (to exploit specialised instructions or to precisely control timing), device driver design, network interfaces, and scheduling strategies. The most critical systems (mission critical or even life critical) require a high verification level which can only be reached by a combination of formal methods and accurate timing analysis, trace analysis, monitoring with dedicated control algorithms, accurate profiling solutions, etc. The dynamicity of CPS implies systems in which the state space cannot be explored at design time. In spite of great progress in that domain, the end-to-end verification of complex hybrid systems is still a challenge. There is also a significant advantage to perform numerical stability property verification through formal methods of these systems. Improving the trade-off between communication availability, autonomy and real-time requires tightly cooperating hardware, platform, programming model (moving from task to event based) and application software. An additional point is the need for the development of appropriate software technologies and tools that enable viable development and implementation processes for systems and applications that make use of the new compute technologies and architectures. To support system design and realisation, further development of software technologies that enable system specification at higher abstraction levels (o.a. model-driven SW realisation, Domain-Specific Languages) are required. Without such SW technologies and tools, the benefits of the computer technologies and architectures will remain theoretical rather than practical.

9.3.2.5. Expected achievements

The expected achievements here are key development platforms and building blocks (hardware and software) and integrated tool-chains covering the entire development cycle from system concept to HW/SW implementation to enable the design of trustable, evolvable and easy-to-maintain cyber-physical systems.

Moreover, “de facto” European standards for interoperable CPS systems will be a strong benefit to foster the development of competitive European products in that domain.

9.3.3. Making “intelligent” machines

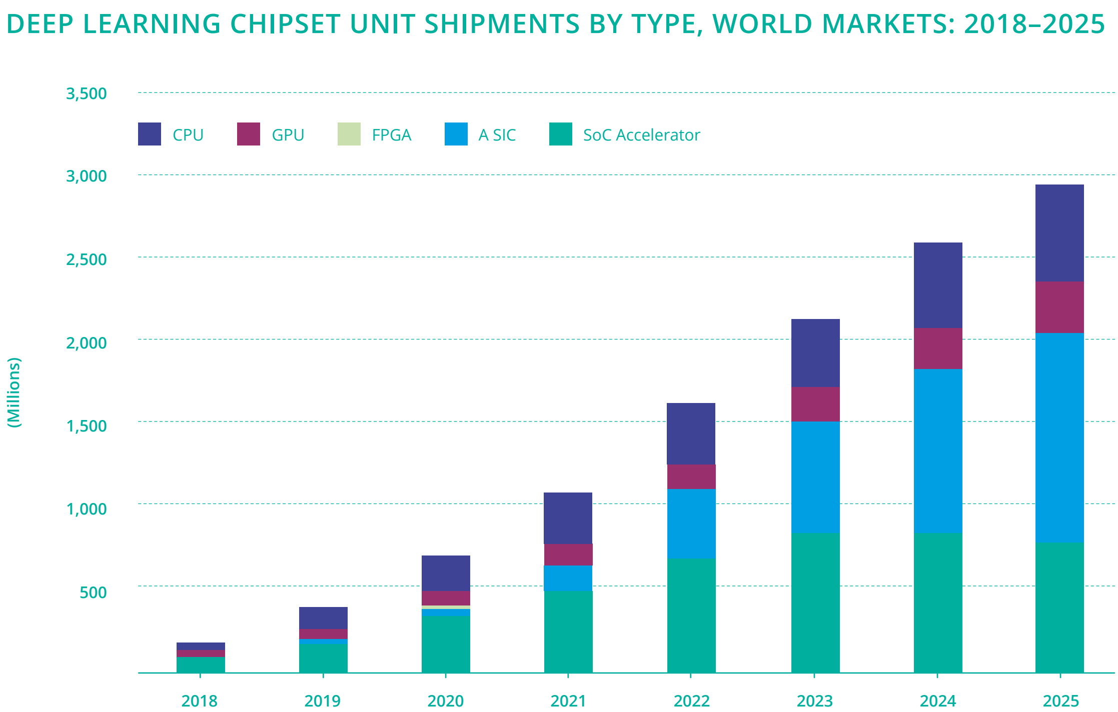
Towards autonomous systems

9.3.3.1. Vision

Artificial Intelligence (AI) again became a very hot topic recently, mainly due to the practical success of Deep Learning on image classification, voice recognition and even in strategic games (AlphaGo from Deepmind/Google beating the best human Go player, and Alpha Zero becoming the best player in chess and in Go within a few hours, even beating its predecessor AlphaGo). According to the “Hype Cycle for Emerging Technologies, 2018” by Gartner, Smart Robots, Virtual Assistants, Deep Learning, Machine Learning, Autonomous Vehicles and Cognitive Computing at the peak of the curve, while Artificial General Intelligence, Deep Reinforcement Learning and Neuromorphic Hardware are still on the rise. According to a report from Tractica, the revenues generated from the direct and indirect application of AI software will grow from USD 1.4 billion in 2016 to

USD 59.8 billion by 2025. IBS has a forecast of a growth of AI processor up to $195B in 2027. These techniques will signify a big technological shift and will have an overall impact. In the domain of Computing and storage, the consequences will be twofold:

- Europe should remain in the AI race and develop efficient solutions for IA systems, both at the hardware and software level. AI, and more especially Deep Learning, requires large amounts of computation (in the exaflop range) with variable precision for the "learning" phase, and embedding AI solutions in edge devices will require low-energy accelerators. As previously seen, Europe's place in CPS systems should drive it to the lead position in Autonomous Cyber-Physical Systems, adding "intelligence" to CPS.
- AI techniques can be used for the design of computing solutions, e.g. for selecting an optimal hardware combination (*generative design*), or for software generation or even generating the best Machine Learning solution (Auto-ML). There are already researchers using Deep Learning for generating Deep Learning networks.



F.55 *Large increase of deep learning chipsets. "Deep Learning Chipset Shipments to Increase to 2.9 Billion Units Annualy by 2025". (https://www.tractica.com/newsroom/press-releases/deep-learning-chipset-shipments-to-increase-to-2-9-billion-units-annually-by-2025/)*

9.3.3.2. Scope and ambition

	Date of original paper	Energy consumption (kWh)
Transformer (65M parameters)	Jun, 2017	27
Transformers (213M parameters)	Jun, 2017	201
ELMo	Feb, 2018	275
BERT (110M parameters)	Oct, 2018	1,507
Transformers (213M parameters) w/neural architecture search	Jan, 2019	656,347

Estimated cost of training a Deep Learning model

F.56

Note: Due to a lack of power draw data on GPT-2's training hardware, the researchers weren't able to calculate its energy consumption. Source: MIT Technology Review, data from Strubell et al. arXiv:1906.02243v1 (for the MIT article, see https://www.technologyreview.com/s/613630/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/)

AI and especially Deep Learning require optimised hardware support for efficient realisation:

- For the learning phase, the large amount of variable precision computations (from float16 to double that) requires accelerators with efficient memory access and large multi-computer engine structures. Energy efficiency is paramount because the number of computations increases exponentially with new networks and new applications (see Figure 55), which directly translates into an explosion in energy consumption (see Figure 56).
- Access to a large storage area is necessary to store all the examples that are used during this phase,
- A new emerging computing paradigm, using unsupervised learning like STDP (Spike-timing-dependent plasticity), 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 ALU and digital operators, STDP can be realised by the physics of some materials, such as those used in Non-Volatile Memories. This could differentiate Europe from the learning accelerators for servers and HPC which require a huge investment, and solutions are already available, either open or closed, such as the NVIDA Volta and Turing GPU, Google's TPU2, etc.
- Developing solutions for AI at the edge (e.g. for self-driving vehicle, personal assistants and robots) is more in line with European requirements (privacy, safety) and knowhow (embedded systems). Solution at the extreme edge (small sensors, etc) will require even more efficient computing systems because of their low cost and ultra-low power requirements. However, Europe has to act quickly, because US and Chinese companies are already also moving in this "intelligence at the edge" direction (e.g. with Intel Compute Stick, Google's Edge TPU, Nvidia's Jetson Nano, etc).

Europe should also be at the forefront of emerging hardware and software solutions for AI, beyond classical Deep Learning, particularly in the use of AI-based solutions to improve the development of systems by selecting optimal solutions to complex problems, in various domains, including the development of new computing solutions.

Finally, hardware and software should be developed to support Self-X systems (self-repairing, analysing, managing, …) to ensure more dependable systems.

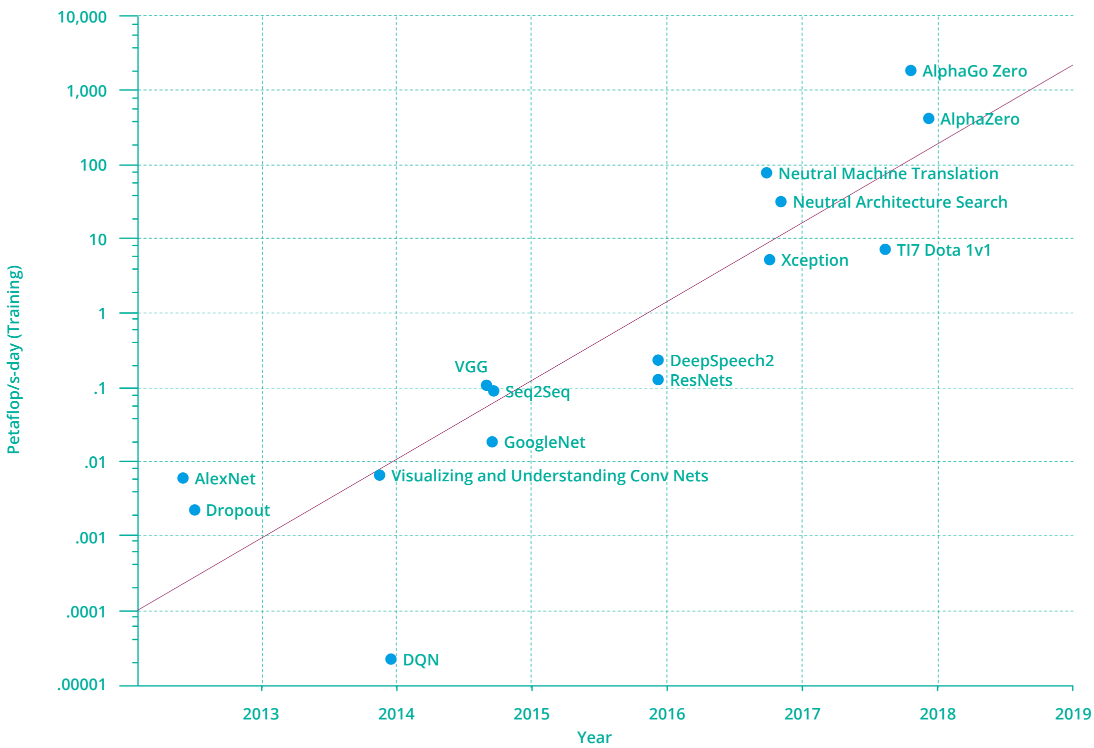
9.3.3.3. Competitive situation and game changers

AI techniques could change the way we interact with computers: instead of programming, i.e. telling the machine how to do things by giving it a list of instructions, we might move to a more declarative or parenting approach where we tell the machine *what* should be done (and not *how* it should be done), e.g. through examples. Typical computing models will be complemented with these new ones.

On the user side, AI techniques will allow more natural interaction, e.g. with language, and AI techniques will be key for a machine to recognise and analyse its environment, e.g. for self-driving cars. For safety, privacy and cost (reduction of the communication bandwidth with server), local intelligence (intelligence at the edge) needs to be developed, working harmoniously with the cloud, but exchanging data with it only when required. This will require more efficient processing capabilities at the edge, and an increase of local storage. In the coming years, the processing capabilities of the IBM Watson used for winning the jeopardy game could be affordable as a home server, and the compete Wikipedia encyclopaedia will fit in its local storage. Dedicated accelerators for Deep Learning and related techniques will allow the development of autonomous robots, intelligent personal assistant, safety systems and autonomous vehicle with the minimum need for accessing extra computing resources and storage.

Currently, AI and Deep Learning are mainly developed by the extended GAFA (Google, Amazon, Facebook, Apple, Microsoft, Baidu) and they make large investment in this domain by acquiring major players (both start-ups and known academics). They also have in-house the large databases required for the learning and the computing facilities (even if they develop accelerators by themselves, for example Google and Apple). We

ALEXNET TO ALPHAGO ZERO: A 300,00X INCREASE IN COMPUTE



F.57 *Exponential increase of computing for AI training*

Source: https://openai.com/blog/ai-and-compute should not forget that, besides the access of large (labelled) databases, this advance of Artificial Intelligence is also due to the progress of computing and storage that allows the processing of greater amounts of data, so that artificial Intelligence algorithms can be "trained" for more applications.

All major companies already develop their own chips for deep learning (e.g. Google with its line of TPUs) or made announcement that they will. The US and Chinese governments have also started initiatives in this field to ensure that they will remain pre-eminent players in the field.

"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)[110]"

It will be a challenge for Europe to be in this race, but the emergence of AI at the edge, and its knowhow in embedded systems, might be winning factors – but here, also, the competition will be fierce. 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 $99. Google Edge TPU is also a $75 USB accelerator integrating the Edge TPU. Nvidia introduced the Jetson Nano, a $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 $12 board (MAIX Bit) (https://wiki.sipeed.com/en/maix/board/bit.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.

The Nvidia Jetson Nano, a $99 board [111]

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[110] *https://openai.com/blog/ai-and-compute/*

[111] *(Source: https://www.nvidia.com/fr-fr/autonomous-machines/embedded-systems/jetson-nano/)*

9.3.3.4. High priority R&D&I areas

System challenges and applications/architecture co-design

As previously seen, managing the complexity of computing systems is an important challenge, and AI inspired techniques can be used to design more efficient hardware and software systems. Analysing the large space of configurations and selecting the best option with clever techniques allow the design of more efficient systems, taking into account a large number of parameters. It is still a research area, but in mechanical design it is already at the product level (*generative design* tools).

There are already experiments in this field to design efficient multi-core systems or generate more efficient code.

Techniques for self-analysing, self-configuration, discovery of the features of connected systems, self-correcting and self-repairing are also domains that need to be developed to cope with the complexity, interoperability and reliability of computing and storage systems.

The hardware challenges

To efficiently support new AI-related applications, for both the server and client (edge side), new accelerators need to be developed. For example, Deep Learning does not usually need 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 compute and storage parts are required (Neural Networks are an ideal "compute in memory" approach). Storage also needs to be adapted to support IA requirements (specific data accesses, co-location compute and storage), memory hierarchy, local vs cloud storage.

Similarly, at the edge side, accelerators for AI applications will more specifically require real-time inferenced, especially to reduce the power consumption. For Deep Learning applications, arithmetic operations are simple (mainly multiply-accumulate) but they are done in very large numbers and the data access is also challenging (also clever schemes are required to reuse data in the case of convolutional neural networks or in system with shared weights). Computing and storage are deeply intertwined. And of course, all the accelerators should 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 the computations (although with low precision and high dispersion, but the Neural Networks approach is able to cope with these limitations).

Over the years, a number of groups have been working on hardware implementations of deep neural networks. These designs vary from specialised but conventional processors optimised for machine learning "kernels" to systems that attempt to directly simulate an ensemble of "silicon" neurons, known as neuromorphic computing.

Recent achievements in this field are:

- the biologically inspired chip "TrueNorth" from IBM that implements one million spiking neurons and 256 million synapses on a chip with 5.5 billion transistors, and
- the neuromorphic chip developed by IMEC, capable of composing music by learning rules of composition[112].
- The Neuram3 H2020 project, which just delivered a prototype chip with better performances than TrueNorth
- Etc.[113]

Besides Deep Learning, the "Human Brain Project", a H2020 FET Flagship Project which targets the fields of neuroscience, computing and brain-related medicine, including, in its SP9, the Neuromorphic Computing platform SpiNNaker and BrainScaleS (https://electronicvisions.github.io/hbp-sp9-guidebook/). This Platform enable experiments with configurable neuromorphic computing systems.

In the U.S., a report of a 2015 roundtable "Neuromorphic Computing: From Materials to Systems Architecture"[114] describes, amongst other things, the need for Neuromorphic Computing and identifies a number of open issues ranging from materials to systems. Early signs of this need appear with the emergence of machine learning based methods applied to problems where traditional approaches are inadequate. These methods are used to analyse the data produced from climate models, in a search of complex patterns not obvious to humans. They are used to recognise features in large-scale cosmology data, where the data volumes are too large for human inspection.

The software challenges

The paradigm introduced by new AI techniques such as Deep Learning could promote more emphasis on *declarative (or statistical)* instead of *imperative* programming, "programming" by examples, where goals and constraints are given, but the system should determine by itself the best way to reach the goals. How this approach can be combined with "classical" systems, how to ensure that the solution is correct, etc, are new challenges. Validation, verification of systems and the ethical questions posed by systems that will determine themselves their choice in a more or less transparent way are also important challenges. Deep learning systems are essentially *black-boxes* and their results (and errors) are often difficult to explain, therefore a current drive towards "explainable AI"[115]. This is also part of the more general challenge described in the previous paragraph consisting of determining whether a complex system, composed of white (we know the internals, how it works), grey (we know the specifications and interfaces) and black (we don't know how it works) boxes, will ensure the Quality of Service and objectives for which it has been designed.

The problem of interoperability and the complexity introduced with the new accelerators, and how they can be combined with classical systems, also need to be resolved.

Artificial Intelligence-derived techniques could be also applied to the software (and hardware) development, making the software development itself more intelligent. There is a growing interest in applying machine learning techniques to existing software repositories, both source code and models, to derive relations, detect clones, etc. For example, Auto-ML are machine learning techniques that allow for optimising applications of machine learning.

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[112] *http://magazine.imec.be/data/83/reader/reader.html#!preferred/1/package/83/pub/89/page/5*

[113] *https://www.cerebras.net/*

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[114] *https://science.energy.gov/~/media/bes/pdf/reports/2016/NCFMtSA_rpt.pdf*

[115] *https://www.darpa.mil/program/explainable-artificial-intelligence*

9.3.3.5. Expected achievements

In the domain of system challenges and applications/architecture co-design, the expected achievement is to provide a platform and tools that allow the complexity of systems to be managed and efficient solutions to be designed with the help of AI related techniques. It should help the partitioning of tasks onto various hardware and accelerators (including those for Deep Learning). Europe should be the leader in generative design tools for designing computing systems.

From the hardware point of view, new efficient accelerators for AI tasks should be developed for edge processing, allowing intelligence to be embedded near the user and limiting the use of remote accesses to ensure safety, privacy and energy efficiency.

From the software side, existing software environments should be extended to support declarative programming, and good coordination with AI related approaches to allow the smooth integration of various approaches.

A European run-time ensuring self-analysing, self-configuration, discovery of the features of connected systems, self-correcting and self-repairing should be developed to become the “de facto” European standard for interoperable and reliable systems.

Solutions should be developed, both at the technical, ethical and legal level to ensure that AI related techniques will be accepted in society, with a focus on the objectives and Quality of Service being correctly ensured.

9.3.4. Developing new disruptive technologies

Moore’s Law has started to break down as the size of transistor has shrunk down to near atomic scale and alternative ways have been investigated to get more computing power, including quantum computing, neuromorphic computing, spintronic, photonic, biochemical computing, etc. for the longer term.

In the US alternative approaches to computing are being gathered under the name “Reboot Computing” including all aspects from materials and devices up to architecture. As it is not possible to cover all the different approaches explored on computing in this SRA due to length restrictions, a few of the promising approaches are selected as examples, but with the clear message that Europe should continue to invest to keep on par with the rest of the world.

There is no clear answer on what technology will be successful, but they will certainly co-exist with silicon technology. For example, Quantum computing will be delivering accelerators for solving a certain kind of problems, but will still be tightly linked with more conventional electronics and computing and storage devices. The silicon technology will remain the backbone and glue of the various other technologies. It is therefore important that we already work on how to integrate those new technologies together with the existing ones, not only at the hardware level, but also at the software level. Most of these new technologies are more long term and are detailed in chapter 11, but we can see that quantum computing, neuromorphic computing, optical computing, spin-based computing will have their role in the future computing and storage systems.

