Strategic Research and Innovation Agenda 2022

ELECTRONIC
COMPONENTS AND SYSTEMS

Strategic Research and Innovation Agenda 2022

ELECTRONIC COMPONENTS AND SYSTEMS

PREPARED BY:

Aeneas

EPoSS
European Association on Smart Systems Integration

Inside
Industry Association

Graphic design/layout
Studio Kraft – Veldhoven, The Netherlands

Editing
Paolo Azzoni (Inside Industry Association) – Eindhoven, The Netherlands

Copyright © ECS
Permission to reproduce any text for non-commercial purposes is granted, provided that it is credited as source.

January 2022
ecscollaborationtool.eu

CONTENTS

Introduction and overview 13
Goals and purposes of ECS-SRIA 2022 15
How to read it 19
Highlights and common challenges for the next few years 20
Main Common Objective 1: boost industrial competitiveness through interdisciplinary technology innovations 20
Main Common Objective 2: ensure EU digital autonomy through secure, safe and reliable ECS supporting key European application domains 21
Main Common Objective 3: establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal 21
Main Common Objective 4: unleash the full potential of intelligent and autonomous ECS-based systems for the European digital era 22
Ensure engineering support across the entire lifecycle of complex ECS-based systems 22
ECS-SRIA and its position in the technology landscape 27
The ECS-SRIA outline 27

1 Foundational Technology Layers 31

1.1 PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING 33
1.1.1 Scope 35
1.1.2 Technology-enabled societal benefits 36
1.1.2.1 Application breakthroughs 37
1.1.3 Strategic advantage for the EU 39
1.1.4 Major Challenges 41
1.1.4.1 Major Challenge 1: advanced computing, memory and in-memory computing concepts 41
1.1.4.2 Major Challenge 2: novel devices and circuits that enable advanced functionality 44
1.1.4.3 Major Challenge 3: advanced heterogeneous integration and packaging solutions 49
1.1.4.4 Major Challenge 4: world-leading and sustainable semiconductor manufacturing equipment and technologies 52
1.1.5 Timeline 57
1.1.6 Synergy with other themes 64

1.2 COMPONENTS, MODULES AND SYSTEMS INTEGRATION 67
1.2.1 Scope 69
1.2.2 Technology-enabled societal benefits 71
1.2.2.1 Application breakthroughs 73
1.2.3 Strategic advantage for the EU 74
1.2.4 Major Challenges 75
1.2.4.1 Major Challenge 1: physical and functional integration 75
1.2.4.2 Major Challenge 2: materials for integration 77
1.2.4.3 Major Challenge 3: technologies, manufacturing and integration processes 80
1.2.4.4 Major Challenge 4: sustainability and recyclability 82
1.2.5 Timeline 84
1.2.6 Synergy with other themes 90

1.3 EMBEDDED SOFTWARE AND BEYOND 93
1.3.1 Introduction 95
1.3.2 Scope 96
1.3.3 Technology-enabled societal benefits 98
1.3.4 Strategic advantage for the EU 101
1.3.5 Major Challenges 101
1.3.5.1 Major Challenge 1: efficient engineering of embedded software 102
1.3.5.2 Major Challenge 2: continuous integration and deployment 107
1.3.5.3 Major Challenge 3: lifecycle management 109
1.3.5.4 Major Challenge 4: embedding data analytics and artificial intelligence 111
1.3.5.5 Major Challenge 5: support for sustainability by embedded software 113
1.3.5.6 Major Challenge 6: software reliability and trust 115
1.3.6 Timeline 117
1.3.7 Synergy with other themes 122

1.4 SYSTEM OF SYSTEMS 125
1.4.1 Scope 127
1.4.2 Technology-enabled societal benefits 129
1.4.2.1 Application breakthroughs 130
1.4.3 Strategic advantage for the EU 132
1.4.4 Major Challenges 134
1.4.4.1 Major Challenge 1: SoS architecture and open integration platforms 134
1.4.4.2 Major Challenge 2: SoS interoperability 140
1.4.4.3 Major Challenge 3: evolvability of SoS composed of embedded and cyber-physical systems 142
1.4.4.4 Major Challenge 4: system of embedded and cyber-physical systems - SoECPS - engineering 144
1.4.4.5 Major Challenge 5: control in SoS composed of embedded and cyber-physical systems 146
1.4.4.6 Major Challenge 6: SoS monitoring and management 147
1.4.5 Timeline 148

2 Cross-Sectional Technologies 157

2.1 EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE 159
2.1.1 Scope 161
2.1.1.1 Introduction 161
2.1.1.2 Positioning edge and cloud solutions 162
2.1.1.3 Positioning Embedded Artificial Intelligence 165
2.1.1.4 Scope of the Chapter 166
2.1.1.5 State of the Art 167
2.1.2 Technology-enabled societal benefits 171
2.1.3 Applications breakthroughs 173
2.1.4 Strategic advantage for the EU 175
2.1.5 Major Challenges 177
2.1.5.1 For Edge Computing 177
2.1.5.2 For Embedded Intelligence 178
2.1.5.3 Major Challenge 1: increasing the energy efficiency of computing systems 179
2.1.5.4 Major Challenge 2: managing the increasing complexity of systems: 186
2.1.5.5 Major Challenge 3: supporting the increasing lifespan of devices and systems 190
2.1.5.6 Major Challenge 4: ensuring European sustainability 194
2.1.6 Timeline 197
2.1.7 Synergy with other themes 204

2.2 CONNECTIVITY 207

2.2.1 Scope 209

2.2.1.1 Scope for OSI layer 1 209

2.2.1.2 Scope for OSI layer 5 and 6 209

2.2.2 Technology-enabled societal benefits 211

2.2.2.1 Applications breakthroughs 212

2.2.3 Strategic advantage for the EU 214

2.2.4 Major Challenges 215

2.2.4.1 Major Challenge 1: strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain 216

2.2.4.2 Major Challenge 2: investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership 219

2.2.4.3 Major Challenge 3: autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics 222

2.2.4.4 Major Challenge 4: architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity 224

2.2.4.5 Major Challenge 5: network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures 225

2.2.5 Timeline 226

2.3 ARCHITECTURE AND DESIGN: METHODS AND TOOLS 233

2.3.1 Scope 235

2.3.2 Technology-enabled societal benefits 237

2.3.3 Strategic advantage for the EU 238

2.3.4 Major Challenges 239

2.3.4.1 Major Challenge 1: extending development processes and frameworks (to handle connected, intelligent, autonomous, evolvable systems) 240

2.3.4.2 Major Challenge 2: managing new functionality in safe, secure and trustworthy systems 243

2.3.4.3 Major Challenge 3: managing complexity 246

2.3.4.4 Major Challenge 4: managing diversity 248

2.3.5 Timeline 250

2.3.6 Synergy with other themes 254

2.4 QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY 257

2.4.1 Scope 259

2.4.2 Technology-enabled societal benefits 260

2.4.3 Strategic advantage for the EU 261

2.4.4 Major Challenges 261

2.4.4.1 Major Challenge 1: ensuring HW quality and reliability 262

2.4.4.2 Major Challenge 2: ensuring dependability in connected software 267

2.4.4.3 Major Challenge 3: ensuring cyber-security and privacy 269

2.4.4.4 Major Challenge 4: ensuring of safety and resilience 272

2.4.4.5 Major Challenge 5: human systems integration 274

2.4.5 Timeline 277

2.4.6 Synergy with other themes 282

3 ECS Key Application Areas 285

3.1 MOBILITY 287

3.1.1 Scope 289
3.1.2 Major Challenges – overview 290
3.1.3 Automotive trends and societal benefits 291
3.1.4 Major Challenges 293
3.1.4.1 Major Challenge 1: enable electrification and sustainable alternative fuels for CO_2-neutral mobility 294
3.1.4.2 Major Challenge 2: enable affordable safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, drones, etc) and mobile machinery (as smart farming) 296
3.1.4.3 Major Challenge 3: enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water 298
3.1.4.4 Major Challenge 4: provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility 300
3.1.4.5 Major Challenge 5: achieve real-time data handling for multimodal mobility and related services 303
3.1.5 Requirement overview 305
3.1.6 Timeline 306
3.1.7 Synergy with other themes 308

3.2 ENERGY 311

3.2.1 Scope 313
3.2.1.1 Change towards the carbon neutral society and challenges for ECS 313
3.2.2 Application trends and societal benefits 314
3.2.2.1 Application trends 314
3.2.3 External requirements and Societal Benefits 316
3.2.4 Strategic advantage for the EU 318
3.2.5 Major Challenges 319
3.2.5.1 Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems 320
3.2.5.2 Major Challenge 2: Energy Management from On-Site to Distribution Systems 323
3.2.5.3 Major Challenge 3: Future Transmission Grids 325
3.2.5.4 Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply 327
3.2.5.5 Major Challenge 5: Cross-Sectional Tasks for Energy System Monitoring & Control 330
3.2.6 Timeline 333
3.2.7 Synergy with other topics 338

3.3 DIGITAL INDUSTRY 341

3.3.1 Scope 343
3.3.2 Application trends and societal benefits 344
3.3.3 Strategic advantage for the EU 345
3.3.4 Major Challenges 347
3.3.4.1 Major Challenge 1: responsive and smart production 347
3.3.4.2 Major Challenge 2: sustainable production 350
3.3.4.3 Major Challenge 3: Artificial Intelligence in digital industry 352
3.3.4.4 Major Challenge 4: industrial service business, lifecycles, remote operations and teleoperation 356
3.3.4.5 Major Challenge 5: digital twins, mixed or augmented reality, telepresence 358
3.3.4.6 Major Challenge 6: autonomous systems, robotics 360
3.3.5 Requirement overview 364
3.3.6 Timeline 365

3.3.7 Synergy with other themes ... 368
3.3.7.1 About engineering tools ... 368
3.3.7.2 About trust, security, cybersecurity, safety, privacy ... 368
3.3.7.3 About digital platforms, application development frameworks and SoS ... 369

3.4 HEALTH AND WELLBEING ... 371
3.4.1 Scope ... 373
3.4.2 Application trends and societal benefits ... 374
3.4.2.1 External requirements ... 374
3.4.2.2 Societal benefits ... 375
3.4.3 Strategic advantage for the EU ... 379
3.4.4 Major Challenges ... 380
3.4.4.1 Major Challenge 1: enable digital health platforms based upon P4 healthcare ... 380
3.4.4.2 Major Challenge 2: enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies ... 382
3.4.4.3 Major Challenge 3: support the development of the home as the central location of the patient, building a more integrated care delivery system ... 385
3.4.4.4 Major Challenge 4: enhance access to personalised and participative treatments for chronic and lifestyle-related diseases ... 387
3.4.4.5 Major Challenge 5: ensure more healthy life years for an ageing population ... 388
3.4.5 Timeline ... 390
3.4.6 Synergy with other themes ... 394

3.5 AGRIFOOD AND NATURAL RESOURCES ... 397
3.5.1 Scope ... 399
3.5.2 Application trends and societal benefits ... 399
3.5.3 Strategic advance for the EU ... 401
3.5.4 Major Challenges ... 404
3.5.4.1 Major Challenge 1: Food Security ... 404
3.5.4.2 Major Challenge 2: food safety ... 406
3.5.4.3 Major Challenge 3: environmental protection and sustainable production ... 409
3.5.4.4 Major Challenge 4: water resource management ... 412
3.5.4.5 Major Challenge 5: biodiversity restoration for ecosystems resilience, conservation and preservation ... 415
3.5.5 Timeline ... 417
3.5.6 Synergy with other themes ... 423

3.6 DIGITAL SOCIETY ... 425
3.6.1 Scope ... 427
3.6.2 Application trends and societal benefits ... 427
3.6.2.1 External requirements ... 427
3.6.2.2 Societal benefits ... 428
3.6.3 Strategic advantage for the EU ... 431
3.6.4 Major Challenges ... 432
3.6.4.1 Major Challenge 1: facilitate individual self-fulfillment ... 433
3.6.4.2 Major Challenge 2: facilitate empowerment and resilience ... 437
3.6.4.3 Major Challenge 3: facilitate inclusion and collective safety ... 439
3.6.4.4 Major Challenge 4: facilitate supportive infrastructure and a sustainable environments ... 444
3.6.5 Timeline ... 447
3.6.6 Synergy with other themes ... 450