9.3.4.1. Quantum Computing

An important aspect for quantum computing is the development of a unified set of methodologies and techniques to use and interact with such a physical quantum machine: at the logical level, how do we encode and test quantum algorithms? The lack of efficient general-purpose quantum computers (e.g. the D-Wave 2000Q System oriented towards Quantum Annealing) leads to a variety of meet-in-the-middle approaches by major actors, with the development of a variety of software-based emulators – including Atos/Bull Quantum Learning Machine, Microsoft's LIQUi|>, Google's Quantum Computing Playground – to assist in the research and development of quantum algorithms, independently from the hardware research activity. One thing can be learned from these approaches: A good computational paradigm for quantum computation is that of a quantum co-processor linked to a classical, conventional computer. Pre- and post-processing are done classically while the quantum co-processor targets the quantum-specific aspects of the computation. This will pose new challenges:

- There is no well-defined model of computation mixing classical and quantum computation, nor a complete compilation and software stack.
- The interfacing between the classical computer and the quantum computer will require new developments, both for the bandwidth, the errors and the fact that quantum machines currently work at very low temperature, where the behaviour of classical electronics is not well defined.
- The instability of quantum states, and interferences, will lead to errors, and error correction is therefore a challenge.
- Close links with quantum technology developments are mandatory and could benefit from various applications (see chapter 10) besides computing: these classes of applications have different requirements in terms of system complexity and number of working quantum devices, but technological development needs are similar: 1. Development of components beyond the quantum device and interfaces between the quantum device and the classical world, 2. Device optimisation and device deselect based on fabrication influenced benchmarking, 3. Control of yield and variability.

9.3.4.2. Neuromorphic computing

Neuromorphic computing is part of the previous challenge making "intelligent" machines and is detailed in the part concerning the hardware challenges, but it has also its place here because it can be performed with different computing elements than ALUs and binary coding. For performing its operations, the information can be coded not only in a spatial way (like in binary code), but in a spatial and temporal way: for example, with "spikes" – the pulses similar to the ones that carry information in the brain – where the moment of emission of the pulse is an important element of the information. Computing using new ways to code information is interesting and can unlock new doors. The processing can be done in an analogue manner, or using the physics of specific materials, as when implementing the STDP learning rule. These materials, storing the information of the neural network in "synapses", can be very small leading to the very dense and low-power realisation of Neural Networks that may also be compatible with the inference phase of Deep Learning approaches. For decades, we were designing computing devices using CMOS gates as switches and binary encoding for representing data: other approaches can be investigated and could potentially be very efficient, if not on general purpose calculations, but at least on domain specific tasks.

9.3.4.3. Optical Computing

Optical computing has been an active topic of research for some decades and while it has not become mainstream, it is still alive today. It is not only university groups that study the issues of optical computing, in either hybrid or pure optical solutions, but also companies, one example being Hewlett Packard Labs which designed an all-optical chip that features 1052 optical components to implement an Ising machine[116]. This chip demonstrates that advances in all-optical information processing, including digital and analogue, classical and quantum as well as those based on Turing computation, are still being made.

We refrain from describing all possible and different approaches to optical computing in detail, as there are quite many, but it is clear that the topic is not dead and deserves to be considered as an alternative implementation to computing with far-reaching consequences.

9.3.4.4. Spin-based Computing

Spintronics can be an alternative for new generation of AI hardware architecture providing small computing approaches and with ultra-low consumption[117]. Furthermore, magnonics (information processing via spin quanta, i.e., magnons) is considered one of the most promising Beyond-CMOS technology[118]. The importance of Spintronics for low-energy consumption is well documented in Europe and abroad. One example from IMEC[119] (Leuven, Belgium) compares a spin wave device with a 10nm FinFET CMOS technology; another example from Ohno's group (Tohoku University, Japan) shows a reduction of energy consumption of more than 80% when specific logic functionalities are addressed by spin-based solution[120].

Indeed, the core aspects of novel spintronic applications[121] are the building blocks for future CPSs: storing, sensing, computing and communicating. Novel approaches (e.g., skyrmions and all-optical switching) permit information to be stored and manipulated faster and with a smaller footprint towards a "universal memory"; spin-based devices (e.g., Tunnel Magneto Resistance) permits going beyond the performances of existing sensors to respond to the growing needs of automotive and IoT markets, together with the automation requested by Industry 4.0. Spin-based devices combining energy harvesting, simple front-end analogue treatments and communicating functionalities at varying frequencies of the EM spectrum (from MHz to THz), will provide novel solutions to sense, compute and exchange information with almost no energy consumption and weight, also useful for IoT or novel robotic systems. Indeed, the breakthrough R&D on spin-transfer torque oscillators and spin wave computing will nourish the future market of spin logic (Beyond CMOS) and give the relevant hardware solutions for neuromorphic computing.

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116 *http://spectrum.ieee.org/semiconductors/processors/hpes-new-chip-marks-a-milestone-in-optical-computing*

117 *J. Grollier et al., "Spintronic Nanodevices for Bioinspired Computing" Proceedings of the IEEE, Vol 104, 2024 (2016) [http://ieeexplore.ieee.org/document/7563364/]*

118 *A. V. Chumak, V. I. Vasyuchka, A. A. Serga, B. Hillebrands, Magnon spintronics. Nature Physics 11, 453 (2015)*

119 *O. Zografos et al., "Design and benchmarking of hybrid CMOS-Spin Wave Device Circuits compared to 10nm CMOS" Proceedings of the 15th IEEE International Conference on Nanotechnology July 27-30, 2015, Rome, Italy [http://ieeexplore.ieee.org/document/7388699]*

120 *T. Hanyu et al., "Standby-Power-Free Integrated Circuits Using MTJ-Based VLSI Computing" Proceedings of the IEEE, vol. 104, 1844 (2016) [doi:10.1109/JPROC.2016.2574939]*

121 *SPINTRONICFACTORY (STF) (http://magnetism.eu/spintronicfactory)*

Thus, implementing spin-based technology together with existing CMOS, will permit both challenges of low energy consumption and memory wall to be solved, providing a solution that is more compact, with reduced consumption and even autonomous in the long term.

9.3.4.5. Scope and ambition

Shrinking transistors have powered 50 years of advances in computing, but now, for both technical and financial reasons, other ways must be found to make computing more capable. What's next will be more exciting: several new emerging technologies are expected to be available within the next five years such as quantum computers, which have the potential to be millions of times more powerful than current technology and neuromorphic computing, which provides chips that are thousands of times more efficient than current technology (see previous challenge), or using spintronic or photonic to compute and store information.

9.3.4.6. Competitive situation and game changers

Even for those new emerging technologies, the starting line is not the same for all actors and hence a levelling in terms of investment is necessary in order to catch up with the original delay.
Europe is starting an action on quantum computing (a Flagship project) and a good synergy should be developed with ECS.

Concerning Neuromorphic Computing, Europe is still in the race, and the development of advance neuromorphic systems (and the supporting software and system integration) should be promoted and applied to industrial problems developed in this SRA, such as CPS and autonomous systems.

9.3.4.7. High priority R&D&I areas

These new technologies require strong investments at all levels varying from hardware to software and integration with classical technologies. Indeed, in a first approach, new accelerator technologies combined with classical computing are being considered to solve specific classes of problem. The best strategy is still to adopt a "meet-in-the-middle" approach, working on many aspects (software, hardware, integration, algorithms) of those technologies at the same time until converging to exploitable solutions.

9.3.4.8. Expected achievements

Within 5 years new acceleration solutions are expected to come from integrating those emerging technologies with classical computing platforms to effectively support specific industrial problems.

9.4.
MAKE IT HAPPEN

9.4.1. Educational Challenge

For both the medium (2020) and long (beyond 2020) terms, the [r]evolution in computing requires a complete flattening of methods and techniques in hardware design (scaled-up architecture, heterogeneity, size, etc), software development (massive parallelism, new concepts, etc) and applications (new modelling, mathematical background). In turn, this creates major challenges in computing education in order to provide skills and competencies for the next generation of computing.

9.4.2. Standardisation

In the medium term, standardisation is focused on smart interfaces, communication protocols and programming models to support heterogeneous architectures and massive computing. For emerging technologies, such as quantum computing and neuromorphic computing, standards are still to be defined and adopted by the computing community.

9.4.3. Advices for policy makers

9.4.3.1. Boosting innovation and education in computing and storage in Europe

Open hardware/silicon can provide a huge boost to education, and RISC-V is already being taught as a standard at many universities. The freedom to implement this at zero cost makes it viable for even a single student/researcher to implement a complicated design without licensing constraints, completely breaking down the de facto corrupting influence of vendors offering "free for education" licences for their IP/tools. Those IP/tools typically require a significant fee once the academic effort needs to be commercialised in any way, or when students graduate to join commercial companies, knowing only how to implement the no-longer-free hardware using no-longer-free tools. However, the existence of a job market in Europe for system architects, designers and IC building is also key to driving education in this field. Policy makers should enforce this by financing projects or favouring the emergence of infrastructures to support it.

9.4.3.2. Organise the computing community

It is important to organise the computing community, and to increase the exchanges between the application owner and the computing and storage specialist, in order to actively drive the innovation. Inside the computing community, synergies should be increased between the High-Performance Computing and Embedded System communities and Open Hardware communities, and also between the compilers and tools and the hardware architects. Initiatives are being taken in that field, mainly by CSA (Coordination and Support Action). Policy makers have a role by favouring structures such as ECS and CSAs, and by financing other supporting structures.

9.4.3.3. Foreign export restriction

Export restrictions can be a roadblock to producing and selling European computing systems. Some key non-European components can be restricted or banned from re-export to some countries, even if the product using them is made in Europe. It is, therefore, imperative to have European technology for those components, which will give European companies more freedom regarding the availability of key components and markets. US export restrictions (one being ITAR, see section 12 of this document) were the reason for China developing its own processor and HPC machine, which was at the top of the top 500 in 2017.

9.4.3.4. Favourite emergence of AI-enabling technology to maintain a high-stake industry

Policy makers should actively support the development of European solutions in a fair way, enforcing the virtual circle: good European education → employment in Europe in the domains (and not having European-trained people hired outside of Europe) → products developed in Europe → using our industrial facilities → software and hardware product developed in Europe → need to hire people with good education and knowledge in the domain.

9.5. TIMEFRAMES

The following table illustrates the roadmaps estimated for computing and storage.

CHALLENGE	TOPIC	2020	2025	2030	2035
Computing performance	HPC	Exascale computing $n10^6$ cores, xEB memory 50–60 MW		Post-Exascale computing 20–30 MW	
System integration	CPS	Integrated computing (MPSoc, $n10^2$ cores) Expanded autonomy Security architectures		Autonomous architectures ($n10^3$ cores) Adaptable Systems	Pervasive computing
		Design methodology Feedback systems Cybersecurity Continuum computing		Cognitive and collaborative knowledge computing	
	Intelligent systems	Heterogeneous accelerators and in-memory		Fusion of computing and storage, distribution with advanced communication	
Disruptive technologies	Quantum computing	Simulation/emulation (5–50 Qubits)		Universal quantum computer	
	Optical computing	160PF, 640Pb/s, 11pJ/bit		10EF, 40 Eb/s, 250 FJ/bit	
	Neuromorphic computing	4.00E+09 neurons 1.00E+12 synapses 4KW		1.00E+10 neurons 1.00E+14 synapses 1KW	

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

Major Challenge 1: INCREASING PERFORMANCE AT ACCEPTABLE COSTS

1 - THE HARDWARE CHALLENGES

1.a Petascale computing 10^5 cores, PB memories, 10-15 MW

1.b Exascale computing 10^6 cores, xEB memories, 50-60 MW

1.c Photonics

1.d 3D Silicon memories

1.e System-In-package

1.f NVM at speed of volatile memory

1.g High-speed low-latency interconnects for tightly connected accelerators

1.h Optimal compute architecture design through software/hardware codesign

1.i Open Source Processor

1.j Open Source Datacenter

1.k SoC microcontroller for Energy harvesting devices

2 - THE SOFTWARE CHALLENGES

2.a Real-Time guarantee for dynamically allocated system

2.b HPC Hierarchical checkpoint and restart

2.c Scalable programming models for heterogeneous architectures

2.d Energy aware programming models

2.e Self healing applications

Major Challenge 2: MAKING COMPUTING SYSTEMS MORE INTEGRATED WITH THE REAL WORLD

1 - SYTEM CHALLENGES AND APPLICATIONS/ARCHITECTURE CO-DESIGN

1.a Run-time resilient and predictable systems

1.b Expanded autonomy

1.c Adaptable systems

Cybersecurity is a major challenge for computing system, please refer to chapter 8 where this challenge is described in detail.

1.d Edge computing

1.e Modelisation, simulation of complex real-time systems

1.f Exascale systems resiliency

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

2 - THE HARDWARE CHALLENGES

2.a Heterogeneous integrated computing, MPSOC, n10^2 cores

2.b Autonomous architectures, n10^3 cores, adaptable systems

2.c Certification of complex safety critical components

2.d Security architectures (with isolation techniques)

2.e Pervasive computing

3 - THE SOFTWARE CHALLENGES

3.a Virtual system integration

3.b Runtime system adaptation

3.c Formal methods (numerical stability analysis, etc)

3.d Accurate timing analysis, trace analysis, monitoring, profiling

Major Challenge 3: MAKING "INTELLIGENT" MACHINES

1 - ACCELERATORS FOR AI

1.a Over 1GB very-low latency near processor memory for deep learning

1.b in-storage computation

1.c Analog neuron implementation for computing

1.d High-end artificial intelligence on the Edge

2 - THE SYSTEM CHALLENGES

2.a AI assisted hardware and software design

2.b Design space exploration of more efficient hardware and software

2.c Self-analyzing, self-configured and self-repairing systems

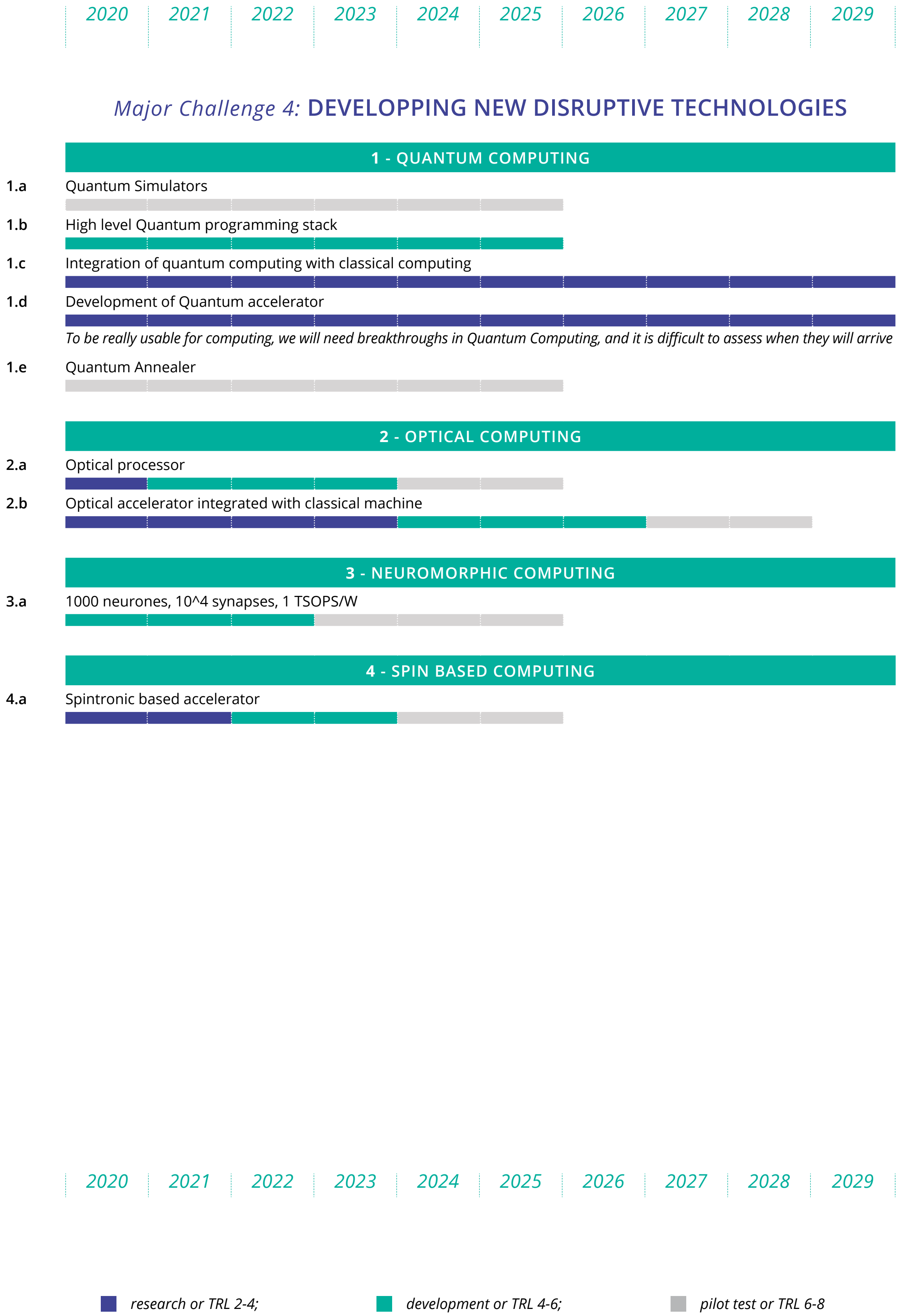
3 - THE HARDWARE CHALLENGES

3.a Declarative programming

3.b Verification & Validation of Deep Learning

3.c Tooling support for designing AI based systems

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029



F.60 *Timelines*

10

Process Technology, Equipment, Materials and Manufacturing for Electronics Components & Systems

10.1. EXECUTIVE SUMMARY

Technological challenges arise from evolving and future technologies such as Internet of Things, Artificial Intelligence, 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, in improved functional building blocks, in ICs, in electronics performance, in heterogeneous integration of functionality, and in the development of novel computing paradigms and their applicability to "extreme" (e.g. cryogenic) environments. Likewise, Industry 4.0 and sustainable manufacturing of semiconductors will require new processes, manufacturing techniques, equipment, and materials.

Furthermore, 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.

Independent access to semiconductor technology for the manufacturing of function-critical Electronics Components and Systems (ECS), and their development and manufacturing in Europe are indispensable for meeting the challenges of the European society, increase sovereignty, and for being competitive in foreign markets.

ECS manufacturing in Europe requires access to advanced materials and equipment and competitive manufacturing techniques. The latter is a self-sustaining sector of European importance and forms the base of the ECS manufacturing value chain.

Consequently, the European position must be reinforced through leadership in all relevant technologies (equipment, materials and manufacturing) by driving the following Major Challenges:

- Develop advanced logic and memory technology for nanoscale integration and application-driven performance, extending from the classical ICT environment as well as more challenging conditions (e.g. cryogenics).
- Develop technology for heterogeneous System-on-Chip (SoC) integration.
- Develop technology for Advanced Packaging and smart System-in-Package (SiP) by combining heterogeneous building blocks in packages.
- Extend world leadership in Semiconductor Equipment, Materials and Manufacturing solutions for advanced or novel semiconductor building blocks, for advanced logic and memory technologies according to Moore's law, and for heterogeneous integration technologies.

10.2.
IMPACT

Semiconductor technology forms the base of the ECS value chain, i.e. the physical building blocks for digital applications. Nano- and micro-electronics have been identified as key enabling technologies for Europe. If Europe wants to control the development of a digital future fitted to its citizens and its social, economic and industrial goals, it needs continued European innovations in the field of semiconductor technology.

Globally, the long-term market trend for electronic components is expected to exceed $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 are high (up to 10 to 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. Europe's semiconductor manufacturing industry suppliers have a long history of successful mechanical engineering, tailor-made machinery, optical equipment, metrology, inspection and testing equipment, and chemical processing tools. In addition, there are suppliers of raw materials, ancillary materials and substrate materials in Europe that successfully export their products to global markets. This history of success is prominent in several domains, foremost in (Extreme Ultra Violet) lithography, metrology and silicon substrates (Fully Depleted -Silicon On Insulator), but also in thermal processing, deposition, cleaning, wafer handling as well as wafer assembly, packaging and reliability.

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

Future and Emerging Technologies (FET) flagship initiatives such as those on graphene and quantum computing have been shown to have a significant impact on European leadership in these technology areas. For Europe to continue to take the lead here, early involvement of equipment suppliers may bring these activities to the next level in parallel with identifying the key 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. New materials and computational paradigms require not only developing new scalable platforms, but also non-trivial adaptations and extensions of existing technologies as enablers of such functionalities. For example, a quantum computer based on superconducting circuits will need efficient "classical" low power cryogenic electronics to enable operation of its quantum circuit.

The creation of manufacturing pilot lines is key (as it has proved successful in 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. They help to maintain an understanding of application needs, cut products' time to market, showcase European capabilities to potential customers worldwide and provide excellent opportunities for advanced education and training to skilled engineers and scientists (for education and training, see also section 0.7.4). The path to Cyber-Physical Production Systems will be significantly enabled by the early availability of innovative semiconductor, sensor and packaging technologies. Having a strong semiconductor portfolio "made in Europe" with early access for lead system suppliers is a winning competitive asset for Europe. The complete value chain must be covered to maintain the competitive situation of the European semiconductor process and integration technology.

Regions around the world have recognised the strategic importance of a local base for key enabling technologies, including electronic components and systems. 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 USA, Europe can reinforce its lead in semiconductor processing, equipment and smart systems based on the priorities set in the ECS SRA. There are also strong arguments for bringing back leading-edge semiconductor manufacturing to Europe – to maintain sovereignty and fully participate in AI and other key technologies of the digital world.

Furthermore, through a traditionally strong and advanced educational system, and through the presence of world-leading research associations, Europe's R&D position throughout the whole stack of competencies, also industry-driven, is remarkable.

10.3. MAJOR CHALLENGES

The following Major Challenges have been identified:

1. Develop advanced logic and memory technology for nanoscale integration and application-driven performance.
   To maintain European competitiveness and sovereignty in the coming generation of advanced and distributed computing infrastructure and diversified system performance, a strong effort in semiconductor process technology and integration is required. Power, performance, area, cost and reliability are still important drivers for compute, memory and compute-in-memory. In addition, as also indicated in recent versions of IRDS (International Roadmap for Devices and Systems)[122], low stand-by and operational power and high operating temperature, for example, are of great importance for European critical applications such as health, IoT and automotive/industrial.

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[122] https://irds.ieee.org/roadmap-2017

2. Develop technology for heterogeneous System-on-Chip (SoC) integration.
   The realisation of smart electronic components and (sub-)systems for European critical applications requires complementing logic and memories with additional functionalities, which are non-scalable with Moore's law, to integrate sensing, actuation, communication, data protection and power management to the system. These heterogeneous features can be implemented on the same System-on-Chip, such as for embedded memories, and for analogue and Smart Power, or realised as discrete components for SiP integration. Advanced technologies, processes and materials need to be developed and industrialised for innovative heterogeneous smart system solutions that enable innovative emerging applications and leverage synergies with processing and manufacturing technologies of scalable devices.

3. Develop technology for advanced packaging and smart (heterogeneous) System-in-Package (SiP) applications by combining heterogeneous building blocks consisting of chiplets, chips, and discrete components bonded together in packages.
   Advanced SiP and bonding technologies are required to deliver the functionality in meeting the demanding specifications and boundary conditions of major electronic component applications. Implementation of additional functionalities in smaller volumes requires new assembly and packaging materials, compatible chip/package interfaces as well as reliable technologies for heterogeneous integration of NEMS/MEMS, sensors, power chips, ambient energy harvesting and storage, processors, or memory. There must be a special focus on electrical capabilities, including storage and temperature constraints, to keep the applications robust and reliable.

4. Extend world leadership in Semiconductor Equipment, Materials and Manufacturing solutions for advanced semiconductors building blocks, for both leading edge logic and memory node technologies and innovative heterogeneous "System on Chip" and "System-in-Package" integration.
   Supply European ECS manufacturing companies with 'best-in-class' equipment and materials, and flexible, agile, sustainable and competitive semiconductor manufacturing solutions, and thereby enable the European application sector to compete in world markets with top quality products.

10.3.1. **Major Challenge 1: Developing advanced logic and memory technology for nanoscale integration and application-driven performance**

Semiconductor process technology and integration actions will focus on the introduction of new materials, new devices and new concepts, in close collaboration with the equipment, materials and modelling/ simulation communities to allow for the diversity of computing infrastructure needed.

The applications range from high performance cloud/edge computing in servers, to office/home computing, to mobile computing, and to ultra-low power data processing at IoT node level up to the highest possible performance. This challenge includes three areas of attention at transistor level:

- extensions of the scaled Si technology roadmaps (including FD SOI, FinFET/Trigate and stacked Gate-All-Around horizontal or vertical nanowires, 3D integration), and further pitch scaling where parallel conduction paths (i.e. nanowires) are brought even closer together.
- exploration and implementation of materials beyond Si (SiGe, SiC, Ge, functional oxides, 2D material heterostructures).

- novel device, circuit and systems concepts for optimum power-performance-area-cost specifications, high energy efficiency and novel paradigms like for neuromorphic, optical and quantum computing.
- long-term challenges such as Steep Slope Switches (Tunnel FET, Negative Capacitance FET, NEMS), spin-based transistors, and alternative high-performance switches, as well as materials (2D, CNT, Ferroelectric, Magnetic, etc) for the above applications.

New memory concepts will be targeted to support the correct memory hierarchy in the various applications. An example is the opportunity to push new memory concepts (RRAM, PCRAM, STT-MRAM, FeFET) to the demonstration level in the IoT infrastructure (from server, over edge to nodes). These alternative memories need 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. Internet of Things 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 challenges will need to be addressed (cf also challenges 2 and 3), where innovative solutions to reduce the cost are required. The options to use advance 3D and Optical I/O technological solutions circumventing limitations of the traditional I/O's architectures are strengths to foster and build 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 like the creation of standards for IoT, reliability for safety or mission-critical applications and security and privacy requirements need close collaboration among all actors 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 to support leading-edge manufacturing equipment development. Implementation of dedicated and sustainable pilot lines for specialised logic processes and devices supporting European critical applications. Exploration of new devices and architectures for low-power or harsh environment applications.

10.3.2. Major Challenge 2: Developing Technology for Heterogeneous System-on-Chip (SoC) Integration

This section covers the integration of the logic/memory building blocks (of 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, energy harvesting and storage devices, RF chips like SiGe or the forthcoming GaN). The resulting multiple (Sub-)Systems-on-Chip should enable Heterogeneous System-in-Package integration of Major Challenge 3.

Depending on the application, advantages of heterogeneous SoC technology can be size, performance, cost, reliability, security and simpler logistics. Therefore, this technology is seen as a key enabler for the 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 requested 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.

Unconventional devices and materials, like 2D-materials, nanowires, quantum dots, spin effects, functional oxides are being investigated to overcome the limits of conventional CMOS logic and memories. Their manufacturing can offer new business opportunities for specific applications like sensors in automotive, consumer electronics or biomedical applications, communication applications like laser and RF generation and detection, and QIP. Progress is needed for further performance increase, miniaturisation, surface conditioning, structuring and innovation in selectivity, reliability and reproducibility.

The driver for SoC integration is always a clear demand from the application domain. To maintain Europe's position, the focus should be on emerging technologies as they appear 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 IP generation are required to reinforce the position of Europe in design concepts and architectures.

More specifically the following challenges are identified (non-exhaustive).

Application-specific logic: Heterogeneous System-on-Chip (SoC) Integration can require specific solutions for logic to be integrated with More-than-Moore technologies, like:

- Embedded non-volatile memories for smart functional devices.
- Tight, logic-memory integration for new architectures for neuromorphic computing. Logic integration with power management devices including compatibility with harsh environment (high temperatures, vibrations, EMI) conditions for industrial, automotive and space.
- Logic integration with RF, optical or sensor technologies
- Ultra-Low Power (ULP) technology platform and design.

Advanced Sensor technologies:

- Mechanical sensors (acceleration, gyroscopes, microphones).
- Selective gas (CO, CO_2, NO_x, VOC, etc.) sensing components.
- Physical sensors (magnetic, optical, RF).
- Transmitter / receiver technologies for applications like LIDAR and Active Phased Array imaging.
- Biological and biochemical sensors.

Advanced Power Electronics technologies with a myriad of options such as:

- Higher power density and frequency, wide-bandgap materials for high temperature electronics, new CMOS/IGBT processes, integrated logic, uni- & bipolar; high voltage classes, lateral to vertical architectures.
- Energy harvesting and storage, micro batteries, supercapacitors and wireless power transfer.
- Ambient energy generation, storage, battery back-up, dynamic load configuration.
- Energy-efficient components and systems.
- Energy autonomous systems for IoT applications.

Advanced RF and Photonics Communication technologies to interface between semiconductors components, sub-systems and systems:

- New energy-efficient RF and mm-wave integrated device options, incl. radar (building on e.g. SiGe/BiCMOS, FDX 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.
- MOEMS and Micro-optics, optical interconnections, photonics-enabled device and system options.
- Solid-state light emitters like LED and Laser.

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 (graphene, MoS2 and other transition metal dichalcogenides, etc), 1D (nanowires etc.) and 0D (nanoparticles, quantum dots etc.) materials, organic, ferro- and piezoelectric, thermoelectric and magnetic thin films materials. Obviously, also safety and environmental aspects should be taken into consideration.

Special attention must be given to packaging with the interfacing of the non-conventional device to the external world, to satisfy requirements like thermal management, harsh environment or biological compatibility. There should be a special focus on chip-package interaction, e.g. with respect to stress, EMC, temperature and application specific environmental integrity.

Expected achievements

Implementation of pilot lines for integrated application-defined sensors, novel IoT-solutions, complex sensor systems or 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 exploration and exploitation of advanced functionalities through integration of novel reliable materials.

10.3.3. Major Challenge 3: Developing technology for Advanced Packaging and Heterogeneous System-in-Package (SiP) integration

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, like CMOS logic, Non-Volatile Memory, NEMS/MEMS, RF, Analogue, sensing, actuating, energy harvesting and storage, etc, into a SiP.

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

Assembly and Packaging (A&P) technologies, especially with a focus on system integration, are a key enabler for the 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, and 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 system-in-package components.

Integration of the above functionalities in miniaturised packages and (sub-)systems in a package require fundamental insight into application needs and system architecture. Process technology to realise this integration is part of this third major challenge and is essential for 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 more important. Today in many cases assembly and packaging costs are becoming higher than the chip cost. To reverse this trend, we must focus on dedicated packaging and SiP process technologies that consider all the levels of chip, package and board/ system, and find the optimum trade-offs between function, cost, power, reliability, etc.

To remain economically sustainable and globally competitive a toolbox must be set-up which includes process technologies that provide cost-effective and outstanding system integration, such as 3D interconnect technologies (including Through Silicon Vias, Si-interposer or Fan Out Wafer-Level Packaging technology) to combine hardware technologies across multiple fields and to enable integration of several devices to multi-functional electronic smart systems (ESS).

As for packaging Systems-on-Chips, due to the miniaturisation and increasing functional density of SiPs, it is important to consider chip/package interaction, e.g. Power, Thermal, Mechanical, Stress, EMC, environment, etc. In addition, the interfaces to the system/board need to be considered. For example, a MEMS device may require a carefully designed package for optimum performance.

At macro-scale level, a system can be seen as consisting of a collection of large functional blocks. These functional blocks have quite different performance requirements (analogue, high voltage, embedded non-volatile memory, advanced CMOS, fast SRAM,...) and technology roadmaps. Therefore, for many applications, it is of increasing interest to split the system in heterogeneous parts, each to be realised by optimum technologies at lower cost per function, and assembled 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.

Research and development priorities are on **innovative approaches like**:

Advanced interconnect and encapsulation technologies

- Interconnect technologies that allow vertical as well as horizontal integration. This includes process technologies for vertical interconnects like Through Silicon Via (TSV), Through Encapsulant Via (TEV) technologies and microbumps, Copper-Copper bonding, as well as process technologies for horizontal interconnects like thin film technologies for redistribution both on chips and on encapsulation materials. A technology base is needed for 3D stacking and horizontal interconnecting of dies or chiplets.
- Encapsulation technologies, handling carriers as well as panels which on the one hand protect dies, and on the other hand allow optimum electrical performance. Chip embedding technologies like chip embedding in mould material (e.g. fan-out WLP or embedded Wafer Level Ball grid array, technologies) and chip embedding in laminate material, for both of which Europe already has a strong capability, must be sustainably supported to prepare the next generation.

- Implementation of advanced nanomaterials including 2D-materials, nanowires, nanoparticles or quantum dots with scalable logic and memory device technologies, which will be key for adding new functionalities and developing multifunctional smart systems.

Specific power and RF application technologies

- Solutions for high-frequency miniaturisation, like for mm-wave applications (> 60 GHz) and for > 100 GHz towards THz applications for which no package solutions exist today.
- Process technologies for integration of additional functionality like antennas, passive devices and Power-Source-in-Package (PSiP) / Power-Source-on-Chip (PwrSoC) embedded micro-generation power sources into a system-in-package. This additional functionality will be an enabler for new applications.
- Packaging of wide bandgap materials like GaN or SiC.
- 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 Section 7.1 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, work which is closely linked to that described in Chapter 6 of this SRA.
- System integration partitioning: The choice of the 3D interconnect level(s) has a significant impact on the system design and the required 3D technology, resulting in a strong interaction need between system design and technology.

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. Research and development in this area needs a strong link, especially with materials and their compatibility, and one that also considers the heat dissipation challenges. Variations and extremities in operating environmental conditions should also be examined to ensure devices work seamlessly and operational life is not impaired. In the last 10 years, 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 design chapter is crucial.
- Solutions to test separate components before assembling them in a single package/subsystem. Concepts such as built-in self-test and self-repair require some amount of logic integration and a design that provides access for die testing.

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

Tailored adoption of digitisation (modelling, virtualisation, process control, automation) is expected to be a major enabler to master complexity of advanced packages and modules as well as in heterogeneous system-in-package integration. Fast (and deep) learning as well as semi-automated AI based decision making will radically innovate these domains with the aim to be faster on the market while fulfilling highest quality standards.

Expected achievements

Keep assembly and packaging, especially SiP manufacturing, in Europe through research and development of proper processes – e.g. parallel processing like front-end technologies and wafer-level processing, as well as with increasing automation and logistics. Special care should be taken to address reliability, robustness and quality. Other expected achievements include: process technology for multi-chip embedding on flexible substrates, process technology for heterogeneous chip integration, continuous improvement of materials aspects and thermal management, including high temperature package characterisation and modelling. In assembly and packaging often dedicated bilateral research and development with equipment and semiconductor suppliers needs to be supported to meet dedicated package designs (e.g. for sensors and MEMS).

10.3.4. **Major Challenge 4:** Extending world leadership in Semiconductor Equipment, Materials and Manufacturing solutions

The equipment, materials and manufacturing sector in Europe is a standalone sector providing the world market with best-in-class equipment, technologies and materials to enable manufacturing of miniaturised Electronics Components. As this field and sector covers such a wide range of process technologies, this major challenge is divided into 3 sub-challenges:

- Nanoscale patterning, layer deposition, metrology & inspection, and other equipment & materials (E&M) for future sub 5 nm node logic and memory technologies. Innovative wafer processing, assembly, packaging and material technologies for front-end-of-line (FEOL) and back-end-of-line (BEOL) to integrate novel technologies such as new low power edge computing, photonics and quantum technologies, both on a chip (SoC) and in semiconductor component packages (SiP & A&P).
- Manufacturing technologies: Develop innovative new fab manufacturing and appropriate equipment & manufacturing solutions that support flexible, sustainable, agile and competitive semiconductor manufacturing in Europe and supply the worldwide market with correspondingly 'best-in-class' hardware and software products. Digitisation in the manufacturing domain, as addressed in SRA-Section 4, Digital Industry (cf. Challenges 1 and 2), needs to "break the wall" within facilities but also along the supply chain allowing to control and optimise all processes with their resources involved in a holistic way.

10.3.4.1. Nanoscale patterning, layer deposition, metrology & inspection and other equipment & materials

The first sub-challenge targets the development of new equipment and material solutions for sub-5 nm node semiconductor technologies that enable high-volume manufacturing and fast prototyping of electronic devices in CMOS and beyond CMOS technologies, and therefore will allow the world market to be supplied with technology leading, competitive products.

The overarching goal of the equipment and material 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. Internationally developed roadmaps such as the IRDS (International Roadmap for Devices and Systems) will also be taken into consideration.

Accordingly, research and development is needed to facilitate innovations for, among others:

- Advanced lithography equipment for sub-5 nm node wafer processing using DUV and EUV, and corresponding sub-systems and infrastructure, e.g. pellicles, masks and resist.
- Mask manufacturing equipment for sub-5 nm node mask patterning, defect inspection and repair, metrology and cleaning.
- Advanced holistic lithography using DUV, EUV, DSA and Alternative Lithography techniques such as e-beam/mask-less lithography and Nano-Imprint for specific low-volume or low resolution applications.
- Next Generation Lithography techniques such as e-beam and mask-less lithography, DSA and Nano-Imprint.
- Multi-dimensional metrology (MDM) and inspection for sub-5 nm devices which combines holistic, hybrid, standalone setups (of Optical, fast AFM, E-Beam, Scatterometry, X-Ray and STEM technologies) for mapping the device material and dimensional properties and defectivity, with productivity aware design (PAD) techniques such as: recipe automation, fleet management, 'close-to-process' monitoring and support big data management with predictive methodologies.
- Thin film processes including thin film deposition, such as (PE)ALD and PIII for doping and material modification, and corresponding equipment and materials. Future solutions could lie in proximity doping and surface functionalisation.
- Equipment and materials for wet processing, wet and dry etching including (atomic layer) selective etch processing, thermal treatment, laser annealing, and wafer preparation.
- Si-substrates, Silicon on Insulator substrates, SiC, III-V materials, advanced substrates with multifunctional layer stacking (e.g. highly dense 3D), including insulators, high resistivity bulk substrates, mobility boosters, corresponding materials, manufacturing equipment and facilities.
- The development of Quantum computing technology will require new types of equipment, materials and manufacturing technologies. As referenced in the Cross References section of this chapter, the results of this Quantum Flagship, and the related Quantum SRA, are likely to influence the ECS SRA from 2020 onwards.
- Advanced proposal for QIP (superconducting circuits, Majorana states, etc) often require cryogenic environments and processing. The development of advanced industrial characterisation equipment in exotic environments should be considered key enablers for such developments to reach the market application stage.

Expected achievements

The European E&M industry for advanced semiconductor technologies is keen to lead the world in miniaturisation and performance increase by supplying new equipment and new materials approximately two years ahead of the volume production introduction schedules of advanced semiconductor manufacturers. The focus will be on equipment and materials for lithography, metrology and wafer processing including the respective infrastructure for sub-5 nm node technologies.

10.3.4.2. Innovative equipment and material technologies for heterogeneous SoC and SiP integration

New technological and business opportunities can be created by applying new skills and knowhow in areas such as 3D heterogeneous integration and advanced system-on-chip (SoC) solutions. The overall goal for European E&M companies is to enable semiconductor manufacturing companies to produce 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 covered in Major Challenge 2 and 3 of this chapter.

For this part of the semiconductor ecosystem, which is a definite European strength, system integration equipment is required that can combine chips from wafers and wafer technologies of various wafer sizes. Innovative solutions will be required to remove any roadblocks.

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 Systems (see Major Challenge 3). The interfaces and handovers between wafer technologies and A&P need to be clearly defined and require innovative equipment.

These technologies will require working more closely together, combining front-end wafer equipment and assembly and packaging (A&P) equipment. Technologies and methodologies well established for Si wafers will partially be reused and adapted for Assembly & Packaging.

Extending the life of installed equipment to match requirements of this domain via proactive lifecycle management (refurbishment) of these products will provide cost effective solutions for specific applications.

New materials and equipment will be required for future Assembly & Packaging, creating new R&D challenges and business opportunities. Over the last decade, nearly all assembly and packaging materials have been replaced by more advanced materials - a process that is expected to continue. This will have a strong impact on future processes and equipment and related market.

Heterogeneous SoC and SiP integration will pose significant challenges and is expected to 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 volume and with higher efficiency, lower power consumption and longer battery life. Application dependent reliability and heat dissipation are very important.

Examples of necessary research on innovative equipment and innovative materials are:

- Enhancing equipment optimised for high-volume manufacturing of large batches of the same chip into efficient reconfigurable equipment for manufacturing of different chips in smaller batches.
- Technologies for testing/validation/verification of heterogeneous chips with ever-increasing number of features and ever-decreasing feature size.
- Technologies and tools for manufacturing and integration of semiconductors component made with advanced nanomaterials (2D materials, nanowires, nanoparticles, quantum dots, etc., as addressed in Major Challenge 2) with logic and memory technologies.
- 3D integration technologies (e.g. chip-to-wafer stacking).
- Chip embedding technologies (e.g. fan-out WLP).
- Substrates for RF and power electronics devices.
- Vertical (e.g. TSV or micro flipchip bumping) and horizontal interconnects (e.g. RDL, thin film technology).
- New processes (e.g. reliable die attach, thinning, handling, encapsulation) for reliable as well as heterogeneous system integration technologies.
- Failure analysis in-line and off-line.
- Metrology for SiP devices.
- Power-Source-in-Package & Power-Source-on-Chip technologies (transducers, storage devices, PMICs, magnetics).

Expected Achievements

Processes, equipment and materials for heterogeneous integration can be partially sourced from previous-generation CMOS infrastructures. However, new technology generations will also require capabilities, which are not yet available in advanced CMOS fabs.