4 Long-Term Vision 453

4.1 INTRODUCTION 455

4.2 MODEL 458

4.3 TECHNOLOGY LONG-TERM CHALLENGES/VISION 459

4.3.1 Process technology, equipment, materials and manufacturing 459
4.3.2 Components, modules and systems integration 461
4.3.3 Embedded software and beyond 462
4.3.4 System of Systems 464
4.3.5 Edge Computing and embedded artificial intelligence 464
4.3.6 Connectivity 467
4.3.7 Architecture and design: methods and tools 469
4.3.8 Quality, reliability, safety and cybersecurity 470

4.4 APPLICATION EVOLUTION AND LONG-TERM CHALLENGES 472

4.4.1 Mobility 472
4.4.2 Energy 474
4.4.3 Digital industry 475
4.4.4 Health and wellbeing 478
4.4.5 Agrifood and natural resources 480
4.4.6 Digital society 482

4.5 CONCLUSIONS 483

Appendix 485

GLOSSARY 486

Introduction 487
SRIA definitions 487

ACRONYMS USED IN THE DOCUMENT 498

LIST OF CONTRIBUTORS 508

MAIN OBJECTIVES: AN ANALYSIS OF ALL MAJOR CHALLENGES 524

Keywords index 531

Strategic Research and Innovation Agenda 2022

INTRODUCTION AND OVERVIEW

GOALS AND PURPOSES OF ECS-SRIA 2022

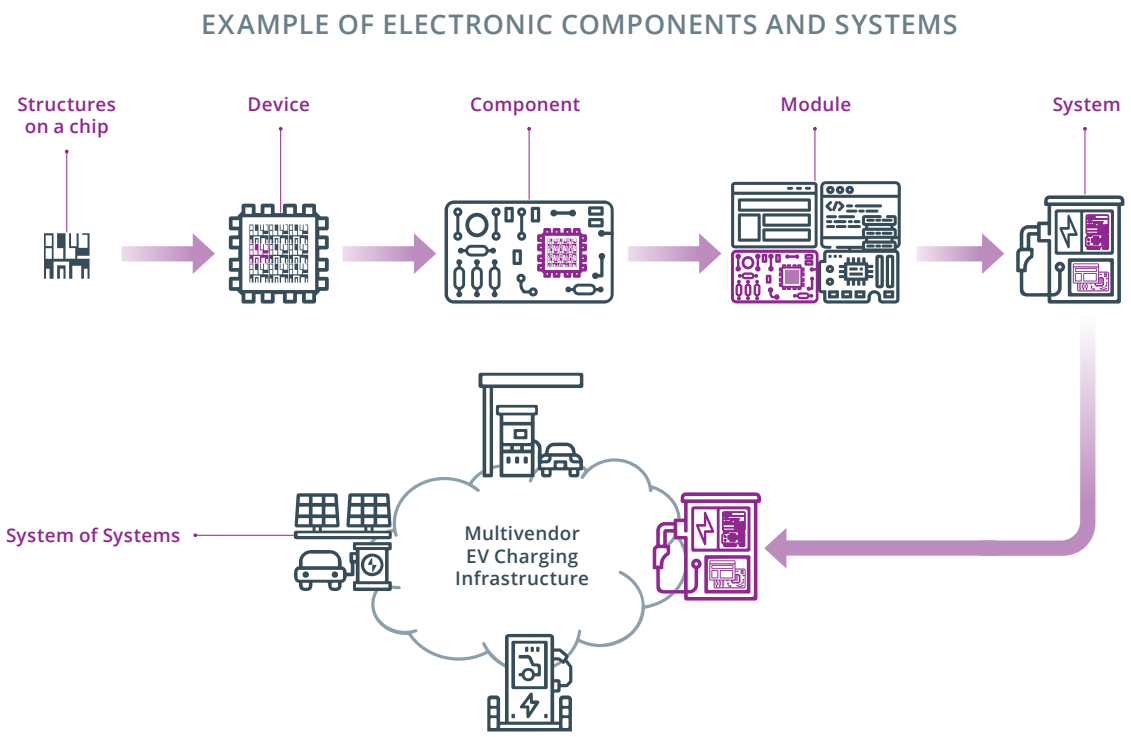
This is the fifth edition of the ECS Strategic Research and Innovation Agenda (ECS-SRIA), jointly developed by members of three industry associations: **AENEAS**, **Inside Industry Association** (formerly ARTEMIS-IA) and **EPOSS**. This revision of the ECS-SRIA 2021 was conducted with the goal to further improve the delineation of the concepts introduced in 2021, the alignment between chapters and to introduce new topics identified during the six thematic workshops organized in May and June 2021. Especially the Chapter 2.1 has been restructured to better delineate the areas of Edge computing and Artificial Intelligence, and their convergence towards Embedded Intelligence on the Edge. Starting from Chapter 2.1, the scope of advanced control has been widened to System of Systems and included in Chapter 1.4, which has been re-organised and extended to cover monitoring, control and management of System of Systems. Chapter 4, Long Term Vision, has been restructured to illustrate the long-term vision of the domains covered by each Chapter of the ECS-SRIA 2022. Finally, a single-diagram outline of the ECS-SRIA has been included, to clarify the roles of the chapters, the technology domains they cover and the synergies between them, simplifying the comprehension of the ECS-SRIA and its "navigation". To improve this further, cross-references have been introduced in the margin of pages to highlight links between chapters.

Why this ECS-SRIA?

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

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

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



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

Designing such artefacts requires an interdisciplinary hierarchical approach, whereby various ECS specialists are working at different abstraction levels. As a result, the same term can have different meanings for specialists of different ECS domains: for instance, a "system" designed and implemented within a given development process may be integrated as a "component" into a higher-level "system" within another development step of the engineering process. Nevertheless, to avoid confusion, this year the ECS-SRIA includes a glossary, to be found in Annex page 482, where many of the key terms are defined to avoid inconsistency across the various chapters. It was also felt that developing a common language was important in building a strong and integrated ECS community. In addition, some of the bricks of the ECS technology "stack" are further detailed below.

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

- Component: a combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case.

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

A component is not self-contained in all its functions, as it requires the close support of other components for operation (e.g. in data processing, power handling, embedded software).

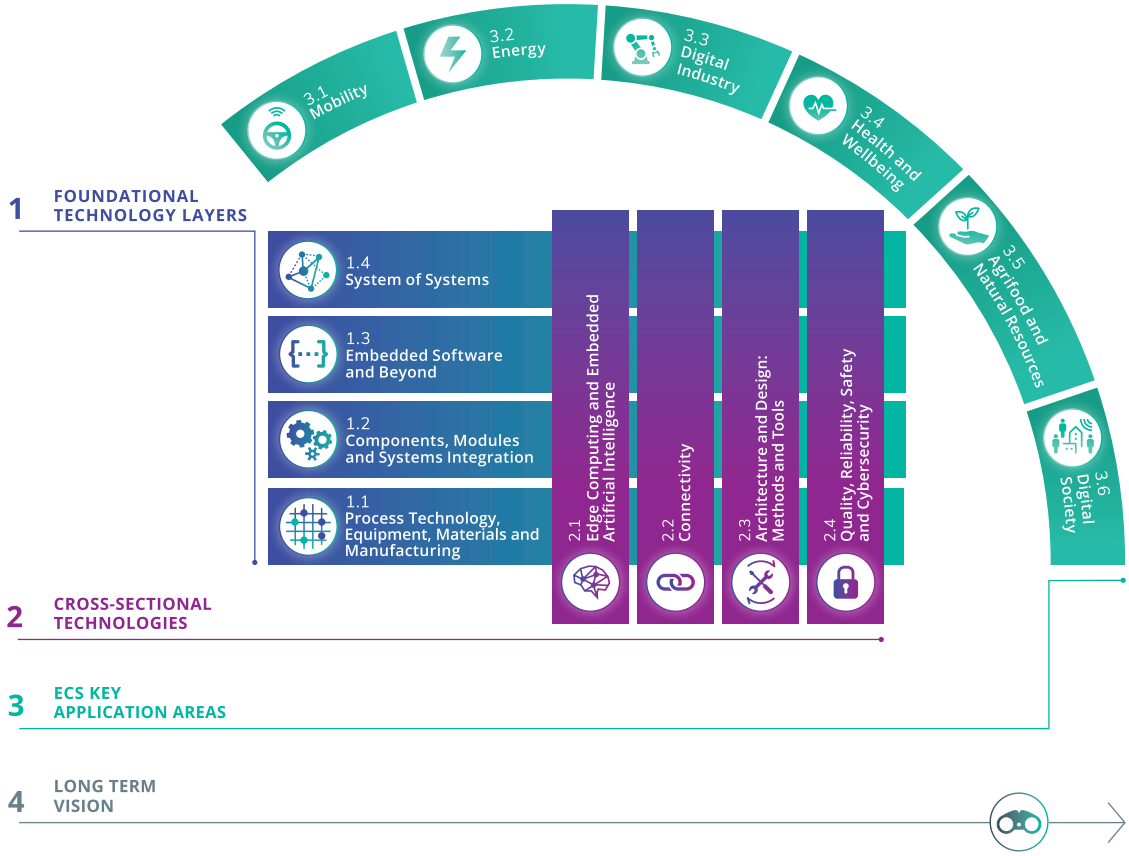
- Module: a combination of correctly integrated components in which their assembly embodies a specific functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and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

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

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

The structure

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



F.2 *The structure of the ECS-SRIA*

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

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

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

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

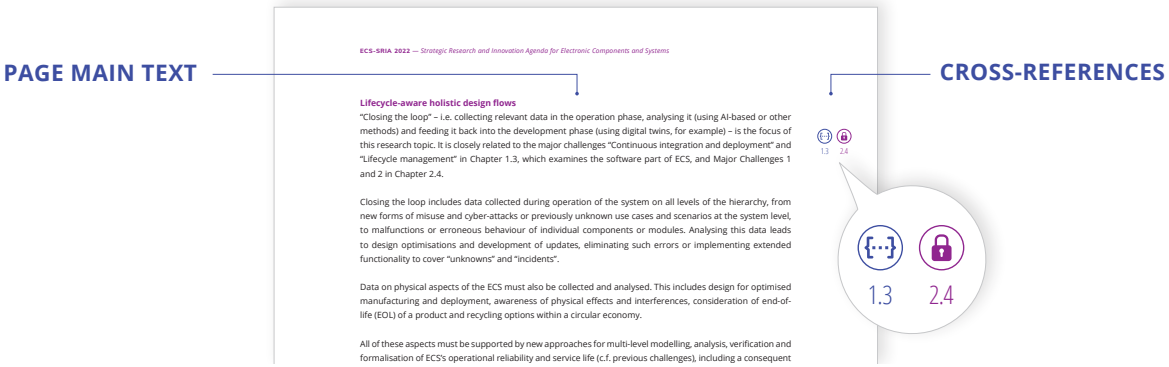
HOW TO READ IT

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

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

A **Glossary** describing the terms used in the document, as well as a List of **Acronyms** used in the document, can be found in the **Appendix**. An **Analytical Index** contains the key concepts covered in the ECS-SRIA and simplifies the "navigation" of the document. At the end, the reader can also find a List of **Contributors** who collectively wrote this ECS-SRIA.

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



Cross-references consist of the Chapter icon and number and appear alongside the text. They indicate that the topic or concept described in the text is also addressed, or used, or deepened, or complemented, or is simply linked to the referenced Chapter.

HIGHLIGHTS AND COMMON CHALLENGES FOR THE NEXT FEW YEARS

In this ECS-SRIA, the Major Challenges identified by the different Chapter teams were analysed and merged into four Main Common Objectives for the ECS community. In addition, three common Roadmaps covering the short term (up to 2026), medium term (until 2031) and the long term (2032 and beyond) provide the key milestones derived by the Chapter teams.

Main Common Objectives

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

Across this document, 68 different Major Challenges are identified that have emerged from the analysis of the foundational technologies, the cross-sectional technologies and the application key areas. The Major Challenges are frequently interdependent – they influence each other, become increasingly demanding, and impact on many areas, including technology innovation, industrial competitiveness, security, safety, business and environmental sustainability, society, etc. From this perspective, the Major Challenges represent key factors for the achievement of the four Main Common Objectives, which are aligned with the European Commission's strategic priorities (see table in Appendix, page 526).

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

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

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

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

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

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

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

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

They will simplify the implementation of the European Strategy for Data [2, 3], and ensure security, privacy-by-design and strategic autonomy all along the industrial and digital value chains. Such technological innovation will also enable the design and development of secure, safe, reliable, dependable, privacy-compliant electronic components and systems, as well as generate new requirements that will drive the development of new technologies, restarting the cycle.