Today's equipment was typically designed for high-volume continuous production in a high-volume advanced logic and memory environment, which means it requires major modifications or re-design. The performance of any future production tools for heterogeneous integration 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 ever-increasing number of features, and interconnects packed onto an IC, puts strong demands on product validation and verification methodologies and on test methodologies and respective equipment.

10.3.4.3. Manufacturing Technologies

The sub-challenge 'Manufacturing' focuses on research and development in Equipment and Manufacturing to enable highly flexible, cost-competitive, 'green' manufacturing of semiconductor products within the European environment. The overarching objective is to develop fab management solutions that support flexible and competitive ECS manufacturing in Europe, as well as the world market. This goal is a translation to the IC-Fab of challenges of the ECS-SRA in chapter 3 "Energy" and chapter 4 "Digital Industry".

Aspects of digitisation, including Industry 4.0, need to be incorporated, with a focus on 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 in productivity, cycle time, quality and yield performance, and at competitive production costs. Furthermore, it will be key to adapt workflows to new, data-driven manufacturing principles adopting artificial intelligence, machine learning and deep learning methods.

Digital twins (addressed in Section 4 in Major Challenge 1 of "Digital Industry") need to become a standard feature of all domains spanning HW, SW, materials, environment, chip/package/board/application interaction, metrology, validation and testability. Equipment and equipment integration need to become even smarter than today, doing intelligent data processing based on enhanced sensors and operating strategies, not only to guarantee stable processes but to learn, adapt and improve from data gathered and pre-processed in real time.

Solutions for manufacturing will have to address related challenges, respecting Industry 4.0 principles, and are similar for most semiconductor manufacturing domains. Innovative in-line solutions are required to control the variability and reproducibility of leading-edge processes. This implies that domains traditionally seen as disconnected (for example, Statistical Process Control (SPC), Fault Detection and Classification (FDC), process compensation and regulation, equipment maintenance and WIP (Work in Progress) management, front-end manufacturing and back-end manufacturing) will have to become tightly data driven and interconnected. Moreover, the blurring of the frontiers between these domains will require considerable consolidation of knowledge capitalisation and exchange of knowledge. Factory Integration and Control Systems will have to become modular and virtualised, allowing information to flow between factories to facilitate rapid diagnostics and decision-making via concepts like Industrial Data Space and BYOD (Bring Your Own Device). Enhancing the data security in the fab environment is of increasing importance.

The focus of manufacturing will be on:

- Cope with high volumes and high quality of devices (e.g. for power semiconductors, sensors and MEMS devices).
- Enable flexible line management for high mix, and distributed manufacturing lines including lines for fabrication and deposition of advanced functional (nano)materials.
- 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 etc.).
- Adopt factory integration and control systems to address the Digital Industry challenge of the ECS-SRA.
- Apply fast (and deep) learning as well as semi-automated AI based decision making to control processes, to enhance quality, to increase reliability, to shorten time to stable yield, and to preserve knowledge and master complexity in these innovative Machine-to Machine domains.
- Apply productivity aware design (PAD) approaches with a focus on predictive maintenance, virtual metrology, factory simulation and scheduling, wafer-handling automation and digitisation of the value chain for artificial intelligence-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, defectivity).

Expected Achievements

Future innovations should address new automation techniques and automation software solutions including AI and machine learning approaches in synergy with Challenge 1 of Digital Industry in Chapter 4 of this ECS-SRA, for which the ECS manufacturing domains represent use cases of an advanced, to be developed, digital twin technology platform.

Generic solutions are required for current and future factories that allow high-productivity manufacture of variable size, and energy-efficient, sustainable, resource-saving volume production. The introduction of control system architectures based on machine learning, making use of high-performance computing systems, should allow for fab digitisation, including predictive yield modelling and holistic risk and decision mastering. This requires the integration of control methods and tools and knowledge systems inside industry.

Focal topics should include factory operation methodologies, data acquisition and analysis concepts, factory information and control systems, materials transport as well as local storage and fully automated equipment loading/unloading.

Further opportunities will emerge from the drive towards “Industry 4.0” in other industrial branches: cross-fertilisation is expected between solutions for semiconductor manufacturing and other manufacturers of high-value products, especially in data-driven manufacturing optimisation.

10.4. STRATEGY

10.4.1. Explore new avenues of application for ECS

Focused projects in the TRLs 2–5 are needed as technology push to enable new applications through new semiconductor components by involving the related communities and industries needed to co-create innovation. Use cases and application requirements can be considered much earlier in the development process. Technologies will drive the realisation of industry roadmaps in SoC and SiP. The required efforts include further CMOS scaling and related equipment development, power electronics, III-V and 2D materials, RF technologies, integrated logic, photonics, 3D integration technologies, MEMS and sensor systems, interlinked with key application challenges. Similarly, to enable the development and production of future generations of SiP hardware in Europe, world-leading research is needed to prepare the proper system integration technologies. Furthermore, attention will be given to emerging technologies and materials, and to new developments in the equipment and materials industry, in which Europe has a leading position.

10.4.2. Implement pilot lines and test beds for ECS

Extended projects will aim at pilot lines for IC, SoC and SiP with an emphasis on TRL 4–8 to deliver industry-compatible flexible and differentiating platforms for the prototyping of essential cross-cutting technologies and to sustain manufacturing competence. Research and development on processing (front-end technologies, wafer-level processing, assembly and packaging as well as automation and logistics) is a prerequisite to set up and to keep SiP manufacturing infrastructure in Europe. In addition, these pilot lines should ensure independent access to leading semiconductor equipment and materials technology for the manufacture of highly competitive, function-critical ECS.

Other TRL 4–8 projects need to target test-beds and demonstration of ECS solutions for emerging applications domains like IoT infrastructure, Industry 4.0 and sustainable mobility. These ECS solutions should incorporate, and where possible apply, advanced technologies and higher TRL results of the Horizon 2020 FET flagship projects Graphene and Quantum Computing.

More advanced R&D activities at TRLs 2–5 can also be included in pilot lines and test-bed projects at higher TRLs to provide the fundamentals to enable EU companies to set up their dedicated technology capability, and to prepare for next-generation products in a sustainable way. This will safeguard Europe's competitive position and keep high-quality and high-skill jobs in Europe.

10.4.3. Demonstrate manufacturing-line capabilities for flexible, high-quality, competitive and 'green' semiconductors

A specific requirement of the European semiconductor manufacturing industry is the ability to cope with high volumes and high quality while enabling flexible line management for high-mix and distributed manufacturing lines.

Therefore, manufacturing science projects and demonstrations at high TRLs, and linked to the details described in Challenge 4, are needed for:

- Integrating emerging AI technology, making best use of digital twin and machine learning approaches. Where possible, they should be connected to the overall European AI community to enhance cross-fertilisation.
- Plug-and-play validation and demonstration of reproducibility for newly implemented technologies and equipment.
- Mastering cost-competitive semiconductor manufacturing in Europe, including packaging and assembly, while achieving sustainability targets (resource-efficiency and "green" manufacturing).

10.4.4. **Invest in workforce education**

Attention should be given to university education in close collaboration with the industry in the above fields, e.g. by means of joint (academia and industry) courses, traineeships, internships and other support actions (incl. EC grants). For more details on education and training, see also section 0.7.4.

10.5. TIMEFRAMES

All leading European industry and research actors align their activities with international roadmaps and timelines. Roadmap exercises are being conducted in various projects and communities like NEREID and the IEEE IRDS in which European academia, RTOs and industry participate. For system integration also the iNEMI and the new Heterogeneous Integration Roadmap activities are considered. The European R&D priorities are to be planned in synchronisation with the global timeframes and developments, which 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:

1. Developing advanced, logic and memory technology for nanoscale integration and application-driven performance.
2. Heterogeneous System-on-Chip (SoC) integration.
3. Advanced Packaging and Heterogeneous System-in-Package (SiP) integration.
4. Maintaining world leadership in Semiconductor Equipment, Materials and Manufacturing solutions.

2020 | *2021* | *2022* | *2023* | *2024* | *20*

Major Challenge 1: 'DEVELOPING ADVANCED LOGIC AND MEMORY TECHNOLOGY & MATERIALS FOR NANOSCALE

CMOS technology platform generations

22 nm FDX implementation (Strained PFET, in-situ doped RSD(Gen1), Gate first)

<N7 horizontal Gate-All-Around NW/ 10 nm FDX (Gate Last, SAC)

<N5 Vertical GAA

Beyond CMOS & new compute paradigm options down-select and implement

Spin

Integrated (embedded NVM) memory systems incl. new storagr architectures for smart systems, IoT and new compute paradigms**

STT-MRAM / ReRAM / PCM / FeFET / other

Wafer based process technologies for 3D integration (cfr also Challenge 3) including (monolithic) 3D-IC **

implementation pilots

Major Challenge 2: 'DEVELOP TECHNOLOGY & MATERIALS FOR HETEROGENEOUS SYSTEM-ON-CHIP (SOC) INTEGRATION'

Technology platform for integrated application defined sensors, including packaging **

implementation pilots

Process technology platforms for new RF and mm-wave integrated device options, incl. radar (SiGe/BiCMOS, FDX, CMOS), photonics options, as well

implementation pilots

Process technology platforms for biomedical devices for minimally invasive healthcare **

implementation pilots

Process technology platforms for power electronics **

Process technology exploration for functional integration of novel materials (e.g. Graphene, TMD's, FerroElectric, Magnetic, e.a.) implemented in

implementation pilots

Continuous improvement and digitization of M2M solutions including Materials stacks, Process technology for multifunctional SoC, modelling, characterization,

Speedup time to stable, high yield and realible M2M processes by adopting AI in electronic components and systems innovation

Enhance test methodology and procedures for validation, verification and analysis of complex M2M solutions

Major Challenge 3: 'DEVELOP TECHNOLOGY & MATERIALS FOR ADVANCED PACKAGING AND HETEROGENEOUS SYSTEM-

Process technology for multi-chip embedding (molded, PCB, flexible substrate, silicon) **

Multi-die embedding (molded) | next gen systems / new applications

... in flexible substrates | implementation pilots | next gen systems / new applications

Process technology for heterogeneous and (2.5 & 3D) SiP integration **

wafer level, interposer (Si), various technologies, e.g. GaN, SiC, Logic & power embedding, intelligent power modules, optical interc.

SiP Technologies (thin wafer/die handling, dicing, stacking) | next gen systems / new applications

Si interposer (TSV), passive, RF-SiP (glass) and sensor integration | next gen systems / new applications

Continuous improvement including digitization of (i) Materials aspects, (ii) Thermal management (iii) high temperature package
(iv) Characterization & modelling, (v) Reliability & failure analysis & test

continuous improvements

iv) Characterization & modelling, (v) Reliability & failure analysis & test, but needs parallel ongoing basic reseach

vi) Speedup time to proven reliability, lifetime and stable yield by adopting AI in electronic components and systems innovation

2020 | *2021* | *2022* | *2023* | *2024* | *20*


25
2026
2027
2028
2029
2030
INTEGRATION AND APPLICATION-DRIVEN PERFORMANCE’
transistors, CNTFET, Steep sub-Vt slope
(NCFET, TFET, NEMS), alternative materials: TMD’s, others
as packaging **
existing pilot line
process metrology, reliability, failure analysis and test **
IN-PACKAGE (SIP) INTEGRATION’
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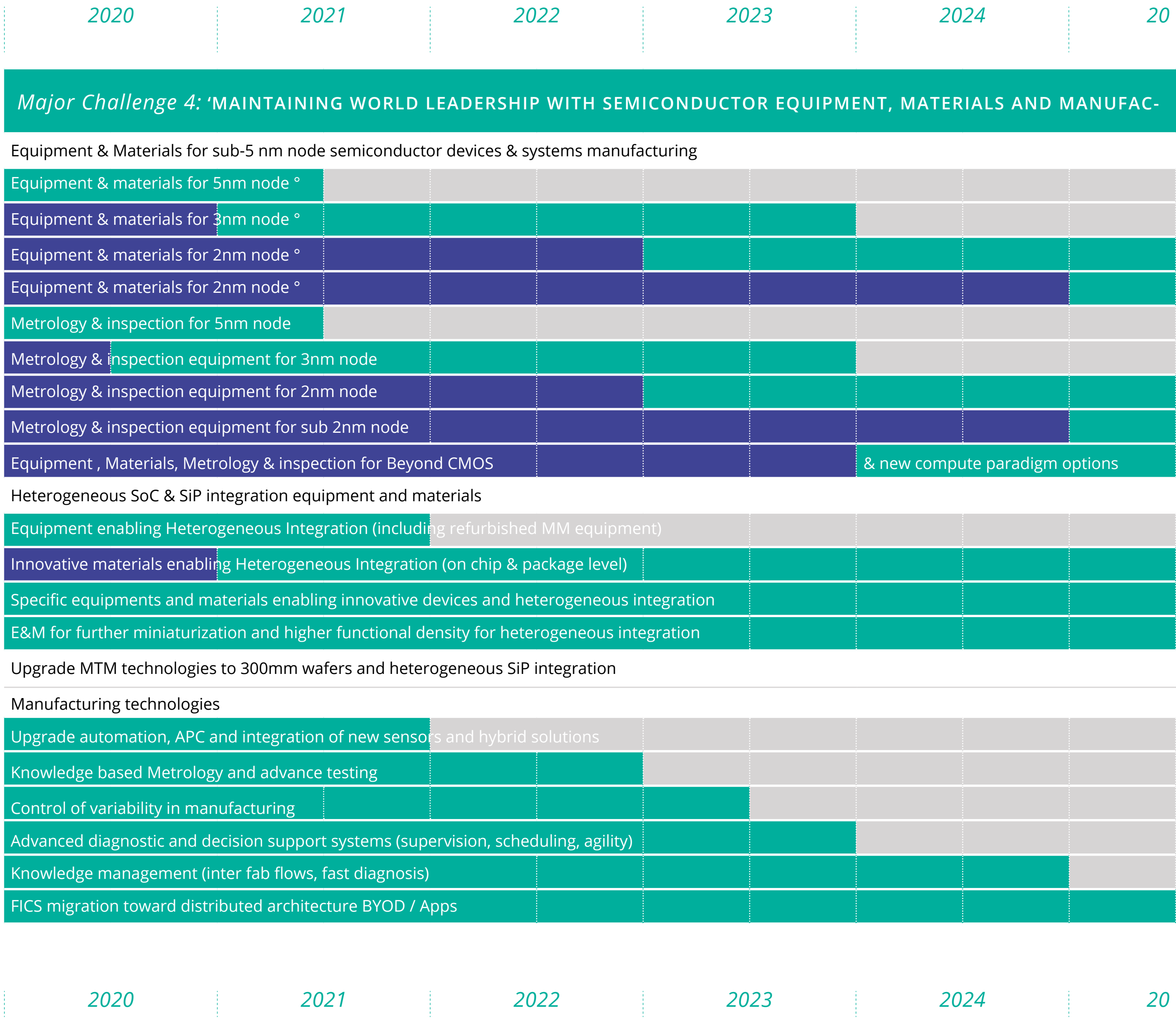
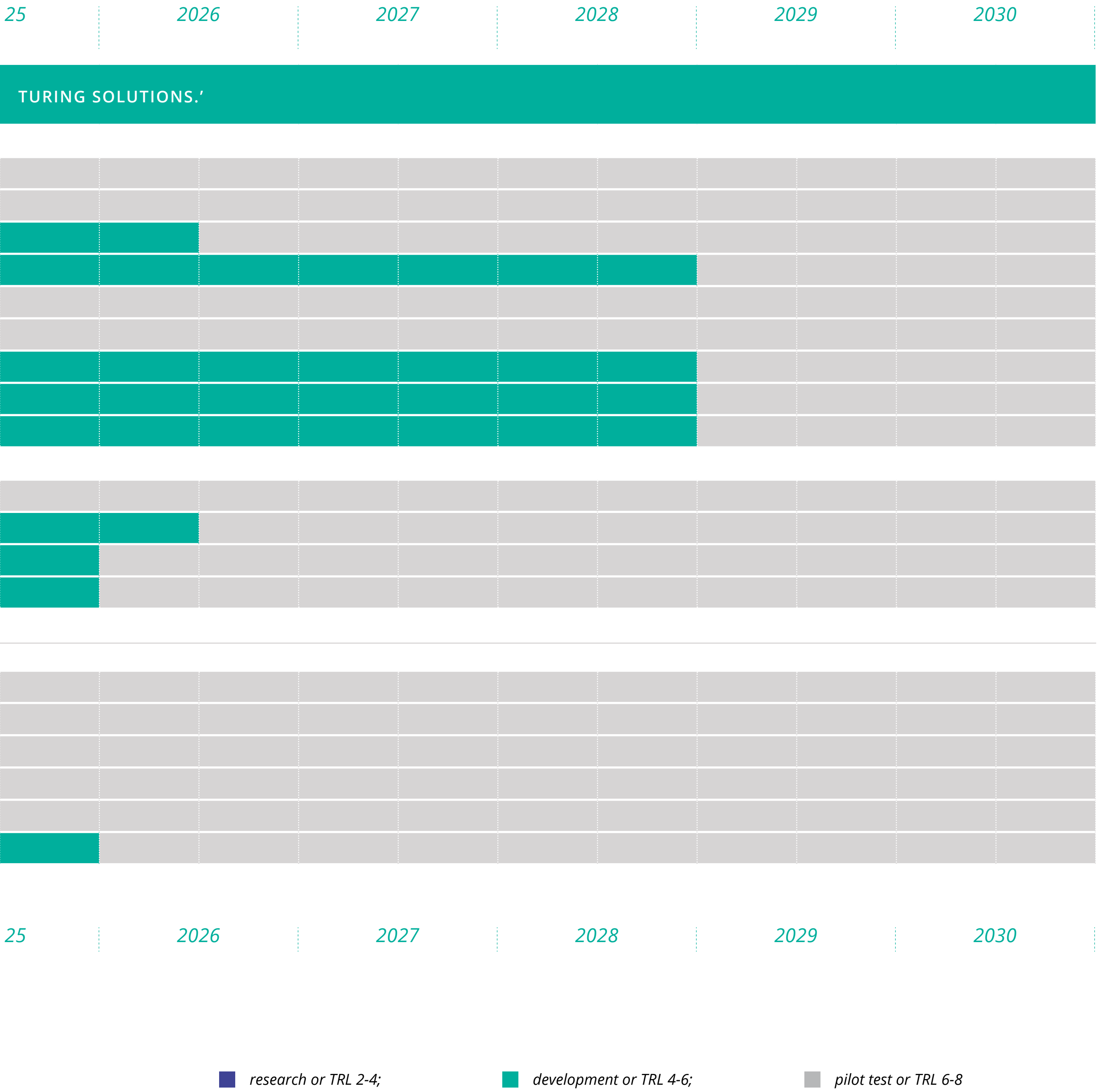


° *Mask technology always 1.5 years ahead wafer technology*

** *Multiple TRL cycles needed to work towards solutions for the challenges*

VM - Virtual Metrology, PdM - Predictive Maintenance, BYOD - "Bring Your Own Device", FICS - Factory Information and Control System; Logic nodes definition



Roadmap timeline for Process Technology, Equipment Materials and Manufacturing

F.61

For Challenge 1 the roadmap for process technology and device/system integration presents relatively clear timelines, although economic factors 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 are less clear (e.g. new computing paradigms) are introduced at low TRL levels although timelines are not very clear. Digitisation of the European ECS value chains lacks well behind Asia and US. It needs attention and effort now to gain competitive advantages.

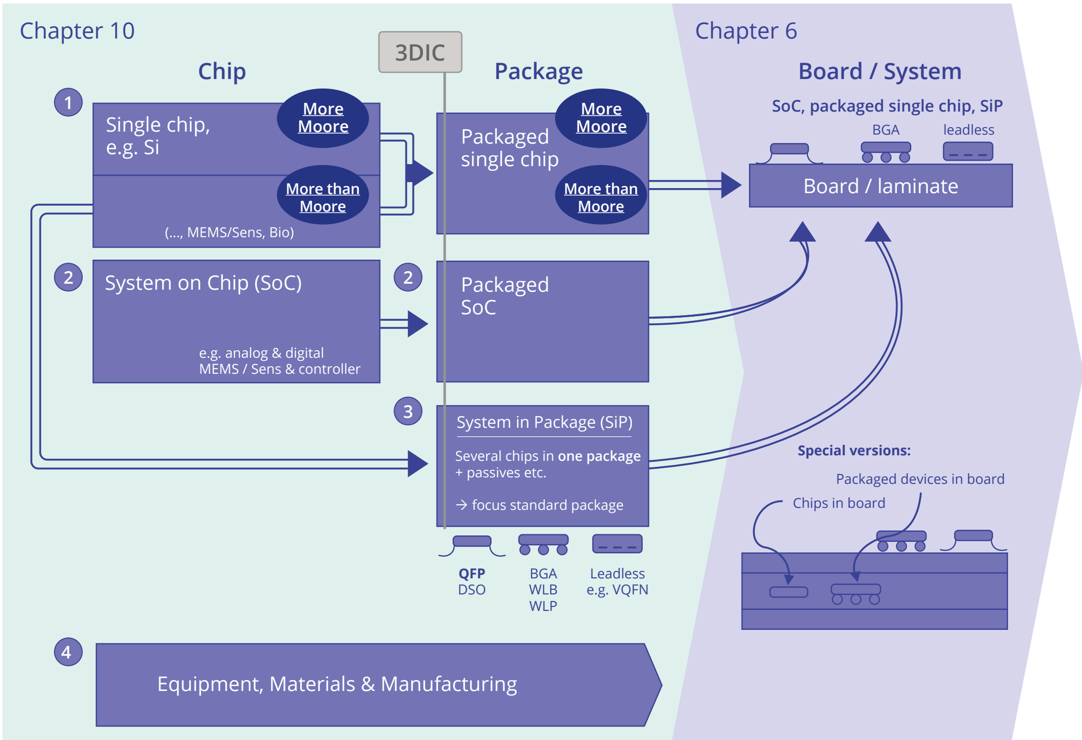
For Challenge 2 and Challenge 3 the timeline of the implementation of new technologies largely depends on the needs and roadmaps of the systems and will result from the interaction within application driven projects and test-bed initiatives. The timing of new Equipment & Manufacturing solutions for these challenges should be derived from the schedules of the major European semiconductor manufacturers. This includes roadmaps for key future semiconductor domains, such as automotive, health care, safety and secuity, power, MEMS, image sensors, biochips, lighting, etc. Fast implementation and modification of these new device technologies will pave the way for the technologies of tomorrow.

Firstly, 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 are of critical importance to maintaining European leadership. Secondly, new equipment and Materials solutions should be developed in line with the needs defined in the roadmaps of Challenge 1 to 3. Lastly, improving manufacturing efficiency, and enhancing yield and reliability are ongoing tasks that need to be performed in accordance with the needs of the 'More-Moore' and 'More-than-Moore' domains. Fundamentals of 'manufacturing science' will concern projects at rather low TRLs (typically 3–5), whereas implementation in pilot lines and full-scale manufacturing lines will contemplate higher TRL projects (typically 7–8). For most of the manufacturing science projects, the execution will be spread along medium to long-term time span, though shorter-term impact, such as improving uptime of equipment thanks to productivity aware design or the improvement of robustness of the manufacturing processes, will get due attention to enhance competitiveness.

10.6.
CROSS REFERENCES & SYNERGIES

Europe needs leadership throughout the value chain from process, materials and equipment to production of devices, systems and solutions and deployment of services to leverage Europe's strong differentiation potential and to drive its competitiveness.

System-Technology co-optimisation is key to all leading-edge innovations (see Figure 62). Specific actions include: specification of technology and product roadmaps for the planning of future products, advanced access to new technologies for prototyping, cooperation on the development of dedicated technologies, advanced access to test-beds and markets.



Close connection between electronics component development in this chapter with next level heterogeneous system integration in chapter 6

F.62

The impact of technology choices on the application and vice versa is becoming very large and decisive in successful market adoption. This is true for all application fields but especially so where the communication, computing and sensing technology is key to deliver the expected (quality of) service or function, e.g. Industry, Automotive, Health. In this respect, one of the most important challenges ahead for Europe is the broad and deep implementation of IoT in the industry, together with so-called 'exponential technologies', jointly named "Industry 4.0". To meet the related challenges, the integration of the whole system must be considered and developers of enabling technologies must work concurrently with integrators and end users being informed of the application need in defining the specification for performance optimisation and integration. Therefore, the scope should not be restricted to semiconductor devices only; instead, research must be combined in all key domains of which the Industry 4.0 is composed, as the importance of a consolidated effort cannot be overemphasised.

Collaboration with the design community:

While there is traditionally a close link to the design community (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 electrical characteristics, models of degradation effects, 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. Use of advanced multi-modal & predictive software tools with well-calibrated physical parameters of electro-thermal models for the identification of critical issues at device and system level, and for the generation of new devices with optimised properties, is opportune to target cost-effective developments.

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 advances in Artificial Intelligence (AI) to 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 combination of sensors is fundamental to maintain Europe leadership in this domain.

Connection with Digitisation of Industry / Industry 4.0

Digitisation, Artificial intelligence and Machine learning evolve in all aspects of Electronics Components & Systems Process Technology, Equipment, Materials and Manufacturing. In general, digitisation topics are already covered by Chapter 4 ”Digital Industry”, yet there are many specific challenges closely related to interaction of processes, materials, equipment and reliability that are addressed also in this chapter.

Connection with Quantum computing

The current status is that Quantum Computing technologies and their applications are expected to break through in the coming 2 decades.

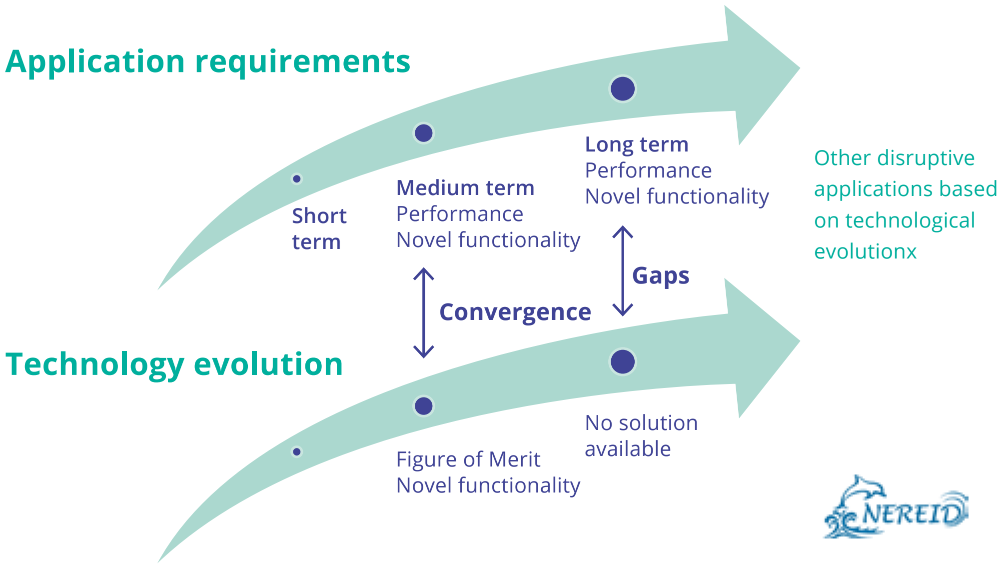
Quantum Computing technologies are addressed with projects from 1/1/2019 onwards in the “Quantum Technologies Flagship” (budget 1BEuro) of the “Future Emerging Technologies” program of Horizon 2020 and its successor Horizon Europe. The results of this Flagship and the related Quantum SRA, are likely to influence the ECS SRA from 2020 onwards, once TRLs of some quantum technologies start to increase.

11

Long term vision

The objective of this chapter is to identify the research subjects that will need to be addressed in the short term at low TRL (TRL1–3) in order to enable the realisation of the European industrial roadmap in the medium (5–10 years) and long term (>10 years).

A long-term vision always has to be based upon the anticipated relationship between the technology evolution and the application requirements. Future applications will be enabled by enhanced performance and novel functionalities generated by new technology options, as projected in technology-application roadmaps, but it is also possible that technology evolution leads to disruptive applications that were not projected in roadmaps. (The emergence of the World Wide Web is a point in case.) To ensure that these opportunities are recognised and used effectively, a cooperation of the academic, institutional and industrial stakeholders that constitute the value chain is a prerequisite.



Technology evolution and application requirements

F.63

A clear strength of Europe is the availability of the many research areas that constitute the expertise basis for the ECS domain. This asset, residing in an extensive ecosystem of universities, RTOs and industrial research organisations, provides the incubator for new disruptive technologies that will enable the creation of novel devices and systems and consequently sustain the competitiveness of the European ECS industry now and in the future. This ecosystem is centred around the ever-growing networked scientific environment and the interdependencies created mainly through the basic and fundamental research actions in the European Framework Programmes. This, in turn, generates the fertile soil where industry can create substantial synergies and deliver breakthroughs to maintain pan-European technological excellence and leadership. It is not an exaggeration to state that this is the cornerstone of European long-term leadership in basic technology.

Over the last decades, the ECS domain has evolved from a technology-driven field to an environment where societal needs and application requirements guide the research agendas of the centres of expertise. The European competences in both 'More Moore' and 'More than Moore' have been instrumental in bringing about this change, resulting in a strong European position in markets that require complex multifunctional smart systems. There is no doubt that the safeguarding and further extension of these competences is essential for a continuous offering of disruptive technologies that will ensure the preservation of the European competitive position.

A list of anticipated disruptive technologies can, by its very nature, never be complete. In this chapter, a long-term vision will be presented for the themes that are of particular importance of this Strategic Research Agenda.

In each of the following sections, the anticipated technology challenges and application opportunities and requirements will be addresses, projected into the timeframe of 2028 and beyond.

11.1. NEW COMPUTING PARADIGMS ('BEYOND CMOS')

There is a need to survey the potential of the emerging 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 the processing speed. Furthermore, fundamental issues like heat dissipation at nanoscale that has turned out to be the most critical bottleneck in information processing, need to be addressed. The Beyond CMOS activities represent medium and long-term research, with the cutting edge in the case specific and tailored performance that can enhance the information processing and reduce the power consumption. The scaling of CMOS devices and circuits is facing a rather fundamental problem arising from dissipation, the so-called "heat death", which has led to the saturation of the clock frequency, to "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 the needs of applications. This has been recognised also in the IRDS (the follower of the ITRS) White Paper for Beyond CMOS in which, in addition to the new Beyond CMOS devices, the importance of non-von Neumann architectures and alternative information processing paradigms, have been stressed. Furthermore, in the Rebooting the IT Revolution: A Call to Action event, organised in the US by SIA and SRC in September 2015, the shift of focus towards networked and distributed intelligent sensors and ubiquitous intelligence was stated.

The potential solutions to solve the "heat death" problem and reduce the dissipation include the use of new materials such as 2D materials in the switches, the use of alternative computing paradigms or the use of different state variables, spins, photons, phonons or mechanical switches, instead of charge. In addition, in the context of new computing paradigms, especially in 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[123] and the distributed computations of IoT devices[124]. However, most of the R&D development exploiting these novel approaches still take place in academic laboratories, with much research still being at the material exploration level.

Emerging technologies cover a wide range of TRLs from 0–1 to 4–5 with a wide range of device concepts, wide range of materials, some of which are compatible with the current CMOS platform, and novel information processing paradigms in the timeframe of five and ten years and further. In addition to information processing, there is potential from the emerging technologies in sensing. In the long run, it is expected that the new ideas will be taken up more broadly by the academia and, eventually, transferred to industry. There is already a relatively strong demand and indirect support to the new approaches in Europe through the existing and forthcoming flagships, focusing on 2D materials, neural networks and quantum technology. The scope of Beyond CMOS activities in Europe covers several emerging technologies, targeting to identify their potential, challenges and shortcomings when applied in information processing. The emerging technologies include spintronics, neuromorphic computing, heat transport at nanoscale and phononic computing, 2D materials, topological insulators, Weyl semimetals, nano-optomechanics and molecular electronics. Besides the already expected support to quantum technologies, spintronics and neuromorphic computation, the 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 advances in functionality, performance and safety.

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123 *A. G. Forte, S. Cirani, and G. Ferrari, "A Distributed Approach to Energy-efficient Data Confidentiality in the Internet of Things," Chapter 5 in Big Data-Enabled Internet of Things, edited by M. Usman Shahid Khan, S. U. Khan, and A. Y. Zomaya, IET, Stevenage, UK, 2019, pp. 75–92. ISBN-13: 978-1-78561-636-5.*

124 *E. Di Pascale, I. Macaluso, A. Nag, M. Kelly and L. Doyle, "The Network As a Computer: A Framework for Distributed Computing Over IoT Mesh Networks," in IEEE Internet of Things Journal, vol. 5, no. 3, pp. 2107–2119, June 2018. doi: 10.1109/JIOT.2018.2823978.*

Quantum computing

Quantum technologies are expected to enable transformative applications including (i) quantum sensing and metrology, which uses the high sensitivity or high precision of quantum devices for applications such as detection of minute magnetic fields or very precise definition of time, (ii) secure communication networks, which involves generation and use of quantum states and resources for communication protocols, requiring also relatively few qubits but high fidelity and long distance transmission of the quantum state and (iii) quantum computing and simulation which require systems with millions to billions of qubits.

In 1982, R. Feynman sketched out roughly how a machine using quantum principles could carry out basic computations and, a few years later, David Deutsch outlined the theoretical basis of a quantum computer in more detail. Thanks to a large spectrum of follow-up research results, such as Shor's integer factorisation algorithm[125], it is expected that quantum computing will contribute significantly to the resolution of problems that classical computing finds hard to solve (factoring, cryptography, optimisation, etc.). The availability of a complete, scalable quantum computer will be a first priority to move these algorithms from blackboard to concrete realisation. During the last three decades, quantum computing has progressed to proof-of-

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125 *P. W. Shor, "Algorithms for Quantum Computation: Discrete Logarithms and Factoring," in Proceedings of the 35th Annual Symposium on Foundations of Computer Science, Santa Fe, NM, USA, 1994, pp. 124–134.*

concept demonstrations of single- and multi-unit qubits (photons, electrons, quantum dots and other approaches), but it is still very much at the research stage, with scientists competing on the manipulation of a handful of qubits.

Reservoir computing

Reservoir computing can be seen as a kind of recurrent neural network where only the parameters of the final output are trained, while all the other parameters are randomly initialised and where some conditions are applied. It can be implemented with optoelectronics [126].

11.2.
PROCESS TECHNOLOGY, EQUIPMENT AND MATERIALS

In the More Moore field, there are strong interests in Europe for specific activities dealing with very low power devices, leading to possible disruptive applications for instance for future IoT systems, for embedded memories, for 3D sequential integration, or for application driven performance, e.g. high temperature operation for the automotive industry.

For future high performance/ultra-low power terascale integration and autonomous nanosystems, new materials (strained semiconductors, Ge, III-V, 2D like TMDs or Phosphorene, 1D as CNT or Nanowire, Ferroelectric, magnetic, etc.), ultimate processing technologies (EUV, immersion multiple patterning, multi e-beam, imprint lithography, self-assembly, etc.) and novel nanodevice architectures (GAA Horizontal or vertical Nanowire FET with co-integration of different channel materials, Nanosheet devices, Carbon NanoTube FET, Negative Capacitance FET, Tunnel FET, NEMS, Hybrid devices e.g. TFET with Fe (ferroelectric) gate, Non-charge-based Memories, 3D integration, etc.) are mandatory for different applications, as well as new circuit design techniques, architectures and embedded software. These nanostructures are also very interesting for advanced sensors (e.g. 1D and 2D materials, Nanowire, CNT or TFET architectures) with high sensitivity, or high performance energy harvesters (e.g. Nanowires).

In the field of alternative memories, Resistive RAM, Magnetic RAM, or Ferrolectric RAM/FeFET will be useful for pushing the limit of integration and performance beyond those afforded by present Non-Volatile, DRAM and SRAM memories.

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[126] *L. Larger, M. C. Soriano, D. Brunner, L. Appeltant, J. M. Gutierrez, L. Pesquera, C. R. Mirasso, and I. Fischer, "Photonic information processing beyond Turing: an optoelectronic implementation of reservoir computing," Opt. Express 20, 3241-3249 (2012)*

3D sequential processes could also be used for the integration of these future high performance sustainable, secure, ubiquitous and pervasive systems, which will be of high added value for many applications in the field of detection and communication of health problems, environmental quality and security, secure transport, building and industrial monitoring, entertainment, education, etc.

These promising technologies for many future applications will allow us to overcome the number of challenges we are facing 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 grand challenges have to be addressed for a successful application of these nanotechnologies. A number of these are described briefly:

- For Nanowires, which are very interesting for very low power nanoscale devices and therefore important for the EU, identify the best material and geometry options for logics (high-speed as well as low-power), develop millimetre wave front-ends with III-V MOSFETs (applications for communication, radar), and consider the 3D aspects of processing.
- For NCFET, useful for very low power, identify the maximum switching speed, the optimal dimensions, develop thin Hafnium based Ferroelectric layers and investigate the scaling potential of the device.
- For TFET, a promising steep subthreshold slope device in the Beyond-CMOS domain, propose novel materials and device architectures to overcome the driving current limitation.
- For NEMS-FET, develop low voltage reliable devices.
- For CNTFET, interesting for very fast and possibly ultimately scaled transistors for logic applications, with self-assembly based fabrication, develop solutions to lower the Schottky barriers at source/drain, to remove the metallic CNTs, faster growing process and design strategies to deal with variability induced by m-CNTs and doping fluctuation. The gatestack architecture is a particular challenge for these fully passivated surfaces.

Novel memory devices are of high importance in the EU for embedded applications:

- OxRAM: HRS broadening is the Challenge. New materials, new programming schemes need to be investigated.
- CBRAM: issues to be investigated are the same ones as OxRAM, with in additiona special focus on data retention, which is probably the most challenging topic for CBRAM.
- MRAM, especially STT/Spin Transfer Torque: etching, thus integration, problems can be much harder to solve than expected. The high current consumption can be a serious drawback for real applications, in particular for IoT.
- FeFET: widen the material screening in addition to the standard Si:HfO2. A lot of work is necessary on the interface between channel and Fe layer.

For 3D sequential integration, a technology with important research activities in the EU, it has to be defined which applications will benefit from very high density interconnections (IoT, neuromorphic…), and develop a 3D place and route tool.

For modelling/simulation, characterisation and reliability, which are strong European domains, new tools have to be developed that take into account all the new materials, technologies and device architectures, in order to speed-up technology optimisation and reduce the cost of technology development.

11.3. SYSTEMS AND COMPONENTS: ARCHITECTURE, DESIGN AND INTEGRATION

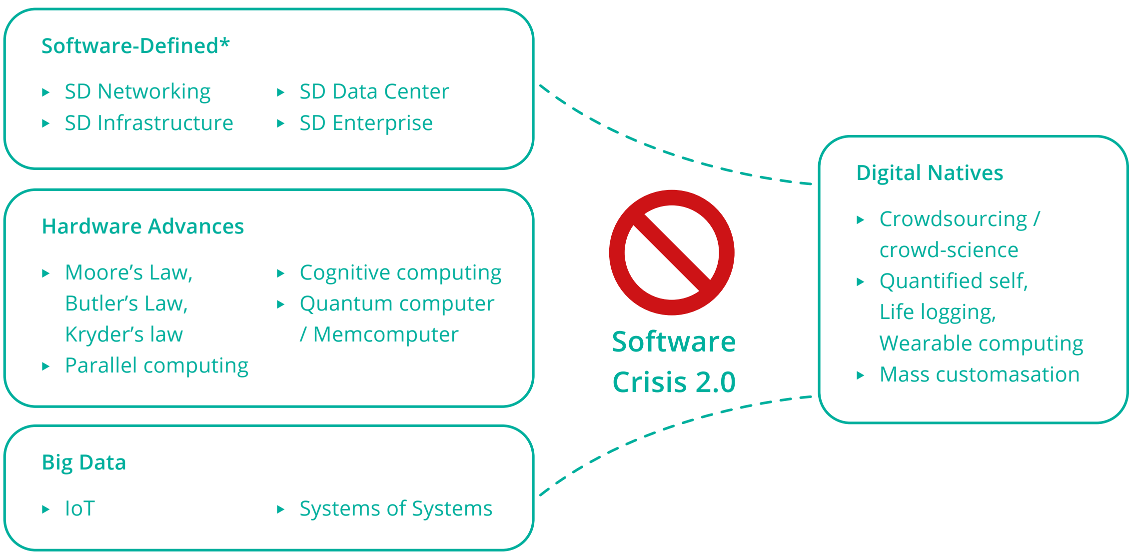
New programming and design models, tools and methods for Software and Computing continuum that will help to address the second software crisis (Software Crisis 2.0[127]). "This crisis stems from the inability to produce software that can leverage the staggering increase in data generated in the past 50 years and the demands of the devices and users that can manipulate it"[128]. The push factors are (see Figure 64):

- The hardware advances: increasing processing power, etc.
- Availability of massive volume of data (Big data)
- The increasing capability of software to efficiently perform tasks that were previously accomplished through some form of hardware. This is known as software-defined X (where "X" can refer to networking, infrastructure, data centre, enterprise, etc.).