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

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

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

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

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

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

- Relying extensively on ECS-based technologies and digitalisation as key factors for lowering our global energy footprint at all the levels of the economy, and by placing sustainability at the heart of combined digital and green transitions.
- Positioning the European players in hardware as front-runners in sustainability to secure a wider market so they can become world leaders. This will need to consider the circular economy, new

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

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

market positioning (by turning small market shares into specialisation areas), the environmental impact of global manufacturing, etc.

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

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

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

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

As discussed, modern digitalisation systems are complex, and heterogeneous solutions are increasingly based on ECS. Therefore, they cannot be considered as real products without the appropriate engineering support across the entire lifecycle, from requirements analysis to design, development, deployment/commissioning, operation/management, remote-maintenance repair and overhaul, retirement/recycling and evolution.
Engineering support represents a key factor for achieving the four Main Objectives as it:

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

The ECS global timeline for Europe

The ECS-SRIA 2022 lists a number of milestones to be reached in the short term (2022–2026), medium term (2027–2031) and long term (2032 and beyond) via collaborative research projects across Europe, reflecting the ambition of the ECS industry towards the achievement of the four Main Objectives identified above. The diagrams (pages 24-26) position some of the most salient of these milestones onto the European ECS roadmap.

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

- **Short term (2022–2026)**
  The industry has a precise idea of what will be achieved during that timeframe.
- **Medium term (2027–2031)**
  There is still reasonably good knowledge of what can possibly be achieved.
- **Long term (2032 and beyond)**
  Expected achievements are more of a prospective nature.

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

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

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

GLOBAL TIMELINE: SHORT TERM 2022–2026

- System of Systems reference architecture and implementation platforms

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

- Physical and chemical sensors and imaging and image-based detection
- Materials enabling recycling and repair
- Additive manufacturing, rapid prototyping, heterogeneous integration in multiple levels

- Semiconductor equipment for 2nm node for logic and memory
- ULP 18nm FDSOI technology
- 3D heterogeneous integration
- Devices enabling 5G connectivity

- Development of new neuromorphic computing technologies and devices
- Leveraging open source or alternatives to develop advanced European AI Edge solutions
- Energy-efficient and „green" AI-based design techniques for inference/learnings

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

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

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

- EV passenger car
- Energy-optimized EV urban and H_2 long distance mobility
- Driver assisted and partially automated mobility
- V&V procedures for partially automated mobility

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

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

- Internet of medical things for patient generated data

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

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

F.3 *Global Timeline: Short term 2022–2026*

GLOBAL TIMELINE: MEDIUM TERM 2027–2031

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

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

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

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

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

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

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

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

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

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

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

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

- Food traceability over the whole value chain
- Improved electrochemical sensors for natural resources quality monitoring
- AI for automatic decisions based on agronomic models and algorithms

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

Global Timeline: Medium term 2027–2031

F.4

GLOBAL TIMELINE: LONG TERM 2032 AND BEYOND

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

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

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

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

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

- Autonomous interopera-bility: from physical layer to instant information understanding

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

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

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

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

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

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

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

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

F.5 *Global Timeline: Long term 2032 and beyond*

ECS-SRIA AND ITS POSITION IN THE TECHNOLOGY LANDSCAPE

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

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

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

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

THE ECS-SRIA OUTLINE

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

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

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

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

CROSS-SECTIONAL TECHNOLOGIES

FOUNDATIONAL TECHNOLOGY LAYERS		2.1 - EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE	2.2 - CONNECTIVITY	2.3 - ARCHITECTURE AND DESIGN: METHODS AND TOOLS	2.4 - QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
		Hardware architectures and their implementation (Systems of Chips, Embedded architectures), for edge and "near the user" devices. Generic technologies for compute, storage and communication (generic embedded architectures) and technologies that are more focused towards edge computing. Technologies for devices using Artificial Intelligence at the edge.	The connectivity and interoperability technology is focused on enabling the projected commercial and societal benefits that are related to the OSI model layers 1, 5 and 6.	Innovations, advancements and extensions in architectures, design processes and methods, and in corresponding tools and frameworks, that are enabling engineers to design and build innovative ECS-based applications with the desired quality properties, efficiently and cost effectively.	Ensure quality, reliability, safety, dependability, privacy and security of ECS as a part of the Design, Implementation, and Validation/ Testing process of complex, heterogeneous and intelligent ECS, including human-systems interaction.
1.4 - SYSTEM OF SYSTEMS	System of Systems (SoS) enable the cooperation, orchestration, management, control and evolution of an entire system composed of embedded and cyber-physical systems (ECPS). This layer covers SoS architecture, technologies to securely and safely compose ECPS in SoS, ECPS and SoS interoperability, advanced control, and open, secure and interoperable SoS platforms, supported by SoS full lifecycle automated engineering.	Artificial intelligence to automatically manage the composition of ECPS in SoS and control their evolution. Artificial intelligence to improve/ automate interoperability. Distributed artificial intelligence to provide the level of automation required to monitor, to support decision making and to control the complexity of SoS.	Connectivity is a key enabler for SoS which, by definition, are composed of connected and distributed ECPS. Connectivity channels and their interfaces are at the base of the composition process from which SoS originate.	Engineering methodologies, tool chains and tools interoperability are fundamental to enable the definition of SoS architectures, the implementation of SoS platform and SoS management across their lifecycle. The heterogeneity of SoS requires automated engineering processes and toolchains, integrated between multiple stakeholders, brands and technologies, supporting efficiency, quality and sustainability.	End-to-end trust (security, privacy, reliability, etc.) covering the entire edge to cloud continuum (trust continuum) is a key factor for SoS. Trust must be preserved during the composition of ECPS in SoS and must be ensured during their evolution. Security, privacy, reliability, etc. must scale following the complexity of SoS, which requires automation to efficiently manage trust.
1.3 - EMBEDDED SOFTWARE AND BEYOND	Facilitate engineering of embedded and cyber physical systems (ECPS), enabling digitalisation through the feasible and economically accountable building of larger software-enabled systems with desired quality . This layer covers new applications of ECPS, continuous integration and deployment, ECPS engineering and management across their lifecycle, including sustainability aspects. Starting from integrated hardware systems, this layer provide the embedded software (OS, libraries, virtualisation, middleware, etc.) required to produce fully functioning embedded and cyber physical systems.	Embedded software represents one of the key enablers of embedded intelligence. Embedding data analytics and artificial intelligence in devices allow to process data on the edge, take decision on the edge, optimise operations, dynamically adapt and improve the cooperation between ECPS and sustainability. This layer provides also software support for AI-specific hardware, machine learning and federated intelligence on the edge.	ECPS are, for the vast majority, connected and this layer provides them with all the elements required to ensure field connectivity, inter-system communications and the capability to interact with cloud platforms. These elements are key to enable the composition of ECPS in SoS, and also for the inclusion of legacy systems.	Software engineering is exceeding the human scale, meaning it can no longer be overseen by a human without supporting tools: current and future ECPS, due to their complexity, require continuous hardware-software integration, both at component and system level. Continuous and automated engineering extends also to ECPS deployment and to their entire lifecycle. These necessities increase when considering embedded AI and new computing paradigms (e.g. neuromorphic).	Trust represents one the strongest barriers for the acceptance of ECPS and it must be ensured in embedded software, in particular for embedded AI. Trust should be ensured by design, and by ensuring it becomes an interdisciplinary solution because, at this level, many technology aspects converge in a single system: hardware, different layers of software, connectivity, development tools, etc. The quality of embedded software also plays a key role in ECPS.
1.2 - COMPONENTS, MODULES AND SYSTEMS INTEGRATION	Multidomain engineering for physical and functional heterogeneous integration of several functionalities into new physical entities at components, modules and system levels. Heterogeneous integration spans SoC, System-in-Package and larger modules and systems, including flexible electronics and photonics solutions. This layer generates hardware integrated systems including low level software (e.g. firmware and operating system drivers).	Smart components, modules and systems are the hardware key enablers for the embedded intelligence. The focus is on integrating machine learning and artificial intelligence on the sensor, module and systems level. New advanced, efficient and specialized processing architectures (based on CPU, embedded GPU, accelerators, neuromorphic computing, FPGA and ASICs) to increase the edge computing performances and reduce power consumption. Low level software support to enable AI-based data analytics is provided.	Connectivity solutions (communication modules & interfaces) that are needed in networked embedded and cyber physical systems (ECPS). Focus is on providing real-time, low-latency, low-power for edge and IoT devices, photonics communications, high-speed 5G and beyond 5G/6G connectivity, and quantum technology preparing the path towards the quantum internet.	Design and simulation methods that enable and support multi-physics and multimodal design, simulation, manufacturing and testing must be addressed (e.g. modelling and design tools for thermal, mechanical and electrical characteristics in small 3D packages). Focus cover also lifecycle engineering for optimized use for materials, for components, modules and systems condition monitoring, predictive maintenance, and to improve their recyclability.	Growing complexity of smart components, modules and systems represents a reliability challenge which requires the continuous improvement of existing methods (e.g. design for reliability) and development of new techniques (e.g. prognostic health management) for reliable ECS. The area also focuses on solutions for ensuring secure integration of systems, sensor level hardware and software security, privacy and data trustworthiness and AI Hardware safety.
1.1 - PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURIN	Semiconductor process technology, equipment, materials and manufacturing form the base of the ECS value chain and, from Single chip (e.g. Si, more Moore), more than Moore technologies (photonics, MEMS/Sens, Bio, etc.) and System on a Chip, they produce the chips (Packaged Single Chip, System in a Package, Packaged SoC) and packaged chip-level building blocks (SoC and Single Chip, Packaged Devices in Board) for all digital applications.	AI adoption covers both the electronic components and their manufacturing process. Add intelligence close to the sensors (Intelligence at the edge) and/or to the data sources (IoT), and integrate the components in a form factor that perfectly suits their applications. Use AI in the operation of semiconductor fabrication, to master complexity, increase reliability, shorten time to stable yield, improve quality, productivity, sustainability, resource saving volume production of semiconductors	Provide process technologies and electronic components required for ECS hyper-connectivity, including 5G/6G communications, advanced RF and photonics communication technologies to interface between semiconductors components, subsystems and systems.	Electronic design and automation methods and tools required to support the use of nanomaterials and metamaterials, the design and manufacturing process of future nano-scale semiconductors and electronic components, including assembly and packaging of electronics on flexible substrates. Production tools for heterogeneous integration and to support flexible, sustainable, agile and competitive high-volume high- quality semiconductor manufacturing are also considered.	End to end security starts from semiconductors. New technologies to address security at silicon level are considered, including application-specific logic, heterogeneous SoC, security by design, etc. Quality and reliability in the semiconductor production are also considered, focusing on maximising quality KPIs, monitor the process with AI, early detect yield/reliability issues, qualify the parameters that influence HW reliability, adopt design for reliability, prognostics health management of ECS etc.