Whereas digital native consumers represent a significant "pull" factor in seeking to take advantage of the opportunities afforded by advances in processing power and increased availability of data [Innovation Potential of Software Technologies in the context of Horizon 2020, 2016].

127 The term "Software Crisis" was coined at the 1968 NATO conference. The Software Crisis 2.0 term was first introduced in B. Fitzgerald, Software Crisis 2.0, IEEE Computer, 45(4), April 2012

187 B. Fitzgerald, Software Crisis 2.0, IEEE Computer, 45(4), April 2012



F.64 *Software Crisis 2.0 from [Innovation Potential of Software Technologies in the context of Horizon 2020, 2016]*

In order to address the software crisis 2.0, new programming and design models, tools and methods are needed to enable active participation by customers in the software ecosystem and make software development customer-led (need-"pull" rather than technology "push"). This is known as Citizen Software (see Figure 65) that is based on empowering each citizen to produce software. The emergence of open platforms to support the citizen-driven programming of software-intensive systems is foreseen [NESSI, SOFTWARE CONTINUUM, Recommendations for ICT Work Programme 2018+]. The idea is that citizens will be able to describe what they need in their language (problem space terms), allowing every citizen and not only those that have programming knowledge to program.

The vision for Citizen Software includes software for cyber-physical systems, in addition to classical general-purpose and embedded computing systems. The emergence of cyber-physical systems and their adoption in a wide range of application domains, such as health, energy, transportation, etc., has led to strong requirements for safe and secure software. Automated program synthesis from high-level specifications is a significant challenge that requires the development of appropriate application specification languages, as well as program verification and testing methods and techniques. Although such methods will produce executable code with desired properties, it is necessary to develop methods for the code's safe and secure execution, especially in cyber-physical systems and considering new classes of attacks, such as false data-injection attacks that target sensors and their measurements rather than the embedded computational components. Runtime program execution monitoring methods are indispensable in this direction, and significant effort has to be spent to develop such methods considering the increasing adoption of smart systems in safety-critical applicatons.

Another foreseen tendency is the automation and the self-managing software (see Figure 65) in order to carry out basic tasks without human intervention. This includes self-adaptation towards fully automated software (able to handle the "unknown unknowns"). AI techniques will play a very important role in this automation.

The demanding performance requirements of software-X systems lead to the need for advanced reconfigurable systems that provide application-specific hardware assists on demand, creating new challenges to hardware-software co-design methods and adaptable hardware-assisted application execution.

Approximate computing provides an additional promising computational approach that exploits trade-offs among computation accuracy, performance and power consumption. Its effectiveness spans application domains from image and video to AI acceleration[129], making the approach an important tool for efficient systems at all levels.

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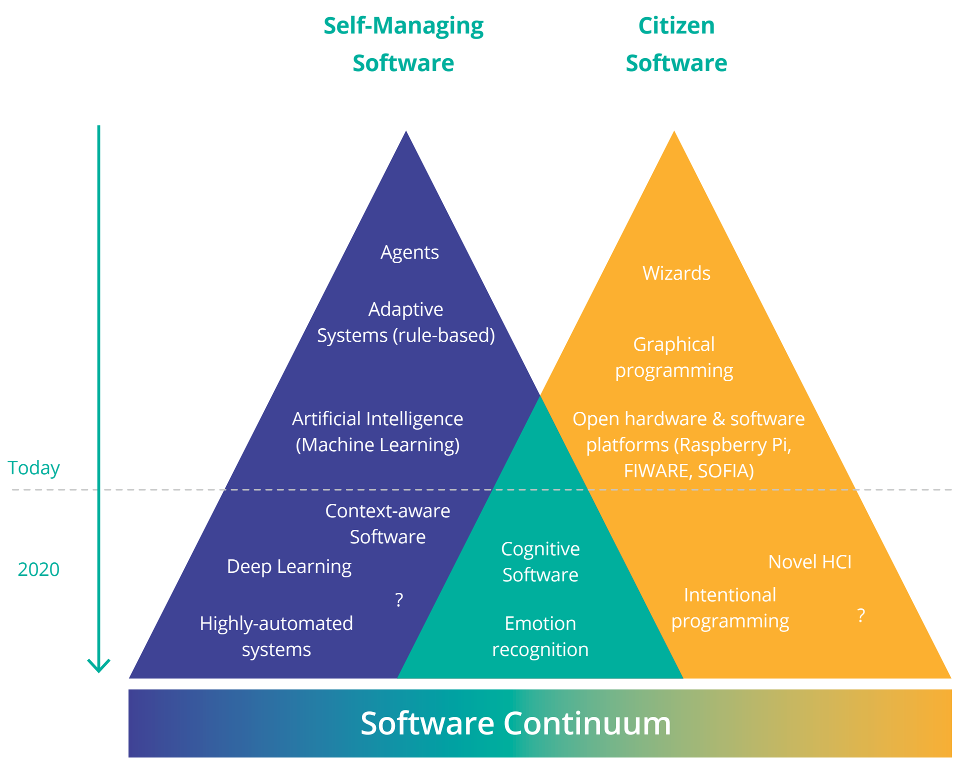
[129] *B. Fleischer, et al., "A Scalable Multi-TeraOPS Deep Learning Processor Core for AI Training and Inference." 2018 Symposium on VLSI Circuits Digest of Technical Papers, pp. 35¬–36.*



F.65 *Software Continuum from [NESSI, SOFTWARE CONTINUUM, Recommendations for ICT Work Programme 2018+]*

To make systems effective, system architectures also need to address distributed data processing, tightly coupled with communication, to ensure that information flow in the system is limited but as complete as possible, which is important to avoid overloading the network. In this context, AI techniques need to be exploited – e.g., extracting limited representative information from a large dataset.

For the integration of technologies into components and smart systems, the challenges that will have to be addressed are determined by the specific application domains. Quantum technologies and photonics constitute typical examples:

Quantum Technology: Quantum Sensing is a very promising new technology which will evolve in mid to long term to exploitation. This technology will provide opportunities in sensing of several physical units like motion related properties as angular rate and also magnetic fields for instance. All at very high resolution, offering new opportunities for demanding applications like very sensitive current measurement for EEG (human brain interface).

Photonics: Photonics is also very well suited for sensing application e.g. on motion related properties as angular rate, but also for instance on media sensing for gases and fluids and for lab on chip applications in the health care field.

11.4. HEALTH & WELLBEING

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

Beyond 2028, personalised and patient-tailored healthcare will be at the forefront of technology advancement. Key challenges include not only technological ones, such as reliability, safety and privacy, but also in terms of regulation and uptake by practitioners, especially when dealing with procurement policies.

A priority will be in bringing these stakeholders closer in the involvement phase of developing key enabling technologies (KETs) for healthcare applications with a customer pull and technology push approach.

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

Digital medicine

Improvements in medicine over the ages greatly benefited from advancements in other disciplines. Medicine evolved over time from a “mechanical” medicine (surgery) toward “chemistry” medicine and more recently biotech medicine. Nowadays the development in ICT and digitisation have an important impact in the way healthcare is addressed. In ten years from now “digital medicine” will be deployed and complement, not necessarily replace, the tools offered to medicine to improve the benefits for patients and medical professionals.

These tools may, for instance, be in silico human models allowing the “digital twin”. However, ECS will have a crucial role in ensuring the necessary link between the digital and the real twins. Sensor signal processing, especially related to data collected from on-body IoT sensors, is a key technology that will advance existing wearables that provide real-time sensed information. This will enable the identification and prediction of a person's health condition. The use of AI technologies based on extended measurement data will enable significant advances in this area.

Furthermore the deployment of smart automated solutions for healthcare will improve clinical outcome and professional proficiency.

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

Some developments are presented below:

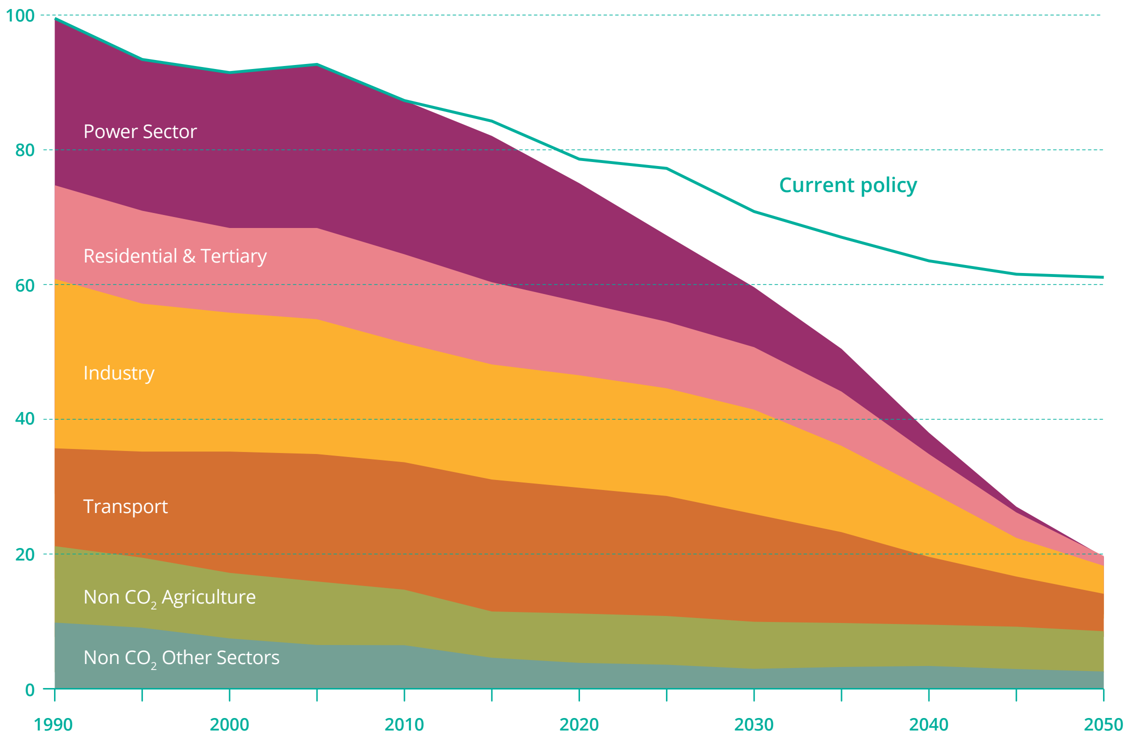
- **Fully personalised medicine** will be enabled by smart monitoring of health parameters, including factors from the molecular to the environmental levels. Developments in healthcare will enable prediction of health evolution and preventive treatment by the concept of "digital twins". Drug development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

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

11.5.
ENERGY

Energy system:
As outlined in the Energy Roadmap 2050,[130] the EU policy envisages by 2050 “a secure, competitive and decarbonised energy system”.

Total GHG emission has to be reduced by over 80%. This implies a “share of RES in electricity consumption reaching 97%”.



GHG Emissions reduction target 2050

F.66

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[130] *https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf*

A possible scenario will imply massively disruptive conditions (very low or perhaps even zero marginal cost on renewable energy injected into the distribution grid), highly decentralised generation systems with a large number of prosumers connected with smart grids without intermediaries (exchange via blockchain).

Energy supply to ECS devices:
On-chip power supply by means of micro-batteries, energy scavenging/harvesting, micro-fuel-cells.

Power Electronics is the technology associated with the efficient conversion, control and conditioning of electric energy from the source to the load. It is the enabling technology for the generation, distribution and efficient use of electrical energy. It is a cross-functional technology covering the very high Giga Watt (GW) power (e.g. in energy transmission lines) down to the very low milli-Watt (mW) power needed to operate a mobile phone. Many market segments such as domestic and office appliances, computer 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 European Union to reduce the energy consumption and CO2 emissions can only be achieved by an extensive application and use of Power Electronics, as power electronics is the basic prerequisite for:

- Efficiently feeding-in wind and solar energy to the grids;
- The stabilisation of the power grids with increasing share of fluctuating renewable energy sources;
- Highly efficient variable speed motor drives;
- Energy efficient and low-emission mobility with hybrid and full electric vehicles;
- An 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 potential that can be achieved by introducing state-of-the-art and future power electronics components into systems is enormous, estimated to more than 25% of the current electricity consumption in the EU countries. Since power electronics is a key technology in achieving a sustainable energy society, the demand for power electronics solutions will show significant growth in the coming decades. The European industry holds a strong position in the field of Silicon based power semiconductors and modules and is establishing robust pillars for the future wide band-gap semiconductors technology. Europe also has high quality power electronics research groups at universities and research institutes with well-established networks and associations in Europe to provide platforms for discussion, cooperation and joint research.

Long-term Vision Roadmaps for power technology need to cover different sectors:

- New highly efficient power devices based on wide band-gap semiconductor materials, like SiC and GaN on silicon, and possibly Ga2O3, AlN, diamond, diamond on silicon or nanowire-based materials.
- New cost-efficient, Si based power devices to enable high efficiencies for mass-market applications, e.g. Super-Junction MOSFETs.
- Power management for very low power applications, as required for IoT, including the development of energy harvesting technology.
- High temperature capable packages serving new materials and 3D technologies with lifetimes fulfilling highest requirements and the integration capabilities.

To pursue the Energy Roadmap till 2050, three major challenges were identified in the Energy chapter:

1. **Ensuring sustainable power generation and energy conversion.**
   Vision: The ultimate vision is and will be the loss free energy conversion and generation. A reachable vision is to reach ~99% efficiency by 2028.

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 the urban mobility and the introduction of storage systems will lead to new challenges in energy management and distribution for communities and cities.
3. **Reducing energy consumption.**
   Vision: The vision for 2030 is to achieve the current EU policy targeted of 30% savings potential by utilising innovative nano-electronics based solutions.

11.6. DIGITAL INDUSTRY

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

From the process industries' point of view, the SPIRE roadmap [131] lists the following targets for 2020-30:

- Replacement of fossil-based materials by bio-based materials requiring completely new processes;

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

- 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 concrete targets in each domain, ending up also in a number of challenges to technologies in the ECSEL SRA.

These are overall targets, which translate into diverse and much more concrete targets in each domain, ending up also in a number of challenges to technologies in the ECSEL SRA.

From the discrete manufacturing point of view, the Factories of the Future (EFFRA) roadmap[132] summarises its vision as follows:

- Agile value networks: lot-size one – distributed manufacturing;
- Excellence in manufacturing: advanced manufacturing processes and services for zero-defect and innovative processes and products;
- The human factor: developing human competences in synergy with technological progress;
- Sustainable value networks: manufacturing driving the circular economy;
- Interoperable digital manufacturing platforms: supporting an eco-system of manufacturing services.

The ongoing ConnectedFactories CSA[133] forecasts the emergence of new concepts, such as

- 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 the need to invest in technology research and innovation projects on the following topics:

- The rise of artificial intelligence (AI), a run on powerful edge and cloud computing networks. Methods and algorithms need to evolve to more complex, reliable and able AI.
- More measurements-originated data, more image or video, 3D design, animation, data, more heterogeneous and unstructured data.

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132 *https://www.effra.eu/factories-future-roadmap*

133 *https://www.effra.eu/connectedfactories*

New production schemes:

  - Modular factories, i.e. smaller standard units to be assembled according to needs, also mobile units;
  - More end-user driven agile production, i.e. end-users more connected to production and logistics chains;
  - Hyper-connected factories.
- Towards closer-to-customers production by new production technologies, e.g., 3D printing, and other novel emerging methods;
- Extending closed-loop production lines to closed-loop regions (extensive recycling, net energy, zero-emission and waste, close to end-users);
- From autonomous to human-machine co-work, as a means to enable flexibility and decrease of excessive complexity.

11.7. TRANSPORT AND SMART MOBILITY

The European Union has issued ambitious policy statements regarding transport and smart mobility:

- "Emissions from transport could be reduced to more than 60% below 1990 levels by 2050." [134]
- "The EU has adopted the Vision Zero and Safe System approach, to eliminate deaths and serious injuries on European roads." [135]
- "Sustainable Mobility for Europe: safe, connected, and clean" [136]

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

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134 https://ec.europa.eu/clima/policies/strategies/2050_en

135 https://ec.europa.eu/transport/road_safety/

136 https://eur-lex.europa.eu/resource.html?uri=cellar%3A0e8b694e-59b5-11e8-ab41-01aa75ed71a1.0003.02/DOC_1&format=PDF

11.8.
CONNECTIVITY AND INTEROPERABILITY

Mobility being everywhere, connectivity and interoperability are today key enablers to support the development of innovative applications in various markets (such as consumer, automotive, digital manufacturing, network infrastructure). The availability of new innovative connectivity technologies (IoT, 5G, car to car, etc.) will enable and enhance a wide range of new business opportunities for the European industry.

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 were identified that will have to be addressed in the connectivity and interoperability roadmap till 2050:

1. **Meeting future connectivity requirements leveraging heterogeneous technologies.**
   Vision: Targeting system and application, we have to consider the interconnection between sub-systems and should focus on individual component technology development according to needs identified at system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key.
2. **Enabling nearly lossless interoperability across protocols, encodings and semantics.**
   Vision: To fully leverage this heterogeneous integration at hardware level, software interoperability is a parallel challenge to provide connectivity that will allow for System of Systems (SoS) integration. Thus, an alternative major challenge is to enable SoS integration through nearly lossless interoperability across protocols, encodings and semantics. To do so, dedicated software tools, reference architecture and standardisation are key to supporting SoS integration, thus enabling the provision of a scalable and evolvable SoS. As it remains very difficult to assume that highly customised embedded systems will be built based on a single, unified, high-level modelling principle and toolset, there is a quest for consolidation, or even the standardisation of basic runtime frameworks, component libraries and subsystem interfaces that will ease the deployment of interoperable components into generic, domain-specific solutions and architectural frameworks in a bottom-up fashion. Such an approach is also expected to provide for better traceability of requirement validation, and formal verification of distributed system compositions and their emerging functional and non-functional properties.
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. One major challenge is to ensure security interoperability across any connectivity. This foresees the usage of different technologies in connectivity networks. Technology differences impose security incompatibilities leading to increased engineering costs. Therefore, the development of an innovative hardware and software security solution that will support and provide correctness and safety is of fundamental importance. Such a solution will have to be linked with the previous challenges to ease SoS engineering, deployment and operation in a seamless manner. Security assessment is a significant issue here considering the criticality of applications. Standards and directives are required not only for technology

transfer and system evaluation, but for legal purposes as well, considering the existing GDPR legal framework and the emerging laws regarding European and national cybersecurity requirements.

11.9.
DATA SCIENCE AND ARTIFICIAL INTELLIGENCE

Humanity, as of today, is already past the Zettabyte Era. By 25 years from now, these technologies will require new storage solutions and new NVM memory concepts, coupled with new hybrid architectures able to process, fuse, exploit and disseminate the information at the edge of the network much further than before. Space exploration and pharmaceutical drug development are among application areas that will be revolutionised by these technologies. Likewise, everyday life will be affected. Personal and wearable gadgets will be able to connect more effectively with the cloud and crunch big data.

12

Appendix to Chapter 0

More details on foreign export restrictions:
One of the most well-known export restrictions is known as ITAR:

The ITAR term is often used as a shortcut for 'US Export Control Laws', which restrict exports of designated goods and technology. These federal laws are implemented by the US Department of Commerce through its Export Administration Regulations (EAR—trade protection), by the US Department of State through its International Traffic in Arms Regulations (ITAR—national security), and by the US Department of Treasury through its Office of Foreign Assets Control (OFAC—trade embargoes). The ITAR is concerned with items that are designed or modified for military use. The EAR regulates items designed for commercial purposes that can have military applications such as computers, pathogens, etc.

Any product that includes or is bundled with US-origin items is subjected to US Export Control Laws, **irrespective of the licensing conditions of these items**. US origin is assumed for any item (commodity, technology, or software) contributed from a US national anywhere in the world, or from a foreign national on US territory. Items physically or virtually located in the US including artefacts in data centres are also considered as US origin. Because of the extra-territorial application of US Export Control Laws, **these become a re-export control** of products from one country to another. If an item is of US origin and subject to US Export Control Laws, it remains so regardless of how many times it is re-exported, transferred, or sold. In particular, an export license is required for any re-export or in-country transfers of US-origin items or non-US made items subject to the EAR, unless the exemptions below apply.