KEY APPLICATION AREAS

3.1 - MOBILITY

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

3.2 - ENERGY

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

3.3 - DIGITAL INDUSTRY

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

3.4 - HEALTH AND WELLBEING

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

3.5 - AGRIFOOD AND NATURAL RESOURCES

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

3.6 - DIGITAL SOCIETY

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

LONG TERM VISION

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

1.1
PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING

1.2
COMPONENTS, MODULES AND SYSTEMS INTEGRATION

1.3
EMBEDDED SOFTWARE AND BEYOND

1.4
SYSTEM OF SYSTEMS

1

Strategic Research and Innovation Agenda 2022

FOUNDATIONAL TECHNOLOGY LAYERS

1.1

PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND MANUFACTURING

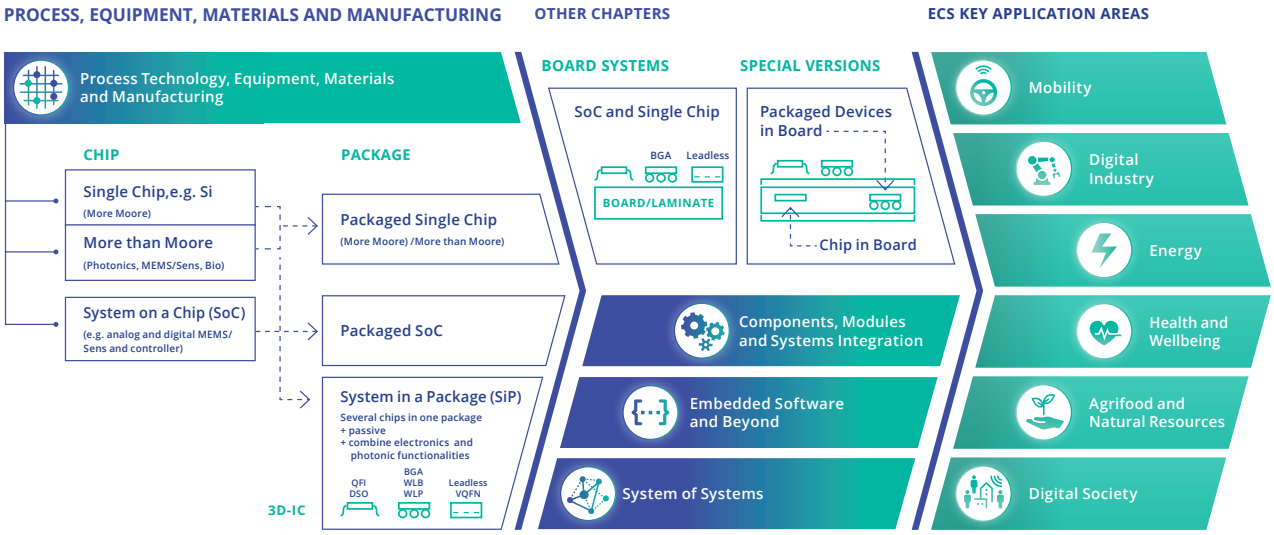
Semiconductor process technology, equipment, materials and manufacturing form the base of the ECS value chain producing the chip and packaged chip-level building blocks for all digital applications.

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

1.1.1 SCOPE

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

- New materials and engineered substrates to improve device performance,
- Process technologies, equipment and manufacturing technology to advance integrated circuit (IC) functionality and/or systems on chips.
- Packaging and integration technologies for chips, chiplets, system on a chip (SoC) and system in a package (SiP).
- Clearly, the scope of this section involves synergies with other sections in this ECS-SRIA. First and foremost, the section links with Components, Modules and System Integration in Chapter 1.2. In addition, this section also links with Embedded Software and System of Systems (SoS) to allow for an integral system technology co-optimisation approach to deliver application-driven solutions. More details about the synergies with other sections are described in Sub-section 1.1.6.



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

F.6

1.1.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

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

European industry in sectors such as healthcare, automotive, energy, smart cities and manufacturing strongly depends on the timely availability of highly specialised electronics devices enabling added value and new functionalities in their products. Moreover, the advances in chips and packaged chips will strongly contribute to Europe's ambition to become climate-neutral by 2050, as promoted by the European Green Deal[7].

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

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

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

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

1.1.2.1 Application breakthroughs

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

In 2019, the globally consumed power of data centres alone was 200 TWh[8], which represents 0.8% of the all power consumed around the world. Investing in more efficient IT hardware including microchips will provide the means to flatten this curve whilst data centre workloads are expected to increase[9],

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

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

1.2 2.1

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

2.2

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

The exponential increase in internet traffic (which is doubling every 2.5 years[2]) sets demanding requirements on data communication technologies. Optical interconnects enable higher bandwidth- distance products, higher bandwidth density, lower electromagnetic interference, and potentially lower power consumption than electrical interconnects. They are being deployed at increasingly shorter distances – for example, within and between data centres. In the longer term, chip-to-chip and even intra-chip communication may be performed with CMOS-compatible photonics. Beyond these applications, emerging precision applications – including atomic clocks, precision metrology, and transformative applications such as quantum communications and information processing – will also benefit from photonic capabilities integrated with electronics, such as silicon and heterogeneous III/V (membrane) photonics, and potentially disruptive technologies such as nanophotonics and graphene photonics.

8 Data Centres and Data Transmission Networks – Analysis - IEA (https://www.iea.org/reports/data-centres-and-data-transmission-networks)

9 https://www.iea.org/commentaries/data-centres-and-energy-from-global-headlines-to-local-headaches

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

1.4 2.1

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

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

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

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

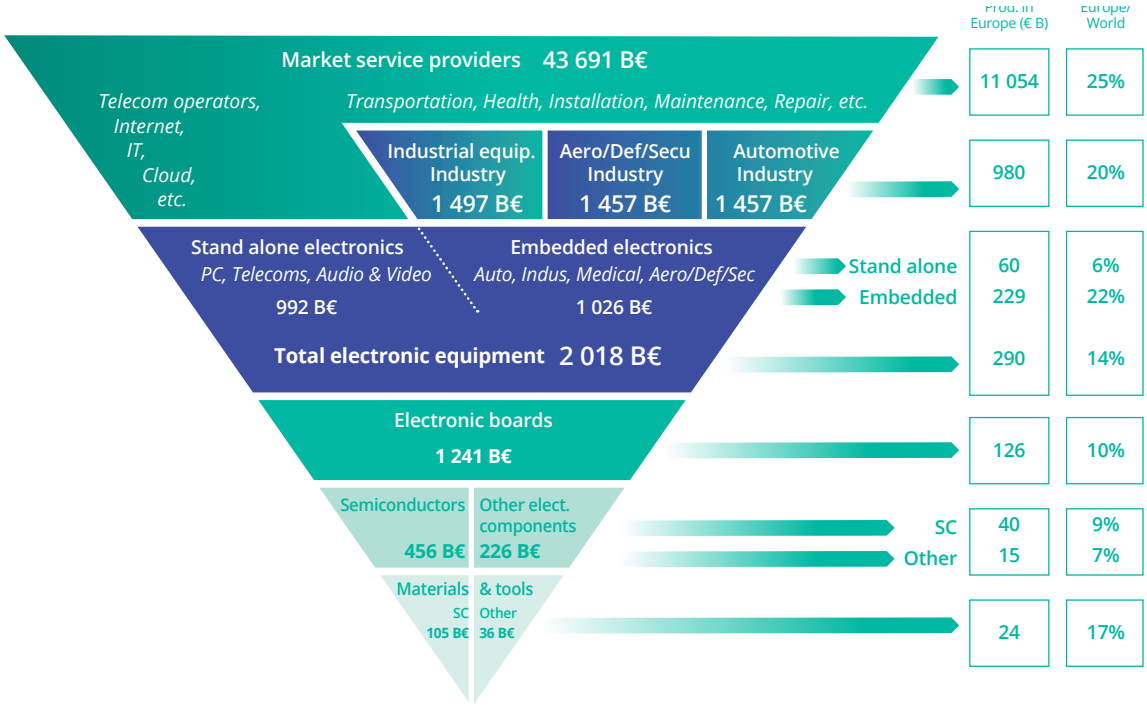
1.2

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

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

1.1.3
STRATEGIC ADVANTAGE FOR THE EU

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



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

F.7

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

In the past, the semiconductor market has been extremely volatile, and R&D investments have been high (up to 10–20% of total revenue). Nonetheless, public/private funding has enabled Europe to lead the world in dedicated semiconductor devices, semiconductor equipment, materials and manufacturing solutions.
Continued investment is vital not only for the ECS industry, but also for the downstream industries that depend on it, including automotive, aviation, space, healthcare, energy, security and telecommunications.
Under Horizon 2020, Future and emerging technologies (FET) flagship initiatives, such as those on graphene and quantum technologies, have been shown to have significant impact on European R&D landscape in these areas. To ensure European leadership in this highly challenging discipline, early involvement of equipment suppliers will bring these activities to the next level in parallel with identifying the best application areas. Importantly, the functionality of a number of current ECS technologies needs to be updated to respond to the challenges that new materials and Quantum Information Processing (QIP) are raising. Advanced materials and computational paradigms require not only the development of new scalable platforms, but also non-trivial adaptations and extensions of existing technologies as enablers of such functionalities. For example, any solid state-based quantum computer will need efficient "classical" low power cryogenic electronics to enable operation of its computing circuit.

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

Given that in the next decade, 85% of overall global growth is projected to take place outside the EU[10], it is essential that strategic industrial ecosystems receive the backing to ensure the robustness that is needed to continue competing globally and to reduce the potential disruptive impact of disasters such as pandemics and climate-related effects. Foreign and domestic investments leveraged by government subsidies have enabled many of these regions to take on a leadership role in several areas of semiconductor manufacturing. Despite competition from East Asia and the US, Europe can reinforce its lead in semiconductor processing and packaging, equipment and smart systems based on the priorities set out in this ECS-SRIA. The first Important Project of Common European Interest (IPCEI) on microelectronics, for example, was a successful step towards strengthening European semiconductor manufacturing in strategic areas where large-scale subsidies in other regions have started to threaten the position of European players. The European Commission has set ambitious targets[11] in its 'Digital Compass' to double 'cutting-edge semiconductor' manufacturing in Europe in 2030 – to maintain strategic autonomy, and to be involved in AI and other key technologies of the digital

10 European Parliament: EVP Dombrovskis speech at hearing Commissioner-Designate for Trade https://ec.europa.eu/commission/commissioners/2019-2024/dombrovskis/announcements/european-parliament-evp-dombrovskis-speech-hearing-commissioner-designate-trade_en

11 Europe's Digital Decade: digital targets for 2030 | European Commission (europa.eu) (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en)

world. In line with this initiative, a second IPCEI on Microelectronics and Communications Technologies is being set-up to achieve digital leadership in Europe.

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

1.1.4 MAJOR CHALLENGES

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

- **Major Challenge 1:** advanced computing, memory and in-memory computing concepts.
  Materials and substrates, process modules and integration technology for novel devices and circuits for advanced computing, memory and in-memory computing concepts based on nano-electronic, photonic or quantum technology.
- **Major Challenge 2:** novel devices and circuits that enable advanced functionality.
  Materials, process modules and integration technology for novel devices and circuits that enable advanced functionality (sensing, actuating, power, connectivity, biomedical, etc).
- **Major Challenge 3:** advanced heterogeneous integration and packaging solutions.
  Advanced heterogeneous integration and packaging solutions for system on a chip (SoC), 2.5 and 3D stacking (including chiplet technology), and smart SiP, sensor integration, photonics, power electronics, and other functionalities required for application domains (such as augmented reality/virtual reality (AR/VR), automotive, (bio)chemical, biomedical, aerospace, etc).
- **Major Challenge 4:** world-leading and sustainable semiconductor manufacturing equipment and technologies.
  World-leading and sustainable semiconductor manufacturing equipment and technologies for the realisation of sub-2 nm node logic and memory according to PPAC roadmap requirements, chips/chiplets with single and/or multi-node layers, advanced functionality devices and heterogeneous integration technology options, as described under Major Challenges 1–3.

1.1.4.1 Major Challenge 1: advanced computing, memory and in-memory computing concepts

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

1.1.4.1.1 State of the art

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

2.1

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

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

1.2 2.1 2.2 3.1

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

2.1

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

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

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

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

overcome these barriers for implementing near- or in-memory computing. However, it will be difficult to replace DRAM and Flash memory since they are cheap, proven and can handle most tasks.

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

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

1.1.4.1.2 Vision and expected outcome

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

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

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

Expected achievements

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

1.1.4.1.3 Key focus areas

This challenge includes the following key focus areas:

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

1.1.4.2 Major Challenge 2: novel devices and circuits that enable advanced functionality

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

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

1.1.4.2.1 State of the art

Besides the highly integrated chips necessary to overcome Major Challenge 1 on advanced computing, memory and in-memory computing concepts, many more devices are needed to achieve advanced functionalities – such as sensing and actuating, power management, and interfaces to other systems. This is what has also been named “more than Moore” in recent years, and is an integral part of all systems, as well

as one of the strengths of European microelectronics. Given the inherently diverse nature of this sector, the state of the art will be captured by providing a few snapshots of key technologies.