The main exemption to the requirements to obtain an export licence according to US Export Control Laws is for items in the 'public domain'. Public domain items do not have an identified copyright owner. Fundamental research performed by academic institutions is also assimilated to 'public domain', but only as far as no access restrictions existed on the grant agreements that funded this research. Access restrictions that remove the 'public domain' exemption of fundamental research include publication content controls or specific treatment of non-US nationals in the contribution to or dissemination of research results. See for instance https://www.umass.edu/research/sites/default/files/documents/export_controls_and_universities_information_and_case_studies.pdf

The second exemption to the requirements to obtain an export licence applies only to EAR, when the value of US-origin items in a product is below a percentage based on 'de minimis' guidelines. The 'de minimis' guidelines set the percentage threshold based on: (1) Export Control Classification Number (ECCN); (2) the ultimate destination of the item; (3) the end-user and end-use of the item. However, the 'de minimis' exemption does not apply in 'except' cases, such as: specific countries of destination (except #1); certain components of high performance computers, and encryption commodities and software (except #2). Further details are available from https://www.bis.doc.gov/index.php/licensing/reexports-and-offshore-transactions/de-minimis-guidelines/18-licensing and https://www.bis.doc.gov/index.php/documents/pdfs/1382-de-minimis-guidance/file

13

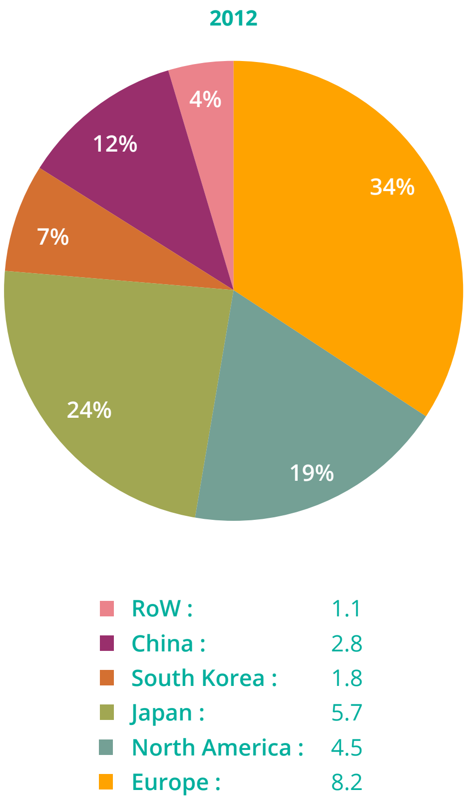
Appendix to chapter 1

13.1.
COMPETITIVE SITUATION OF AUTOMOTIVE INDUSTRY IN EUROPE

The European Commission's Strategic Transport Research and Innovation Agenda (STRIA) describing this transformation distinguishes seven transversal dimensions of change:

- Cooperative, connected and automated transport,
- Electrification,
- Vehicle design and manufacturing,
- Low emission alternative energies for transport,
- Network and traffic management,
- Smart mobility and services,
- as well as Infrastructure.

[137] S. Analytics, "Automotive Semiconductor Demand Forecast 2011-2020," Strategy Analytics, Boston, 2013



Automotive Revenues by Regions (USD billions) [137]

Source: (Analytics, 2013)

F.67

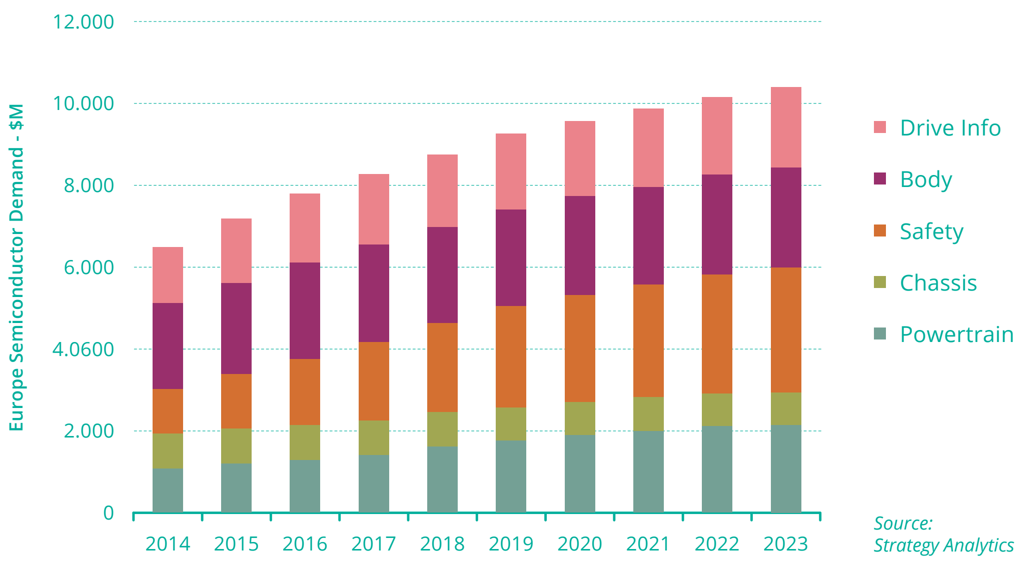
Mid- and long term (2030/2050) research and innovation needs have been identified for all these areas in the roadmaps of the STRIA summaries of which were published as part of the Europe on the Move package by the European Commission in May 2017 [138].

More specifically, the European Union is home to 15 international car manufacturers producing around 20 million vehicles per year. It is also home to world-leading automotive electronics semiconductor, embedded software and system suppliers.

Automotive semiconductor revenues in Europe reached €4.0 billion in 2012, representing more than 30% of the world market. According to Strategy Analytics1, automotive semiconductor revenues are expected to grow 7% (CAGR) over the five-year forecast period.

The revenues in Europe are split over the following market segments:

[138] *E. Commission, "STRIA Roadmap 3 - Smart mobility and Transport Services and Systems," Horizon 2020 Commission expert group to assist the Strategic Research and Innovation Agenda (STRIA) initiative (E03420) , Brussels, 2017*

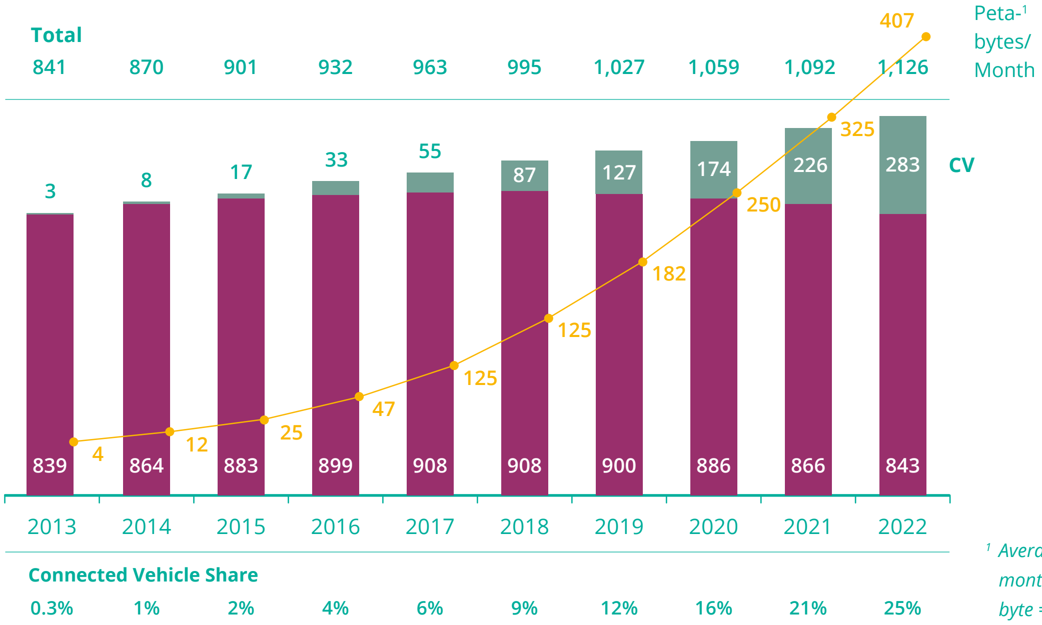


F.68 *Automative Revenues by Market Segments (USD Millions)* *Source: Strategy Analytics*

Of all the cars sold, more and more of these cars will be connected in the future. According to CISCO, 25% of all cars will be connected in 2023.

GLOBAL PASSENGER VEHICLE POPULATION & SHARE OF CONNECTED VEHICLES

(in millions)



[1] *Average of 1.5 GB/ month/vehicle, 1 Peta-byte = 1,048,576 GB*

Global Passenger Vehicle Population *Source: CISCO 2011* **F.69**

13.2.
DETAILS TO HIGH PRIORITY R&D&I TOPICS FOR MAJOR CHALLENGE 2 IN APPLICATION CHAPTER TRANSPORT & SMART MOBILITY

Environment recognition

- New trusted integrated sensors also for harsh conditions (cameras, radar, lidar, ultrasonic, ...), including their SW for real-time data acquisition management.
- Sensor fusion, video data analysis and annotation.
- Methods to evaluate, reproduce, overcome and validate fault (and/or degraded) behaviour for exceptional situations in environment perception.
- Lifetime, reliability, robustness.
- Quality attributes of sensors; aging of sensors; influence of environment to sensor quality; handling of quality attributes of sensors in software; electromagnetic compatibility.
- Redundancy concepts.
- Traffic scene interpretation (also for different countries); scenario categorization; catalogue of safety relevant scenarios; scenario description language, system context modelling; tools and methods required for scene interpretation.
- Scene and object recognition.
- Driver health/emotion/intention recognition.
- Support and harmonization of object lists, identifications, attributes, sensor protocols; open platforms for scenarios.

Localization, maps, and positioning

- Crowd-sourced or shared data acquisition of mapping data
- Situation-aware turn-by-turn navigation
- Reliable, accurate and high-precision localization, GNSS Galileo & GPS, lane-level resolution positioning
- Combination and fusion of different available data sources (stationary/infrastructure-based, dynamic data, cloud data …).

Control strategies

- Transport system level: optimisation of throughput and safety of all traffic in a larger area (e.g. city, motorway section …). Provides system data and recommendations to the lower levels such as speed limits, personalised re-routing.
- Cluster-of-vehicles level: strategies to optimise the flow and safety of a group of closely-spaced, temporarily connected vehicles, perhaps travelling together (possibly forming a platoon) or approaching an intersection.
- Individual-vehicle level: control strategy for optimisation of safety and speed of individual vehicle, based on available data at each of the level. This is the ultimate decision and responsibility level.
- Framework for scene interpretation, environment object handling to separate sensing from control strategies.
- Mission-oriented automated system SW: Mapping and routing, online mission verification, emergency control SW, fail operational strategies.

- Technical goal-oriented collaborative automated system: Mapping and routing, control strategies & real-time data processing; ADAS functions, ADV functions.
- Fault-tolerant control strategies & real-time data processing.
- Distributed control (network of control units, multi-core, multi-processor, cloud-based).
- Human-vehicle interaction (e.g. handover scenarios, VRUs interaction).

HW and SW platforms for control units for automated mobility and transportation (including also support for artificial intelligence)

- Artificial intelligence (AI) – intelligence versus deterministic response.
- New methods, tools, HW and SW for development of AI -based systems.
- Efficient and safe use of resources in multi-core/many-core processor architectures.
- Test procedures for AI enabled components, standardisation of test procedures.
- Bring AI towards industrialisation.
- Disruptive applications for AI in mobility and transportation.

Communication inside and outside vehicle

- Dynamically reconfigurable networks ("Drive-by connectivity").
- Networks that support real-time, mixed criticality, availability, dependability.
- Big-data handling and data-governance inside vehicles and between vehicles and the environment.
- Seamless integration and cooperation of multiple communication platforms (amongst others: V2X, Radar, DAB / digital audio broadcasting, 5G, eLicense Plates, NFC, Bluetooth, 802.11p, etc).
- Safe and secure communication (e.g. build-in data security and privacy).
- Intelligent in-vehicle networking (wire-based and wireless).
- Secured high-speed in-vehicle networks.
- Multi-layered privacy protecting and secure elements in architectures and components.
- Standards and interoperability.

Testing and dependability

- Test methods for connected, cooperative, automated mixed-criticality systems.
- Methods and tools to support virtual approval (shift towards virtual homologation).
- Functional safety along life-cycle.
- Model-centric development and virtualisation of testing by digitalisation.
- Sensor, actuator, communication test infrastructure and tools (including deep learning sensor algorithms).
- Test methods for AI-based systems.
- System validation and non-regression testing from real-world data.
- Large scale field tests of secure highly automated vehicles, field operational tests (FOT), naturalistic driving studies (NDS).
- Software tools for automatic validation.
- Contemporaneous logging and secure, reliable and privacy protected data retention for incident reconstruction.
- Continuous cross-industry learning processes for the development of highly automated transport systems are established enabling fast take up of new features and capabilities mandated from analysing fleet data with the objective to continuously enhance system safety and performance.
- Alignment of test procedures/scenarios/methods of test-fields/labs for connected, automated operation.
- Cost-effective usage of test infrastructure validation of fail-operational concept for unknown environments.

- Training methods for automated driving functions (e.g. compare open loop ADV functions with manual driver reactions).

Swarm data collection and continuous updating

- Check field operational data and derive scenarios of it, approval of scenarios for further validation usage.
- Learning process for automated vehicles (including necessary online SW update-infrastructure), SW improvement cycle using field data / big data analysis.
- Safe and secure over-the-air SW update.
- Reliable and temper-free black box recorder for near incident data (including dependable communication and near-incident scenario evaluation, definition of minimal dataset).

Predictive health monitoring for connected and automated mobility

- Self-aware systems guaranteeing that the risk produced by highly automated transport systems is reduced to an acceptable minimum.
- On-board diagnostics for automated transport systems.
- Methods for self-assessment / self-diagnosis of health state, degradation, system state, system condition across all ECS levels.
- Methods and tools (development of ECS but also in-vehicle usage) to cope worst case scenarios

Functional safety and fail-operational architecture and functions (sensors, electronics, embedded software and system integration)

- A common evolvable fault tolerant system architecture, including onboard and infrastructure, is standardised to enable the necessary innovation speed and allow affordable validation efforts.
- Strategies for HW and SW redundancy.
- Fail-silent and fail-safe systems.
- Development frameworks to design fail-operational ECS.
- Service-oriented distributed dynamically reconfigurable HW/SW architecture.
- Strategies for safe operation / safe stop / safe actuation in emergency situations.
- New generation technologies for automated driving based on competitive consumer electronics.

14

Appendix to chapter 6

This appendix gives a detailed list of topics in each R&D&I Area of every Major Challenge of Chapter 6 *Systems and Components: Architecture, Design and Integration.*

14.1. MAJOR CHALLENGE 1: MANAGING CRITICAL, AUTONOMOUS, COOPERATING, EVOLVABLE SYSTEMS

Major Challenge 1 topics are collected in three categories (high priority R&D&I areas):

Models, model libraries and model-based design technologies

- Re-usable, validated and standardised models and libraries for
  - system contexts (use cases, scenarios)
  - environment (including different environment factors and conditions)
  - human behaviour (as operators, users, cooperation partners)
  - for system behaviour, including
    - environment/situation perception (incl. sensor models)
    - situation interpretation and prediction
    - self-awareness, -management and -healing (incl. reconfiguration)
    - handling of uncertainty, inaccuracy and faults
- Advanced modelling techniques for future ECS
  - combining rigorous (functional, physical and data based) behavioural and property modelling and measurement/observation-based modelling
  - supporting V&V of heterogeneous systems,
  - supporting alteration management and model transformation
  - for learning and adaptive systems
- Model-based design methods and interoperable toolchains for critical systems, supporting constraint-driven requirements (including standards like ISO26262, EAL6+), and (incremental) certification and homologation
- Extended specification capabilities (including requirement engineering, mission profiles, use cases, architectural design, transition of informal to formal specification ...) to enable executable and consistent specifications of all design aspects and in all stages of development

Verification and Validation (V&V) and Test for critical systems: Methods and Tools

- Model-based verification, validation and test methodology and interoperable tool chains and platforms for critical systems,
  - supporting heterogeneous systems
  - starting from high levels and spanning different levels of abstraction
  - including coverage, error mode analysis, generation of HW/SW V&V from models and connection of model-based design and verification
- Automated derivation of verification procedures and tools from requirements and models, back annotation of verification results, interface between requirement engineering and V&V environment

- V&V and test methods including tool support
  - for lifecycle and in-service phase, including support for
    - monitoring systems' state of health and exception conditions
    - reconfiguration, adaptation, handling of faults and ageing
    - upgrades in the field and evolvability
    - maintainability
    - special situations (start-up, power-down, …)
  - for (AI-based) adaptive, cognitive and learning systems, including V&V for strategy synthesis and unsupervised learning
  - for Human-Machine Interaction, collaborative decision-making, cooperation strategies and activities, etc., including human (health) state and intention prediction
  - for autonomous systems including (a) environment/situation perception (incl. sensor models), (b) situation interpretation and prediction, and (c) handling of uncertainty, inaccuracy and faults
- Methods for the hierarchical verification of the whole system (incl. reuse of already verified components, scene and environmental analysis, connection of formal and simulative methods, incremental verification)
- Concepts and procedures for the evaluation of functional safety, robustness and reliability (hierarchical management of requirements, criteria and system characteristics/functions, determination of errors and failure probabilities, …)

(Virtual) Engineering of Electronic Component and Systems (ECS)

- Collaboration concepts and methods, platforms and interoperable tools for interdisciplinary, holistic virtual engineering of ECS covering the whole value chain, spanning organisations, engineering domains and development activities
- Methods and interoperable tools for virtual prototyping of complex, networked systems with a large number of components (e.g., IOT systems), including usage of digital twins, support for distributed design and development, etc.
- Engineering support (libraries, platforms, interoperable tools)
  - for (AI-based) evolvable and adaptable systems including adaptation to human needs and capabilities, to changing and unknown environments/situations/contexts, enabling upgradability while ensuring functional, structural and semantic integrity during runtime, all embedded within holistic lifecycle management
  - for the design and operation of Open-World Systems (distributed control loops, cognitive systems, handling of unreliable information, safe fall-back strategies, legacy systems/components, monitoring, self-awareness and self-healing, fault tolerance layers, etc.)
  - for the design and operation of cognitive, cooperating systems (sufficient observability of the environment, handling of unknowns, online synthesis of (cooperation) strategies, reasoning engines, value governance, learning …)

14.2. MAJOR CHALLENGE 2: MANAGING COMPLEXITY

Major Challenge 2 topics are grouped in four categories (high priority R&D&I areas):

Systems Architecture

- Extended methods for architectural design: Support for
  - systems with thousands of components
  - metrics for functional and non-functional properties
  - early architectural exploration, considering use cases and application context, enabling evaluation of design alternatives (e.g. centralised vs. decentralised…) and consistency checking
- Design methods and architectural principles, platforms and libraries supporting
  - V&V, Test, and Life-Cycle-Management of complex, networked ECS: Modular Architectures and platforms supporting compositional and incremental V&V and Test, Adaptability, Upgradability, Evolvability, Maintainability)
  - Self-Management, Self-Awareness and Self-Healing (including monitoring and diagnosis on hardware and software level in real-time, self-assessment, support for re-configuration, redundancy, down to integrated DFT/BIST tests)
  - cognitive and adaptive systems (support for cognitive computing, adaptive algorithms, artificial intelligence, machine learning, neuromorphic architectures…)
- Model-based system architecture, including models representing requirements and specifications in dynamic and executable architectures, to ensure, among other things, preservation of consistency of architectures throughout the design process and lifecycle

System Design

- Hierarchical concepts and standards for IP modelling (component-based design, reusable components on all levels, extended analysis techniques, coverage and error mode analysis, architecture and system models for Soft-IP)
- Methods and tools for component-based HW/SW co-design for complete products, including heterogeneous systems, heterogeneous computing, embedded cores, software blocks, digital and analogue IP, subsystems, (possibly unknown) system environment and a (fast-) changing application context
- Methods and tools for model-driven engineering, supporting model creation and transformation (including model extraction and model learning), model languages (including domain-specific languages), model management and scalability of model-based approaches
- Methods and tools for efficient virtual prototyping (fast simulation/emulation of embedded platforms, early software integration and validation, adaptive, re-configurable real-time platforms, co-simulation of heterogeneous modelling paradigms, cloud-support, cognitive computing)
- Design and analysis methods for multi-/many-core systems, including support for complex software stacks and DSLs, and for migration of legacy software)

Methods and tools to increase design efficiency

- Seamless and consistent design and toolchain for automated transfer of abstract (system level) descriptions into functional HW/SW blocks (High-Level synthesis, Generator-based design, Co-Simulation of heterogeneous models) with inclusion of design checking and consideration of simultaneous technology and product development.
- Strong support of package, board and sensor/MEMS (co-)design including die-embedding and 2.5/3D integration (design exploration, mixed discipline modelling, multi-criteria evaluation of functional and non-functional properties, optimisation, and integrated DFT development
- New methods and tools to support new design paradigms: multi-/many-core architectures, increased software content, NoCs (Network on Chips), GALS, neural architectures, design knowledge acquisition, artificial intelligence, big data methods, machine learning, etc.
- Support of new technologies: FD-SOI, graphene, nanotubes, <7nm technology, etc. ...
- New approaches to handle analogue/mixed signal design (capturing and formalising designer knowledge, guided design, automatic generation of blocks, synthesis of analogue blocks)

Complexity reduction for V&V and Test

- V&V methods to prove safeness and soundness of real-time complexity reduction in situational representation and situational prediction
- Hierarchical system verification using already verified components and verification process reuse
- Methods and tools to support scenario-based V&V and Test, including scenario analysis, scenario selection, combination of formal proof, simulation and test techniques
- Virtual platform in the loop, enabling the efficient combination of model-based design and virtual platform-based verification and simulation
- Methods and tools for V&V automation and optimisation including test optimisation and test system generation, including handling of product variability

14.3. MAJOR CHALLENGE 3: MANAGING DIVERSITY

The main R&D&I activities of major challenge 3 are grouped in four categories (high priority R&D&I areas):

Multi-objective optimisation of components and systems

- Integrated development processes for application-spanning product engineering along the value chain (modelling at different abstraction levels, management of constraints in different domains, multi-criteria, cross-domain optimisation, standardised interfaces)
- Consistent and complete co-design and integrated simulation of IC, package and board in the application context (integration of communication systems, mechatronics components and their interfaces)
- Modular design of 2.5 and 3D integrated systems (reuse, 3D IPs, COTS and supply chain integration, multi-criteria design space exploration for performance, cost, power, reliability, etc. ...)