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

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

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

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

2.2

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

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

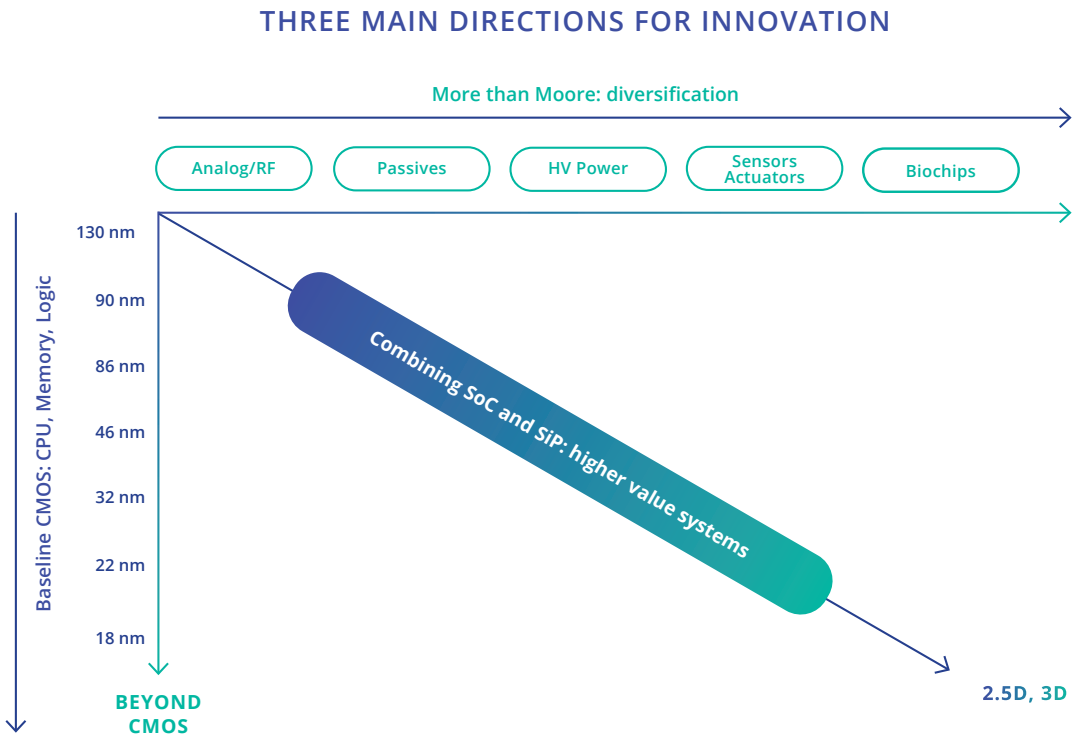
1.1.4.2.2 Vision and expected outcome

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

3.1 3.4

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

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



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

F.8

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

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

3.1

Expected achievements

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

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

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

1.1.4.2.3 Key focus areas

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

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

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

Advanced sensor technologies:

- Mechanical sensors (e.g. acceleration, gyroscopes, microphones).
- Chemical sensor devices such as selective gas-sensing components for environmental monitoring or smart medicine and smart health (e.g. CO, CO_2, NOx, O3, toluene, VOCs, acetone, H2S).
- Physical sensors (magnetic, optical, RF).
- Transmitter/receiver technologies for applications such as lidar and active phased array imaging.
- Biomedical and biochemical sensors.

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

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

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

- New energy-efficient RF and mm-wave integrated device options, including radar (building on e.g. SiGe/BiCMOS, FD SOI, CMOS, PIC).
- Development of new RF cryogenic electronics for QIP, and characterisation of logic devices at quantum-enabling cryogenic temperatures (sub 1K).
- Energy-efficient computing and communication, including a focus on developing new technologies.
- Bringing MOEMS and micro-optics, nanophotonics, optical interconnections, photonics-enabled device and system options into a CMOS-compatible manufacturing and/or packaging flow.
- Integration of solid-state light emitters such as LED and laser with, or onto, a CMOS-compatible platform.

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

1.2

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

1.1.4.3 Major Challenge 3: advanced heterogeneous integration and packaging solutions

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

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

1.1.4.3.1 State of the art

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

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

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

2.2 3.1

1.1.4.3.2 Vision and expected outcome

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

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

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

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

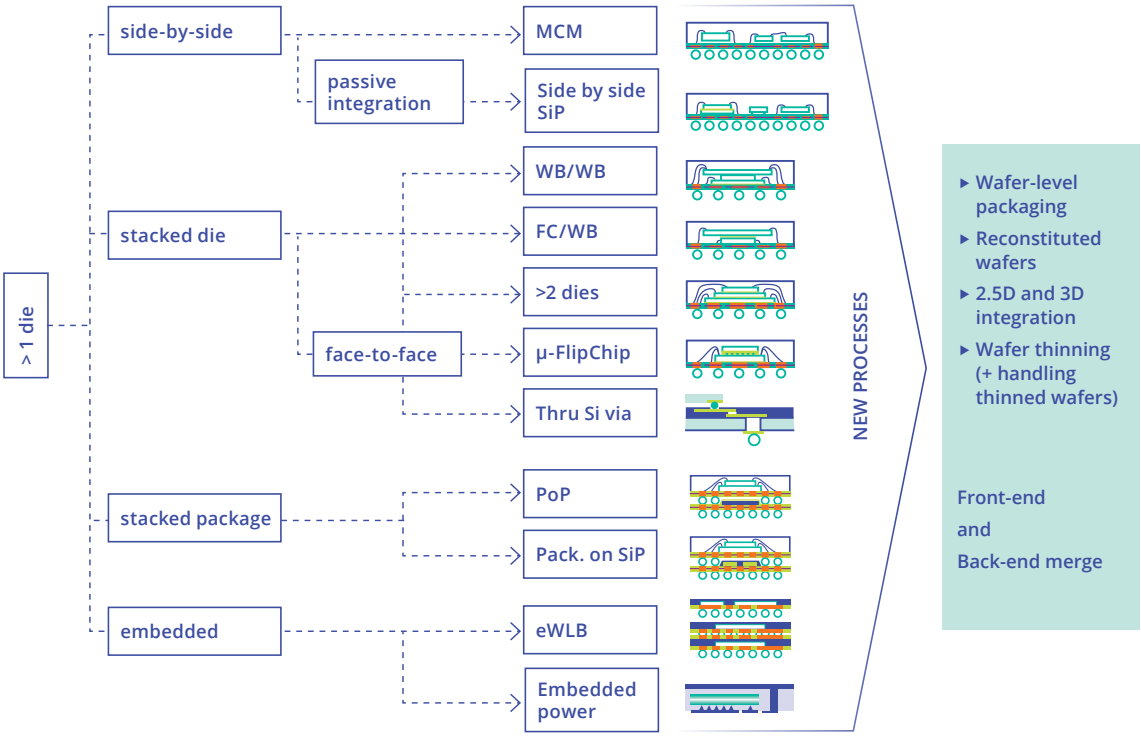
Compared to chip technology, assembly and packaging are becoming increasingly important. In many cases, assembly and packaging costs are becoming higher than the chip cost. To reverse this trend, we must focus on dedicated packaging and SiP process technologies that consider all the levels of chip, package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

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

At the macro-scale level, a system consists of a collection of large functional blocks. These blocks have quite different performance requirements (analogue, high voltage, eNVM, advanced CMOS, fast static RAM (SRAM),

multi-sensing capability, etc) and technology roadmaps. Therefore, for many applications it is of increasing interest to split the system into heterogeneous parts, each realised by optimum technologies at lower cost per function, and assembled with parts using high-density 3D interconnect processes.

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



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

F.9

1.1.4.3.3 Key focus areas

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

Advanced interconnect, encapsulation and packaging technologies:

- Interconnect technologies that allow vertical as well as horizontal integration: this includes process technologies for vertical interconnects, such as TSV, through-encapsulant via (TEV) technologies and microbumps, and copper/copper bonding, as well as process technologies for horizontal interconnects such as thin film technologies for redistribution both on chips and encapsulation materials. A technology base is needed for 3D stacking as well as horizontal interconnecting of dies and chiplets. This also includes interconnects through optical interfaces, most notably off-chip, but also within a package.
- Implementation of advanced nanomaterials and metamaterials, including low-thermal-budget-processing 2D materials, nanowires, nanoparticles and quantum dots with scalable logic and memory device technologies, which will be key for adding new functionalities and developing multifunctional smart systems.
- Specific power and RF application technologies.

- Solutions for high-frequency miniaturisation, such as for mm-wave applications (> 60 GHz) and for > 100 GHz towards THz applications for which no package solutions currently exist.

3D integration technologies:

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

Enhanced reliability, robustness and sustainability technologies:

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

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

1.1.4.4 Major Challenge 4: world-leading and sustainable semiconductor manufacturing equipment and technologies

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

The semiconductor equipment and manufacturing sector in Europe provides the global market with best-in-class equipment and materials to enable the manufacturing of miniaturised electronic components. The European equipment industry, RTOs and small and medium-sized enterprises (SMEs) active in this sector have a long history of successful mechanical engineering, tailor-made machinery, optical equipment, metrology, inspection and testing equipment, and chemical processing tools. This history of success is

prominent in several domains, foremost in lithography (in particular EUV) and metrology, but also in thermal processing, deposition, cleaning and wafer handling, as well as wafer assembly, packaging and in overall product reliability.

1.1.4.4.1 State of the art

At the forefront of semiconductor manufacturing equipment is the production of logic and high-performance memory, which are applied mainly in portable devices as well as advanced cloud computing and data storage facilities. The continuous increase of device density known as Moore's law is being driven by an ability to create ever-smaller features on wafers. The technology leaps required to keep up with Moore's law have already been achieved via additional roadmaps complementing ongoing 2D pattern size reductions. They are realised by combining various devices, materials, and 3D and system architecture aspects that required dedicated long-term investment in high-tech equipment solutions. Enabled by current deposition, lithography, etch, processing and metrology tools and their performance, the 5nm technology node is in production by market leaders, solutions for 3nm node has been taped out late 2021[12], and even Angstrom nodes[13] are being explored.

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

1.1.4.4.2 Vision and expected outcome

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

The overarching goal of equipment development is to lead the world in miniaturisation techniques by providing appropriate products two years ahead of the shrink roadmap of world's leading semiconductor device and components manufacturers[14]. Internationally developed roadmaps such as the International Roadmap for Devices and Systems (IRDS) will also be taken into consideration[15]. Currently, leading integrated device manufacturers (IDMs) are forecasting a continuation of the technology roadmap following Moore's law at least until 2029[16], which corresponds to at least four new generations after the current technology node.

12 3nm Technology - Taiwan Semiconductor Manufacturing Company Limited (tsmc.com) (https://www.tsmc.com/english/dedicatedFoundry/technology/logic/l_3nm)

13 Intel Accelerated (https://www.intel.com/content/www/us/en/events/accelerated.html)

14 https://investor.tsmc.com/english/encrypt/files/encrypt_file/qr/phase5_support/TSMC%201Q20%20transcript.pdf

15 https://irds.ieee.org/

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

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

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

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

Today's equipment was typically designed for the high-volume continuous production of advanced logic and memory devices, which requires major modifications or re-design when used as production tools for heterogeneous integration. Extending the life of installed equipment to match requirements of this domain via proactive lifecycle management (refurbishment) of these products will provide cost-effective solutions for specific applications. The performance must be enhanced for smaller batch production providing high flexibility and productivity at low cost of ownership.
Furthermore, the trend in solutions of ever-decreasing feature size with an ever-increasing number of features, and interconnects packed onto an IC, puts strong demands on product validation and verification methodologies, as well as on test methodologies and respective equipment.

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

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

Expected outcome

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

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

1.1.4.4.3 Key focus areas

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

- Advanced patterning equipment for sub-2 nm node wafer processing using deep ultraviolet (DUV) and EUV lithography, and corresponding subsystems and infrastructure (e.g. pellicles, masks and resist).
- Mask manufacturing equipment for sub-2 nm node mask patterning and tuning, defect inspection and repair, metrology and cleaning.
- Advanced holistic lithography using DUV, EUV and next-generation lithography techniques, such as e-beam and mask-less lithography, directed self-assembly (DSA) and nano-imprinting.
- Multi-dimensional metrology (MDM) and inspection for sub-3 nm node devices that combine a all the spectrum of physical tools and data processing techniques.
- Thin film processes including thin film and atomic layer deposition, doping and material modification, and corresponding equipment and materials.
- Equipment and manufacturing technology for wet and dry processing, wet and dry etching, including (atomic layer) selective etch processing, thermal treatment, laser annealing and wafer preparation.
- Technologies and tools for the manufacturing and integration of semiconductor components made with advanced nanomaterials and metamaterials (low-thermal-budget-processing 2D materials, nanowires, nanoparticles, quantum dots, etc) with logic and memory technologies.
- High-volume manufacturing tools for the production of III-V, SiC or other exotic material substrates of up to 200 mm, or 300 mm in the future.
- Dedicated equipment for manufacturing of electronics on flexible, structural and/or bio-compatible substrates.

Assembly equipment:

- Equipment and manufacturing technology supporting 3D integration and interconnect capabilities such as chip-to-wafer stacking, fan-out WLP, multi-die packaging, “2.5D” interposers, wafer-to-wafer sequential processing, TSVs and transistor stacking.
- Enhanced equipment optimised for high-volume manufacturing of large batches of the same package into efficient reconfigurable equipment for the manufacturing of different packages in smaller batches.

- New process tools for die separation, attachment, thinning, handling and encapsulation for reliable heterogeneous integration on chip and in package, as well as assembly and packaging of electronics on flexible substrates.
- Equipment development to suit the requirements of multi-component assembly on flexible and stretchable substrates, especially in roll-to-roll for both conductive adhesives and soldering.

Test equipment:

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

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

- Enable flexible line management for high-mix and distributed manufacturing lines, including lines for fabrication and deposition of advanced functional (nano) materials.
- Enhance equipment optimised for high-volume manufacturing of large batches of the same chip into efficient reconfigurable equipment for the manufacturing of different chips in smaller batches.
- Enable productivity enhancements (e.g. wafer diameter conversions) for heterogeneous integration technologies to significantly improve cost-competitiveness.
- New manufacturing techniques combining chip and packaging technologies (e.g. chip embedding) will also require new manufacturing logistics and technologies (e.g. panel moulding).
- Adopt factory integration and control systems to address the digital industry challenge of the ECS-SRIA, and to apply fast (and deep) learning as well as semi-automated AI-based decision- making to control processes, to enhance quality, increase reliability, shorten time to stable yield, and preserve knowledge and master complexity in these innovative machine-to-machine domains.
- Apply PAD approaches with a focus on predictive maintenance, virtual metrology, factory simulation and scheduling, wafer-handling automation and the digitisation of the value chain for AI-based decision management. In addition, attention should be given to control system architecture based on machine learning: viz. predictive yield modelling, and holistic risk and decision-mastering (integrate control methods and tools and knowledge systems).
- Doubling semiconductor manufacturing in Europe in 2030 also means evolving and upgrading installed base through incremental approaches, which will necessary mean increased complexity. Managing such hybrid factories will require advanced decision support and diagnosis techniques leveraging IA but also integrating existing human knowledge and know how.
- Develop comprehensive modelling and sharing techniques to enable seamless flow and utilization of information across the whole value chain will require significant evolution of the existing knowledge management techniques and technologies (NLP to exploit existing documentation, diffusion and sharing of cutting-edge or strategic knowledge).
- Future innovations should also address new environmentally friendly solutions for manufacturing (e.g. in terms of energy consumption, chemical usage) and environmentally friendly new materials (e.g. in terms of quality, functionality, defects) in parallel with addressing the continued cost of ownership challenges. This will entail, for example, new precursors, chemicals for deposition and other wafer-processing materials, as well as gas delivery, gas handling, pumps and abatement systems.

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

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

1.1.5 TIMELINE

All leading European industry and research actors should align their activities with international roadmaps and timelines. Roadmap exercises are being conducted in various projects and communities, including NEREID[17] and the IEEE's IRDS[18], in which European academia, RTOs and industry are participating. For system integration, the International Electronics Manufacturing Initiative (iNEMI)[19] and the new Heterogeneous Integration Roadmap activities are also considered. The European R&D priorities are planned in synchronisation with global timeframes and developments that are under continuous adaptation. The timelines below are high-level derivatives from these global evolutions, and follow the structure of the four Major Challenges described above.

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

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

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

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

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

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

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022 – 2026)
Major Challenge 1: advanced computing, memory and in-memory computing concepts	**Topic 1.1:** extensions of the scaled Si technology roadmaps High-performance Ultra-low power 3D integration	• N3 - N2 R&D • 2nd generation gate-all-around devices, forksheet integration • 18 nm FDSOI at technology platform integration level
	Topic 1.2: exploration and implementation of unconventional devices based on materials beyond Si	• SiGe (high Ge) channel • Cu alternative solutions
	Topic 1.3: novel device, circuit and systems concepts, such as for near/in-memory, neuromorphic, optical and quantum computing neuromorphic, optical and quantum computing	• Near/in-memory computing • 3D heterogeneous integration (logic/memory)
	Topic 1.4: long-term challenges such as steep-slope switches, spin-based transistors and alternatives	
	Topic 1.5: new eNVM technologies	• PCRAM • STT-MRAM • FDSOI embedded MRAM
Major Challenge 2: nNovel devices and circuits that enable advanced functionality	**Topic 2.1:** application-specific logic integration	• ULP 18 nm FDSOI technology integration
	Topic 2.2: advanced sensor technologies	• Continuous improvement of sensitivity (imagers, IMU, etc), range (lidar), and reduction of sensor area and energy consumption • Development of miniaturised low power chemical sensors • Development of biomedical sensors integrated with micro/nanofluidics • Heterogeneous integration of sensor technologies with (ULP) logic/memory technologies • 22 nm FDSOI for the IoT
	Topic 2.3: advanced power electronics technologies	• Silicon, BCD, SiC and GaN-based technologies and substrate materials • Energy-efficient systems, including energy harvesting
	Topic 2.4: advanced RF and photonics communication technologies	• Enable 5G connectivity • RF and mm-wave integrated device options building on, for example, SiGe/BiCMOS (increase of ft), RF and FDSOI, CMOS, PIC • GaN/S, GaN/SOIi and GaN/SiC technologies • Next-generation SOI for mm-wave • photonics SOI • 200 mm POI

MID TERM (2027-2031)	LONG TERM (2032 AND BEYOND)
• N1,5 R&D - 3rd generation of Gate-All-Around devices • CFET introduction • 12/10 nm FDSOI at technology platform integration level • 3D monolithic integration	• Sub-1 nm node logic and memory technology (nanowires, nanosheets) at process and device research level • Vertically stacked nanosheets • 3D monolithic integration • Beyond 10 nm FDSOI at technology platform integration level
• Ge channel • Optical interconnects • 2D materials exploration	• III-V channel • Low-thermal-budget-processing 2D materials device integration
• In-memory computing • Neuromorphic computing (spiking) • 3D monolithic integration • Photonic SOI	• Quantum computing • Optical computing
• TFET • CNTFET • 2D material FET	• NCFET • NEMS switch • Topologic insulator electronic devices • Spin wave devices • Mott FET (VO2, HfO2, etc)
• PCRAM • VCMA-MRAM • ReRAM • FeRAM	• ReRAM (MLC) • Hi-density ReRAM

• 12 nm FDSOI technology integration • New architectures for neuromorphic computing • 3D stacking for monolithic integration	• 3D monolithic integration
• Quantum sensors • Ultra-low power chemical sensor systems for pollution monitoring • Energy autonomous sensor systems • Multi-sensor systems for IoT • Integrated biomedical sensor system • Heterogeneous integration of sensor technologies with novel device, circuit and systems memory and computing concepts • 12nm FD-SOI for IoT	• Nanoelectronic sensor devices with individual molecule sensitivity and selectivity • Nanoelectronic biomedical sensor systems • Monolithic integration of sensor technologies with novel devices, circuit and systems memory and computing concepts • Beyond 10 nm FDSOI for IoT
• New CMOS and IGBT processes • Smart GaN devices (combining logic and power devices) • Vertical GaN power devices • Towards 300 mm GaN and 200 mm SiC substrates • Energy-autonomous systems • Energy harvesting and energy storage systems	• B-Ga_2O_3 • Diamond
• Improve RF front-End components roadmap (switchs, LNA, antenna tuners) : • Strained materials • Tiny silicon thickness and uniformity • Improve linearity substrate behaviour • RF substrate options for advanced CMOS nodes • • Integration of IIIV semiconductors on silicon and SOI • Integration of IIIV semiconductors on photonics SOI	• 3D stacking of different functions (RF with digital, ...) • New materials for advanced functions

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022 – 2026)
Major Challenge 2: novel devices and circuits that enable advanced functionality	**Topic 2.5:** flexible and structural substrate electronics	• Increased reliability of materials and process techniques, reduction of pattern size
Major Challenge 3: advanced heterogeneous integration and packaging solutions	**Topic 3.1:** advanced interconnect, encapsulation and packaging technolgies	• Vertical as well as horizontal integration via TSV, TEV, microbumps • Fan-out WLP or embedded wafer-level BGAs and chip-embedding in laminate materials • Advanced wafer-stacking technologies • Packaging & bonding technologies with advanced thermal management capability
	Topic 3.2: specific power and RF application technologies	• RF miniaturisation for mm-wave applications • Package integration of additional functionality such as antennas, passive devices and power sources
	Topic 3.3: 3D integration technologies	• Chip I/O-pad level 3D-SiC • Chip-package-board co-design
	Topic 3.4: enhanced reliability, robustness and sustainability technologies	• Enable testing of separate components, before assembly via concepts such as BIST and self-repair
Major Challenge 4: world-leading and sustainable semiconductor manufacturing equipment and technologies	**Topic 4.1:** wafer fabrication equipment for nanoscale patterning, layer deposition, metrology, and inspection for advanced logic and memory technologies	• Manufacturing equipment for 2 nm node logic and memory
	Topic 4.2: wafer fabrication equipment for new transistor front end of line (FEOL) and new interconnect back end of line (BEOL) concepts	• Manufacturing equipment for 2 nm node transistor and 3D heterogeneous integration interconnect concepts
	Topic 4.3: wafer fabrication equipment for new materials and processes	• Manufacturing equipment for 2 nm node materials and processes • Equipment for manufacturing of components with advanced nanomaterials • Production tools for III-V, GaN, SiC or other exotic material substrates
	Topic 4.4: assembly and test equipment enabling advanced packaging of single and/or multi-node chips/chiplets	• Assembly and test equipment for chip-to-wafer stacking, fan-out WLP, multi-die packaging, “2.5D” interposers and TSVs • 300 mm photonic SOI • 200 mm POI
	Topic 4.5: sustainable semiconductor manufacturing	• Reduction of CO_2 and GHG emission and of the electrical consumption of semiconductor production lines • Use of recycled and reclaimed water

MID TERM (2027-2031)	LONG TERM (2032 AND BEYOND)
• 3D stacking/horizontal connecting of dies/chiplets • Advanced nanomaterials (including low-thermal-budget-processing 2D materials, nanowires, nanoparticles, etc) • Critical raw materials elimination from packaging bill of materials such as W, Co, Mo, Be, BeO	
• RF miniaturisation for THz applications • Packaging of wide bandgap materials (GaN, SiC, etc)	• New cryogenic compatible packaging platforms for QIP
• 3D SoC • System technology co-optimisation • 3D stacking for monolithic integration	• Ultimate transistor-level 3D ICs
• Novel material solutions for high reliability, robustness and high quality	
• Manufacturing equipment for 1 nm node logic and memory • Equipment to enable novel switches, transistors and alternatives based on, for example, 2D materials, topologic insulator and spin-wave devices	• Manufacturing equipment for sub-1 nm node logic and memory
• Manufacturing equipment for 1 nm node transistor and 3D monolithic integrated and optical interconnect concepts	• Manufacturing equipment for sub 1 nm node transistor and 3D monolithic and optical interconnect concepts
• Manufacturing equipment for 1 nm node materials and processes • Equipment for materials and processes for new eNVM types such as (high-density) ReRAM • Production tools for 300mm wafer substrates based on selected exotic materials	• Manufacturing equipment for sub 1 nm node materials and processes
• Assembly and test equipment to enable next-generation autonomous sensors, power electronics and RF/optical communication packaged ICs	
• No CO_2 and GHG emission from semiconductor production lines • Use of 100% renewable energy sources	• Use of recycled metals to prevent the scarcity of some mineral ores • Use of 100% recycled and reclaimed water

1.1.6 SYNERGY WITH OTHER THEMES

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

The new advanced applications that will drive the future of European economy can rise only through a tight interaction among the key foundational technology layers, with Chapter 1.1 (**Process Technology, Equipment, Materials and Manufacturing**) providing the basic physical components and their manufacturing technology, Chapter 1.2 (**Components, Modules and System Integration**) their integration technology into smart systems, Chapter 1.3 (**Embedded Software and Beyond**) the software and control technology and finally Chapter 1.4 (**System of Systems**) the methodology to design and combine Smart Systems in System of Systems that can solve all the application issues in a global way.

Foundation technologies cannot be developed in complete isolation from each other: embedded software depends on the physical characteristics of the components, and smart systems require a tight co-development of hardware and software. In the end, Systems of Systems depend on the available components and embedded software elements, and in their turn, they influence their development priorities.