Modelling and simulation of heterogeneous systems

- Hierarchical approaches for the modelling of heterogeneous systems (consistent models at different abstraction levels, model simplification and order reduction, model transformation and adaptive models with automatic adjustment of abstraction level, accuracy and complexity)
- Modelling methods to take account of operating conditions, statistical scattering and system changes (application-specific loads, variations in production, commissioning and operation, degradation and ageing effects)
- Methods and tools for the modelling and integration of heterogeneous subsystems (analogue, digital, RF, antennas, power, memory, buses, optics, passive components)
- Methods for hardware software co-simulation of heterogeneous systems at different abstraction levels (co-simulation of software and sensors and different modelling paradigms, hardware-in-the-loop simulation, heterogeneous simulation (from FEM to inaccurately described systems in one environment)
- Modelling methods and model libraries for learning, adaptive systems
- Models and model libraries for chemical and biological systems

Integration of analogue and digital design methods

- Metrics for testability and diagnostic efficiency (including verification, validation and test), especially for AMS designs.
- Harmonisation of methodological approaches and tooling environments for analogue, RF and digital design (reuse of analogue IP on system level, synthesis and verification for analogue and RF components and heterogeneous systems considering the package)
- Automation of analogue and RF design (high-level description, synthesis acceleration and physical design, modularisation, use of standardised components)

Connecting digital and physical world

- Advanced simulation methods (environmental modelling, multi-modal simulation, simulation of (digital) functional and physical effects, multi-level/multi-rate simulation, emulation and coupling with real hardware, connection of virtual and physical world).
- Novel More than Moore design methods and tools (design exploration, automated variant generation and evaluation, synthesis approaches for sensor components and package structures).

14.4.
MAJOR CHALLENGE 4: MANAGING MULTIPLE CONSTRAINTS

R&D&I activities in this challenge are grouped in three categories (high priority R&D&I areas)

Ultra-Low Power Design methods

- Advanced methods for ultra-low-power design (efficiency modelling, low-power optimisation taking into account performance parameters)
- Design methods for (autonomous) ultra-low-power systems, taking into account application-specific requirements (function and performance, safety and security, communication, energy demand profiles/energy recovery, system life, boundary conditions for energy harvesting and storage)
- Method for comprehensive assessment and optimisation of power management and power consumption (normal operation, switching on and off, behaviour in the event of a fault) including the inclusion of parasitic effects (substrate couplings, etc.)

Efficient modelling, test and analysis for reliable, complex systems considering physical effects and constraints

- Hierarchical modelling and early assessment of critical physical effects and properties (ESD, substrate coupling, latch-up, EMC, thermal-electrical interactions, thermo-mechanical stress, power and signal integrity) from SoC up to system level
- Design and development of error-robust circuits and systems (methods for monitoring and fault detection, adaptation strategies, intelligent redundancy concepts, adaptive algorithms)
- Production-related design techniques (modelling, characterisation, variability and reliability analysis, yield optimisation, lithography friendliness, measurement and prognosis of yield losses)
- Consistent methods and new approaches for (multi-level) modelling, analysis, verification and formalisation of ECS's operational reliability and service life (comprehensive consideration of operating conditions and dependencies between hardware and software, detection and evaluation of complex fault failure probabilities and dependencies)
- Consistent design system able to model and optimise variability, operational reliability (including degradation/ageing), yield and system reliability (including the consequences for the qualification), considering dependencies
- Analysis techniques for new circuit concepts and special operating conditions (Voltage Domain Check, especially for start-ups, Floating Node Analysis …)
- Advanced test methods (test generation for analogue and RF design, baseband testing with massive BIST usage, hierarchical production test (including diagnostics, online test troubleshooting or error correction), intelligent concepts for test termination, automated metrics/tools for testability and diagnosis, extraction of diagnostic information)
- Methods and tools for monitoring, diagnostics and error prediction for ECS (online and real-time monitoring and diagnostics, intelligent self-monitoring of safety-critical components, life expectancy)

Safe systems with structural variability

- Architectures, components and methods for adaptive, expanding systems (self-) monitoring, diagnostics, update mechanisms, strategies for maintaining functional and data security, lifecycle management, adaptive safety and certification concepts)
- Design methods and tools for adaptive, expanding systems (realisation of real-time requirements, high availability and functional and IT security, evaluation of non-functional properties, analysis of safety and resilience under variable operating conditions)
- Novel simulation approaches for the rapid evaluation of function, safety and reliability (real-time simulation and simulation of mixed virtual real systems, approximate computing, approaches for mixed criticality)
- Security concepts for highly connected and adaptive, expanding systems (self-monitoring, environmental analysis, ageing-resistant chip identification techniques, ensuring functional safety through robustness guarantees).

14.5. MAJOR CHALLENGE 5: INTEGRATING MINIATURISED FEATURES OF VARIOUS TECHNOLOGIES AND MATERIALS INTO SMART COMPONENTS

The main R&D&I activities in the three identified categories (high priority R&D&I areas) of Major Challenge 5 are:

Activity field 1: Functional Features

- Various sensors and systems in package for autonomous cars, industrial robots, smart energy, health, environmental applications, etc.
- Selective gas (CO, CO2, NOx, VOC, etc.) sensing components
- Low-power wireless architectures
- PMICs with high efficiency at very low power levels and over a wide range of input voltages (AC & DC)
- Selective detection of allergens, residues in food/water, atmospheric particles, etc.
- Disease monitoring & diagnostics (at home, POC, animal health)
- Bio-sensors and bio-actuators
- MOEMS and micro-optics
- Component-level features for self-diagnosis (PHM detectors)
- Harvesters and storage devices (e.g. microbatteries, supercapacitors), including 2D, 3D and solid-state for feeding low or zero power devices
- Hardware solutions for security and privacy
- IC functionalities for neuromorphic computing
- Machine learning and artificial intelligence (including testing of learning components)

Activity field 2: Materials

- Surface coatings for multi-functionality on the same base structures, including self-cleaning materials
- High-efficiency photonic materials
- New / alternative organic and bio-compatible materials
- New materials and features for sensing (CNT, graphene, nitrogen voids, e.g. in diamond, etc.)
- Low quiescent/leakage power material/devices 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, triboelectricity …) and higher performing electrodes and electrolytes for improved capacity and conductivity of energy storage devices
- Rare earths replacement, e.g. for magnetics
- Heterogeneous integration of new materials, sensors, actuators for miniaturised chips (also for high temperature and photonic applications)
- III/V and other wide bandgap semiconductor materials (e.g. SiC), integration on silicon and their use for power electronics

Activity field 3: Integration Technologies and Manufacturing

- 2D and 3D printing technologies for heterogeneous system integration and rapid manufacturing
- Robust integration of multi-component systems (sensors, actuators, electronics, communication, energy supply (including fluidics and photonics)
- Key technology areas (printing, etching, coating, etc.)
- Manufacturing & health monitoring tools (including tests, inspection and self-diagnosis) for components
- Quantum sensors and associated integration

14.6.
MAJOR CHALLENGE 6: PROVIDING EFFECTIVE MODULE INTEGRATION FOR HIGHLY DEMANDING ENVIRONMENTS

The main R&D&I activities in the three identified categories (high priority R&D&I areas) of Major Challenge 6 are:

Activity field 1: Functional Features

- Board-level signal processing and control features for self-diagnosis and self-learning
- Smart power (mini-) modules for low-power sensing/actuation and efficient power transfer
- Low-power sensor nodes for real-time data processing (neuronal networks (low TRL), power saving architecture (mid-TRL …)
- High-performance signal quality in harsh environmental conditions
- Protective housing and coating features (e.g. against chemicals)
- Photonics features like optical sources, paths and connectors integrated into PCB
- Advanced and active cooling systems, thermal management

- EMI optimised boards – TRL dependent on switching frequencies, introduction of wide bandgap materials
- 3D board & module design – TRL dependent on materials, components, etc
- Board-level high-speed communication features (dependent on frequencies, filters, multimode capability, acoustically decoupled FE components, etc)

Activity field 2: Materials

- Heterogeneous integration of new materials for miniaturised sensor & actuator modules
- Recycling and repair of modules
- Transducer materials (e.g. CMOS compatible piezo, e.g. 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
- Materials for flexible devices, flexible "board/stripe", hydrophobic barriers, agent reservoirs, inks for printing, etc
- Materials for coating, potting and overmolding (TRL dependent on temperature levels, etc)
- New thermal interface materials (depends on temperature capabilities, etc)
- New substrate materials at the board level – rigid or flexible – TRL dependent on power, frequencies, applications, single-use, multi-use, long lifetime, etc

Activity field 3: Integration Technologies and Manufacturing

- Transfer printing of heterogeneous components on various substrates
- Heterogeneous 3D integration of sensors, actuators, electronics, communication, and energy supply features for miniaturised modules
- Highly miniaturised engineering and computer technologies with biochemical processes
- Bio-mimicking (bio-hybrids, fluidics)
- Manufacturing & health monitoring tools (including tests, inspection and self-diagnosis) for components
- Direct manufacturing and rapid prototyping
- Automation and customisation ('towards I4.0') in module manufacturing
- Flexible and stretchable devices and substrates; structural electronics
- Chips, passives and packaged components embedded in board
- 3D printing of IC components on top of PCBs
- Monolithic/heterogeneous 3D integration of RF FE components, low vertical form factor (<100 µm), minimisation of external matching networks by integration

14.7. MAJOR CHALLENGE 7: INCREASING COMPACTNESS AND CAPABILITIES BY FUNCTIONAL AND PHYSICAL SYSTEMS INTEGRATION

The main R&D&I activities in the three identified categories (high priority R&D&I areas) of Major Challenge 7 are:

Activity field 1: Physical Systems Integration

- Effective and reliable energy generation, harvesting and transfer
- In-situ monitoring in automation, process industry and medical application
- Biomedical remote sensing
- Low power RF architectures for asset tracking and low data rate communication (e.g. UWB, LoRA)
- System integration of wide bandgap semiconductors
- Improved signal integrity (EMC)Perception techniques
- Modularity and compatibility across development generations (interface definition, standardisation)
- New materials for improved thermal management
- Thermal management at system level
- New materials and concepts for humidity transport into, and out of, the (sensing) systems

Activity field 2: Functional systems integration

- Recycling and repair of systems
- ICT for diverse (material) resource monitoring and prognosis
- Efficient computing architectures for real-time data processing in sensor nodes
- System health management based on PoF models (and not statistical)
- Manufacturing and health monitoring tools (including tests, inspection and self-diagnosis)
- Perception techniques
- Sensor fusion and cyber-physical systems
- Volume reduction (per lot due to customisation) in systems manufacturing
- Data and system safety, security and privacy

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Further reading

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10. E. I. A. -. W. G. SRA, “Strategic Research Agenda,” EPoSS Industry Association, Berlin, 2017

15.2. FURTHER READING FOR CHAPTER 4

- 5G white papers, info graphics
  - https://networks.nokia.com/innovation/5g
  - https://apps.networks.nokia.com/5g/index.html
- AI will change field service:
  http://www.7wdata.be/enterprise-software/4-ways-ai-will-transform-the-field-service-industry/

15.3.
FURTHER READING FOR CHAPTER 5

Several relevant documents are mentioned that provide suggestions for further elaboration:

- AIOTI strategy document, online at https://aioti.eu/
- IERC: the European Research Cluster on the Internet of Things
- "Internet of Things beyond the Hype", online at: http://www.internet-of-things-research.eu/
- The future of cities; Scenarios that show how people may experience cities in 2035, Philips Lighting. Online at http://www.lighting.philips.com/main/systems/connected-lighting/connected-lighting-for-smart-cities/city-scenarios
- Wearable technology and the IoT, Ericsson, online at: https://www.ericsson.com/en/networked-society/trends-and-insights/consumerlab/consumer-insights/reports/wearable-technology-and-the-internet-of-things#thedemographicdivide
- Edelman-Digital-Trends-Report 2017, online at: https://edelmandigital.com/wp-content/uploads/2016/12/2017-Edelman-Digital-Trends-Report.pdf
- State of the Media Industry 2017, Ooyala, on line at: http://go.ooyala.com/rs/447-EQK-225/images/Ooyala-State-of-the-Media-Industry-2017.pdf

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Acronyms used in the document

Acronym	*Meaning*
2D, 2.5D	*2-Dimensional, 2.5-Dimensional (dice located near each other on a TSV silicon interposer, as opposed to 3D integration scheme)*
3D, 3D-IC, 3D IPs	*3-Dimensional, 3-Dimensional Integrated Circuit (dice stacked upon each other), 3-Dimensional Intellectual Property*
5G	*5th Generation wireless communication network*
AC/DC	*Alternating current to Direct Current*
AD	*Automated Driving*
ADAS	*Advanced Driver Assistance System*
AI	*Artificial Intelligence*
AIOTI	*Alliance for Internet of Things Innovation*
AR	*Augmented Reality*
AUTOSAR	*AUTomotive Open System Architecture*
A&P	*Assembly and Packaging*
BCI	*Brain Computer Interface*
BIST	*Build-In Self-Test*
CMOS	*Complementary Metal Oxide Semiconductor*
CNT	*Carbon Nano Tubes*
CoO	*Cost of Ownership*
COTS	*Components of the Shelf*
CPPS	*Cyber Physical Production Systems*
CPS	*Cyber-Physical System*
DC/AC	*Direct Current to Alternating current*
DDoS	*Distributed Denial of Service*
DfR	*Design for Reliability*
DfT	*Design for Test*
DfX	*Design for X, where X can stand for Manufacturing, Reliability, Testability, etc... Alternatively, it can denote Design for Excellence (depending on context)*
DoE	*Design of Experiment*
DRAM	*Dynamic Random-Access Memory*
DRM	*demand/response management*
DSL	*Domain Specific Language*
DSP	*Digital Signal Processor*
DUV	*Deep Ultra Violet*
ECS	*Electronic Component(s) and System(s)w*
EDA	*Electronic Design Automation*
Edge computing	*Performing data processing at the edge of the network, near the source of the data*
EE	*Electric and Electronics*

EMC	*Electro-Magnetic Compatibility*
EMI	*Electromagnetic interference*
ESD	*Electrostatic discharge*
ETSI	*European Telecommunications Standards Institute*
EUV	*Extreme Ultra Violet*
EV	*Electric Vehicles*
eWLB	*Embedded Wafer Level Ball grid array*
E&M	*Equipment and Material*
FD-SOI	*Fully Depleted Silicon-On-Insulator*
FEM	*Finite Element Method*
FPGA	*Field-programmable gate array*
GALS	*Globally asynchronous locally synchronous*
GaN	*Gallium nitride*
GDP	*Gross Domestic Product*
GPS	*Global Positioning System*
GPU	*Graphics Processing Unit*
GSM	*Global System for Mobile Communications*
HMI	*Human Machine Interface*
HPC	*High-Performance Computing*
HPU	*Holographic Processing Unit*
HW	*Hardware*
HW/SW	*Hardware / Software*
IC	*Integrated Circuit*
ICT	*Information and Communication Technologies*
IEA	*International Energy Agency*
IERC	*the European Research Cluster on the Internet of Things*
IGBT	*Insulated-Gate Bipolar Transistor*
III-V	*Chemical compound of materials with 3 and 5 electrons in the outer shell respectively*
iNEMI	*International Electronics Manufacturing Initiative*
IoT	*Internet of Things*
IP	*Intellectual Property / Internet Protocol (depending on context)*
IRDS	*International Roadmap for Devices and Systems*
ITAR	*International Traffic in Arms Regulations*
ITRS	*International Technology Roadmap for Semiconductors*
ITU	*International Telecommunication Union*
KET	*Key Enabling Technologies*

LAE	*Large Area Electronics*
LE	*Large Enterprise*
LED	*Light-emitting diode*
LoC	*Lab on Chip*
LoRa	*Long Range digital wireless communication*
LV	*Low Voltage*
M2M	*Machine to Machine*
MC	*Major Challenge*
MDM	*Multi-Dimensional Metrology*
MEMS	*Micro Electro Mechanical Systems*
MEPS	*Minimum Energy Performance Standards*
MIL	*United States Military Standard*
ML	*Machine Learning*
MM	*More Moore*
MMI	*Machine to Machine Interface*
MNBS	*Micro Nano Bio System*
MOEMS	*Micro-Opto-Electro-Mechanical System*
MR	*Mixed Reality*
MtM	*More than Moore*
MV	*Medium Voltage*
NAND	*Negative-AND is a logic gate which produces an output which is false only if all its inputs are true*
NEMS	*Nano Electro Mechanical Systems*
NIS	*Network and Information Systems*
NoCs	*Network on Chips*
NVM	*Non-Volatile Memory*
OEM	*Original Equipment Manufacturer*
OSAS	*Obstructive Sleep Apnea Syndrome*
PAD	*Productivity Aware Design*
PCB	*Printed Circuit Board*
PCRAM	*Phase Change Random Access Memory*
PE-ALD	*Plasma Enhanced Atomic Layer Deposition*
PFSI	*Physical and Functional Systems Integration*
PHM	*Prognostic Health Management*
PIII	*Plasma-immersion ion implantation*
PMIC	*Power Management Integrated Circuit*
PoC	*Point of Care or Proof of Concept (depending on context)*

PoF	*Physics of Failure*
PSD2	*The revised European Payment Services Directive*
PV	*Photo Voltaic*
QIP	*Quantum Information Processing*
RDL	*Redistribution Layer*
R&D&I	*Research and Development and Innovation*
RF	*Radio Frequency*
RRAM	*Resistive Random-Access Memory*
Safety	*Protecting from any malfunction that might occur*
SCM	*Storage Class Memory: A non-volatile memory technology that is capable of replacing hard disks.*
SDN	*Software Defined Network*
Security	*Protection from the negative influences of the outside world*
SiP	*System in Package*
Si-Photonics	*Silicon-Photonics is the study and application of photonic systems which use silicon as an optical medium.*
SME	*Small and Medium Enterprise*
SMTBF	*System Mean Time Between Failures*
SoA	*Safe operating Area*
SoC	*System on Chip*
SoS	*System of Systems*
SRA	*Strategic Research Agenda*
SSI	*Smart System Integration*
STDP	*Spike-Timing-Dependent Plasticity*
STEM	*Science, Technology, Engineering and Mathematics / Scanning Transmission Electron Microscopy (depending on context)*
STT-RAM	*Spin-transfer torque random-access memory*
SW	*Software*
TAM	*Total Available Market*
TEV	*Through Encapsulant Via*
TIM	*Thermal Interface Materials*
TRL	*Technology Readiness Level*
TSV	*Through Silicon Via*
UCTE	*European Network of Transmission System Operators for Electricity*
ULP	*Ultra-Low Power*
UWB	*Ultra Wide Band (communication)*
V&V	*Verification and Validation*
VC	*Venture Capitalist*

VOC	*Volatile Organic Compounds*
VR	*Virtual Reality*
VRE	*variable renewable energy*
WBG	*Wide Bandgap Semiconductors*
WLP	*Wafer Level Packaging*

E C S