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

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

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

In the photonics domain, the Integrated Photonic Systems Roadmap (IPSR)[20] is defining the way forward, and this roadmap is aligned with the activities being exploited by AIM Photonics in the US. In this roadmap, we increasingly see a trend towards multi-PIC application modules. Similar to the IC industry, the PIC-based developments also do not rely on just silicon photonics for their functionality. Hybrid and heterogeneous integration of functionality from different platforms is essential to enable the currently required and

20 https://www.photonicsmanufacturing.org/events/2020-ipsr-i-integrated-systems-roadmap-0

new functionality. This trend also spreads further to integration with electronic ICs, which is becoming a commercial reality. The combination of electronics and photonics at an increasingly intimate scale will be a requirement to keeping Europe at the forefront of this – strategic – foundational technology development. The focus should therefore be to maintain both the manufacturing foundries of chips and the packaging in Europe.

1.2

Foundational Technology Layers

COMPONENTS, MODULES AND SYSTEMS INTEGRATION

1.2.1 SCOPE

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

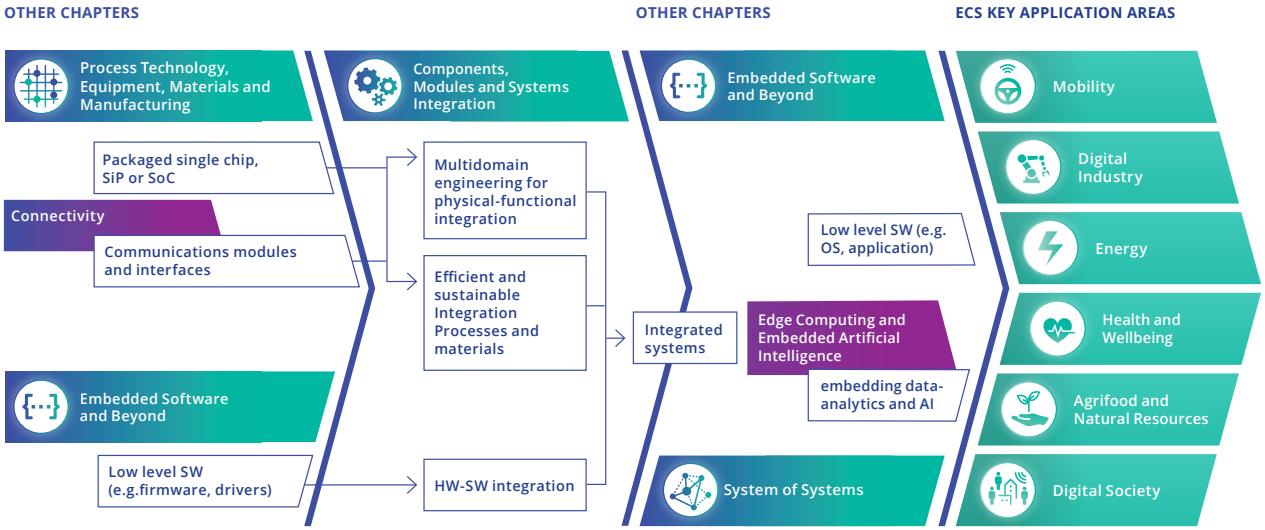
In the development of ever better smart systems and innovative products, heterogeneous integration becomes more and more important at every level of integration, from semiconductor SoC to System-in-Package (SiP) and ultimately to larger modules and systems. The importance of SiP technologies in integration terms is emphasized by the treatment of SiP in both chapters from their specific point-of-view. Particularly, in this Chapter alternative technologies (such as additive manufacturing), complementary materials (both at the functional and structural/substrate level) and heterogeneous approaches to assembly and integration are considered. The term heterogeneous integration is used in its widest meaning: components should be taken to mean any unit, whether individual die, MEMS device, passive component or assembled package, that are integrated into a single component, module or system.

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

Considering the new requirements imposed by modern and future smart systems, mastering the integration technologies at component, module and systems levels, is a significant capability of European industries. Such a strength needs to be sustained and reinforced to ensure Europe leading position in smart systems engineering, as well as to move innovations into real-life products, services and markets. Currently, semiconductor devices and technologies are the key components providing advanced functionality. Nonetheless, this essential part of electronic systems must be integrated with other elements, such as passive and further active devices increasing the functionality level using a wide range of packaging schemes, i.e. heterogeneous integration. Developments of heterogeneous integration technologies and platforms include also flexible electronics and photonics solutions.

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

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

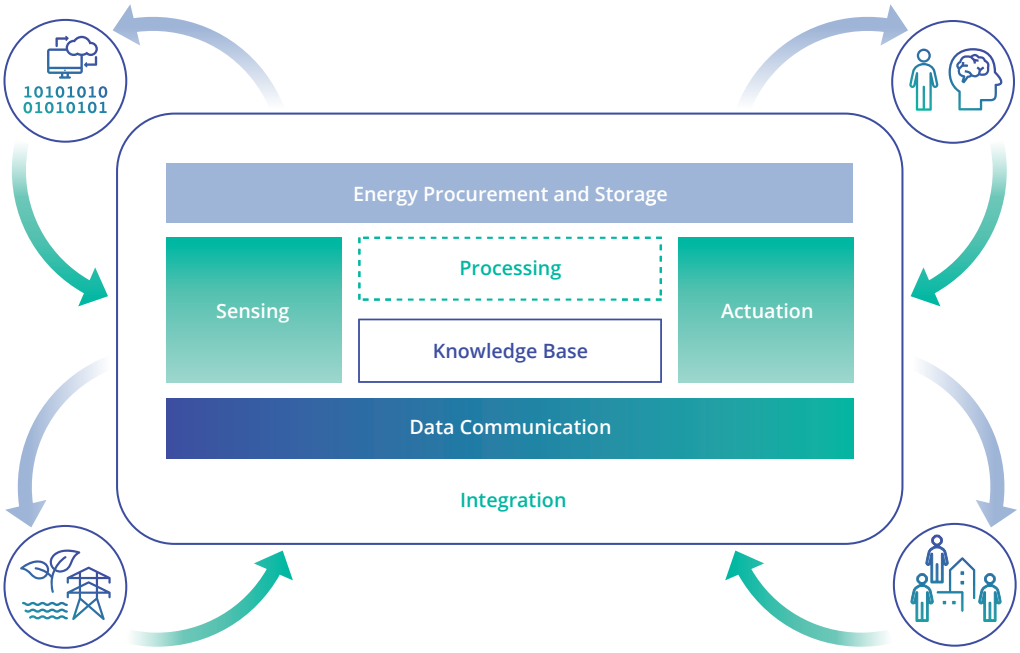


F.10 *The Components, Modules and Systems Integration focused on physical-functional integration of devices and components into integrated systems, using sustainable and efficient materials and integration processes.*

1.2.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

Societal benefits of smart components, modules and systems stem from the applications that they are enabling, as described in the Application chapters. Improved integration technologies and miniaturization, together with cost-, energy- and resource-efficient and eco-friendly manufacturing, will make future applications affordable for the broader public, and support sustainability of products and production technologies, enabling responsible use of resources, e.g. by means of assisting in the development of a circular economy, in alignment of the European Green Deal[21] and UN sustainable development goals[22].

Figure F.11 defines an integrated smart system showing its components and modules, while interacting with the natural, man-made and societal environment. Smart systems integrate sensing and/or actuation as well as signal processing to enable actions. Smart systems utilize multifunctional perception, and are predictive, configurable, contextual and adaptive.



Smart systems interact with the user, the (natural, man-made and social) environment and the data sphere. Smart systems provide (and use) cognitive support to (and from) their surroundings (Source: EPoSS)

F.11

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

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

22 *https://sdgs.un.org/goals*

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

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

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

- Embedded intelligence (typically realized by a combination of hardware and software components) in the ECS – higher functionality, less or changed requirements for interfaces, improved interoperability, haptic interfaces, and lower demand for power resources.
- Greater performance and digital configurability of sensors, analogue and RF devices, while at the same time reducing energy consumption, which impacts component, module and system integration, transmission of RF waves and interconnects, without decreasing component performance (e.g. in the detection limit of MEMS/NEMS sensors).
- Greater performance in power electronics devices through an impact on the thermal characteristics and higher power density and electromagnetic interference (EMI) performance of components, modules and systems, in addition to higher integration levels enabling effective switching capabilities.
- Energy savings, efficiency and harvesting through smart and intelligent battery management, combination of functions and/or digital interfacing with sensors, transceivers and microcontrollers to minimize system-level power consumption, multi-source energy harvesting and high density, low leakage storage devices to avoid battery replacement, integration of new power-saving techniques (e.g. GaN-based or MEMS-based switching switching) in combination with energy-efficient packaging technologies.
- Improved reliability, security, safety, self-monitoring, fail-operational, faultlessness and trustworthiness, both at software as well as hardware-level.
- Wearable and/or disposable sensors with flexible and stretchable materials, opening a new area for sensors in, for instance, healthcare and wellness applications, and materials and substrates for printed circuits and hybrid integration of traditional integrated circuits with printed electronics.
- Structural electronics, opening a new form of electronics integration on/in various materials (plastics, laminates, glass, textile, etc.), enabling novel smart systems in automotive, aviation, consumer electronics, healthcare, industry etc.
- Non-fossil and biodegradable materials for electronics for greener electronics and reducing environmental impact of ECS.

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

1.2.2.1 Application breakthroughs

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

Applications are the driver for such approaches:

- Communication landscape with 5G, 6G, including Non-Terrestrial Networks (NTN), high bandwidth, time-sensitive network (TSN) operations and near-field communication, as well as navigation and localization.
- Autonomous systems, including energy autonomy – in mobility, transport, logistic, manufacturing or control of buildings and micro-grids, etc. (ensuring faster time response and decreasing the impact of human error).
- For low data rate communications, lower power consumption devices and supporting architectures are needed, particularly to support the autonomy of IoT edge devices.
- Ultra long-life time remote or difficult to access applications, e.g. structural monitoring of bridges, tunnels, civil structures.
- Healthcare landscape with applications towards assisted care, Point-of-Care devices and telemedicine, including disabled assistance as well as treatment.
- Adaptive lighting systems with high-speed interfaces, thermal and optical arrangements, and the reduction of light contamination by intelligent illumination.
- Energy systems for high-power charging and/or highly variable and changing conditions.
- Industry 4.0 manufacturing landscape to enable agility and autonomy, as well as energy and resource efficiency, including manufacturing up to lot-size-1.
- Overall transition from stable controlled environments to harsh environments with longer operational life time and variable conditions.
- The transition in mobility towards zero-emission power trains, with their significant cost and energy efficiency challenges.
- Sensing of environmental parameters in agriculture or aquaculture, in manufacturing and working places, at home and in urban areas.
- Imaging applications for security, healthcare, digital industry, (precision) agriculture, digital society (television, social media) and perception.
- Optical Integration for higher data transfer rates, and more energy efficient cloud and edge computing solutions.

1.2.3
STRATEGIC ADVANTAGE FOR THE EU

Components, modules and systems are versatile in terms of design, size, material and composition, and thus the network of stakeholders involved in the production process of smart systems is equally complex. Europe's supply chain for smart systems production consists of more than 6,000 large companies and SMEs[23]. New models that will bring greater efficiency and more agile production processes need to be developed. This will ensure an effective and swift reaction to sudden market shocks as well as flexible manufacturing, accommodating shorter lifecycles of products and fabrication-on-demand. The current Covid-19 pandemic has revealed the vulnerability of global, distributed value chains. Emphasizing and supporting ECS manufacturing and subcontracting can lead to increasing smart systems activity for European industry. In the ECS sector, this means about nine million jobs across Europe.[24]

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

Smart electronic components and systems generally integrate more-Moore information processing devices and communication elements, and more-than-Moore devices that are more akin to the components and modules level. These more-than-Moore devices enable the physical-digital transduction: devices that physically (mechanically, optically, etc.), chemically and biologically interact with their environment, translating real-world quantities and phenomena into data and/or energy after some electrical transduction, and vice versa. In short, they comprise the sensing and actuating elements, and the devices needed to power them.

According to Yole Développement[25], the global MEMS and sensor market (excluding RF filter modules) will almost double from US$48 billion in 2018 to US$93 billion in 2024. Assuming the same annual growth rate, the market should reach US$180 billion by 2030, with Europe supplying at least one-third to one-half of this market, with hopefully the same success in other microsystems' markets. To summarize, investing in the future of electronic components and systems integration has the following strategic advantages for Europe:

- Enabling successful Twin Transition (Green and Digital) in an economically feasible way.
- Strengthening European economy through the generation of high-tech jobs and more value-added products within Europe.
- Ensuring European sovereignty in electronic components and systems (from semiconductor to packaging), and key digital technologies.
- Securing strategic Intellectual Property from European companies on advanced technologies in microelectronic ecosystem with regards to heterogeneous integration.

23 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

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

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

1.2.4 MAJOR CHALLENGES

The following four Major Challenges are identified:

- **Major Challenge 1:** physical and functional integration.
- **Major Challenge 2:** materials for integration.
- **Major Challenge 3:** technologies, manufacturing and integration processes.
- **Major Challenge 4:** decarbonization and recyclability.

1.2.4.1 Major Challenge 1: physical and functional integration

1.2.4.1.1 State of the art

Physical and functional integration considers the development of new elements and methods enabling more functionalities to be integrated physically on components, modules and system levels, in the most effective form factor. This requires interdisciplinary technology innovations as smart components, modules and systems may utilize a combination of features based on nanoelectronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, micro-fluidic, acoustic, radiation, radio frequency, biological, chemical and quantum principles. Further, many types of devices are to be integrated together, such as sensors, actuators, energy generators/batteries, storage devices, microcontrollers/data processing devices, transceivers, as well as MNBS, MEMS/NEMS, MOEMS and LAE devices. Such integration goes beyond the compact monolithic SoC approaches supported by the semiconductor technologies covered in the **Process Technology, Equipment, Materials and Manufacturing** Chapter. The integration of functions in the same module was previously achieved by using hybrid integrated circuits or multi-chip modules (MCM). The current trend focuses on the system in a package (SiP), where all functions are designed together to improve performance and compactness, something that also enables the heterogeneous integration of separate devices with different fabrication processes and methods. SiP is a mixed arena between the previous **Process Technology, Equipment, Materials and Manufacturing** Chapter and this one. In the former Chapter, SiP approaches result from the natural technological evolution of back-end semiconductor processes and are mostly related to the compact hybrid/heterogeneous integration of technologically 'homogeneous' components (e.g. chiplets) while this Chapter is more open to the flexible integration of components with a higher degree of technological heterogeneity in different sort of platforms.

1.1

1.2.4.1.2 Vision and expected outcome

Given the broad range of physical scenarios they face, smart components, modules and systems need to interact with many environments:

- Well-controlled laboratory-like conditions, e.g. in vitro: lab-on-chip, organ-on-chip, etc.
- Real-life scenarios including in vivo: in the body, permanently in implants, temporary as in ingestibles, or on the body in wearable devices,
- and harsh environments (physical, chemical but also electrical, e.g. EMC).

There are a multitude of operational issues affecting smart components, modules and systems regarding energy, performance and size. With respect to energy, for portable IoT devices, there is a need of low-power operation and provision of energy autonomy (self-powered devices or devices providing short-/medium-/long-term autonomy depending on the application) on the one hand, and dealing with high-power density and thermal stress on the other. Regarding size, the optimal “minimum” size must be achieved. This means

that fast response/latency issues, adequate operation time/cycling, i.e. from real-time continuous monitoring to event-triggered operation, and multi-parameter performance must be considered.

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

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

1.4

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

1.3 2.1 2.3

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

1.2.4.1.3 Key focus areas of physical and functional integration

- Sensing, imaging and actuation :
  - Sensors and actuators leveraging the integration of MEMS/NEMS, MOEMS and micro-optics elements. Imaging systems: lidars and radars, including multi-modal and hyperspectral, i.e. spectrally resolved, sensors.
  - Selective sensing components and selective detection of gas and volatiles, allergens, residues in food/water, atmospheric particles and detection of substances.
  - Sensors and actuators for biological, medical and diagnostic applications, and for sensing of human vital signs and bio- markers.
  - Energy-autonomous multi-sensor nodes and systems for IoT applications.
  - High-performance sensors for harsh environmental conditions.
  - Sensing devices and power sources compliant with integration in wearables, considering flexibility, biocompatibility, hybrid integration.
  - Flexible and stretchable sensors and modules, e.g. OLED displays, OPVs, touch surfaces and other sensors/actuators, conformal antennas.
  - Photonics features such as optical sources, waveguides and connectors integrated into photonic integrated circuits or photonic systems in a package on silicon, PCBs or other component carriers.

  - Sensors and systems utilizing quantum principles, e.g. single photon sensors, including required cryogenic and cooling components and systems.

- Communications, enabling:
  - Module-level high-speed communication features, including current and new frequency bands.
  - New front-end components, filters and functionalities e.g. active antennas for 5G and 6G communications and non-terrestrial network solutions.
  - Low latency and low power communications in-package/module as well as at system level for the edge and IoT devices.
  - Strategies and components for Electromagnetic interference (EMI) mitigation.
  - High-performance signal quality in harsh environmental conditions.

- Energy and thermal management:
  - Low-power/low-loss modules for low-power sensing, actuation, processing and communication.
  - Efficient power transfer solutions, energy harvesters and storage devices.
  - Energy-autonomous multi-sensor nodes and systems for IoT applications.
  - Power electronics modules and their packaging, using novel power electronics devices with integrated functionalities (e.g. sensors).
  - Power management components and modules compatible with harsh environments (high temperatures, vibrations, electromagnetic interference (EMI) conditions for industrial, automotive and space technology).
  - Thermal management at different integration levels including advanced and active cooling systems.
  - Solutions for thermal management for integrated photonics.
  - Highly efficient smart compact cooling solutions and approaches for room temperature operation for quantum devices.

- Information processing:
  - Component-level features for self-diagnosis (PHM detectors) and module-level signal processing and control features for self-diagnosis, self-monitoring and self-learning.
  - Sensor level hardware and software solutions for security and privacy and data trustability.
  - Machine learning and artificial intelligence on the sensor, module and systems level, i.e. on the edge.
  - Data analysis embedded on different levels for smarter devices, including AI on the sensor level.
  - Integrated solutions, both Software and hardware for edge AI.
  - Use of quantum computing and integrating quantum computing for data-analysis.

1.2.4.2 Major Challenge 2: materials for integration

1.2.4.2.1 State of the art

Smart components, modules and systems leverage a multitude of materials, such as silicon and other-than-silicon semiconductors, precious and rare earth metals, ceramics, polymers, glass, inks and functional materials for sensing, actuation and energy harvesting, as well as hybrid combinations on substrates (e.g. Si, ceramic, polymer, glass), in packages and in systems. In this sense, the scope considered in this Chapter

extends the coverage of the usual materials in semiconductor-based technologies. Indeed, not only non-silicon materials, but even non-silicon-compatible materials are needed to interact wholly and efficiently with the physical world by benefiting from different transduction principles, and new substrates may be considered to better serve different types of application scenarios.

1.1

1.2.4.2.2 Vision and expected outcome

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

For instance, MEMS/NEMS development focuses on sensors and actuators. The former rely on new generations of inertial measurement units (accelerometers and gyroscopes) with increased performance, with or without AI support, magnetometers, pressure sensors, microphones, as well as particle sensors; the latter rely on piezoelectric micro-mirrors, print heads, oscillators (membranes and cantilevers), tunable lenses, loudspeakers and piezoelectric micromachined ultrasound transducers (PMUTs). New piezoelectric materials, such as scandium aluminum nitride (ScAlN) enables new applications for the MEMS devices.

Flexible electronics aims at ever thinner and more flexible electronic components and systems[26] e.g. for displays, wearables and novel human-machine interfaces (HMI). Structural and 3D electronics enable incorporating electronics in 3D surfaces and mechanical components by means of molding, additive manufacturing or laser direct structuring (LDS). Novel flexible and stretchable substrates (such as thermoplastic polyurethane (TPU) and polydimethylsiloxane (PDMS), as well as new materials for active components, including conductive and dielectric inks, with organic materials, metal oxides, nanomaterials and 2D materials are required for realizing new applications in touch panels to RF antennas, control electronics, embedded lighting and sensors/actuators.

Non-fossil, biocompatible and even biodegradable substrates and packaging materials are required to reduce the environmental impact of the electronics industry in general. In addition, exploiting these materials enable new applications in areas such as implantable electronics. All these new materials must be well-characterized to obtain "first-time-right" design of these electronic systems. The materials' property data are fundamental for design, modelling and reliability investigations. Here, close links to the Chapter on **Quality, Reliability, Safety and Cybersecurity** and the Chapter on **Architecture and Design: Methods and Tools** are critical. Europe has a very strong academic network and an advanced position in material characterization and simulation techniques. Nevertheless, it is important to highlight that most organic materials used in composite, molding, lamination and additive materials comes from Asia.

2.3 2.4

1.2.4.2.3 Key focus areas of materials for integration

- Materials for active components and functional materials:
  - New materials and features for sensing and actuation (metal nanowires, carbon nanotubes (CNTs), graphene, cellulose nanofibers, biocarbons, metal–organic frameworks (MOFs), nitrogen voids in diamond, metamaterials, etc.).

26 *OA-E Roadmap for Organic and Printed Electronics, 8th edition, 2020.*

- Functional materials for flexible and stretchable devices; organic and inorganic semiconductor materials and inks, perovskites for OPV.
- Functional materials for integrated photonics; for efficient modulation, higher bandwidth, modulation/detection.
- Materials for affordable infrared imaging, integrated with Si (readout and image processing) electronics.
- Non-toxic materials for efficient energy sources, storage and harvesting devices (thermoelectric, piezoelectric, tribo-electricity, etc.), and higher performing electrodes and electrolytes for improved capacity and low leakage for energy storage devices.
- Materials for functional components at frequencies above 10 GHz: CMOS or GaN-compatible thin film piezoelectric materials, materials for high-efficiency acoustic transduction.
- Materials for integration and packaging of semiconductor electronics and superconducting devices at cryogenic temperatures, including 3D technologies.
- Replacement materials to comply with Restriction of Hazardous Substances Directive (ROHS) regulations and minimize critical raw materials (CRM) dependence, including rare earths replacement (e.g. for magnetics).
- Transducer materials (e.g. CMOS-compatible piezo) that can be integrated into SiPs.
- Topological insulators for low-loss electronics.
- Magnetic materials for inductors and power integrity.

▸ Materials for packaging, integration substrates and for protective purposes:
- Protective housing and coating features for harsh environments.
- Surface coatings for multi-functionality on the same base structures, including self-cleaning materials.
- New functional materials for packaging that enable integration of sensing or other functionality into the packaging itself, e.g. packaging as a part of the antenna or sensor functionality.
- New materials for housings and coating features and new substrate materials for specific requirements; high power, high frequencies, disposable, bio-compatible, non-fossil.
- New/alternative non-fossil, organic and biocompatible and compostable substrate materials for e.g. implants, ingestibles, wearables, biosensors.
- Barrier materials, dielectrics, and transparent conductor materials and inks for flexible electronics and additive manufacturing.
- Adhesives, bonding materials for integrating chips on flexible substrates and for additive manufacturing.
- New thermal interface materials (dependent on temperature capabilities, and processes, e.g. for additive manufacturing).
- Materials for multiscale, self-assembling processes.
- High-performance materials for passives enabling close coupled passives for high density heterogeneous integration such as magnetic cores, high k dielectrics.

▸ Material properties:
- Material properties database for simulation and reliability.
- Design of new materials from properties requirements by the means of Materials by design, materials genome and digital design approach.

1.2.4.3 Major Challenge 3: technologies, manufacturing and integration processes

1.2.4.3.1 State of the art

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

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

2.3

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

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

1.1 2.4

1.2.4.3.2 Vision and expected outcome

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

2.2 3.4

The complexity and diversity of heterogeneous components, modules and systems substantially exceed that of mere microelectronic components due to their multi-physics and multiple domain nature. Environmental

and sustainability issues (production, disposal, re-use, lifecycle and circular economy) also need to be considered.

Components, modules and systems will include more integrated functionalities (see Major Challenge 1). In addition, more components will be integrated into single modules and substrates and module packaging will include integrated components and functionalities, rendering them a functional part of the modules and systems rather than "passive" boards and frames. In this multifunctional and multimodal integration on the component, module and system level, the development of manufacturing methods that meet the accuracy and repeatability criteria of high-quality and high-reliability products are a necessity. These methods will enable zero-defect manufacturing starting at lot one. Furthermore, design and simulation methods that enable and support such multi-physics and multimodal design and manufacturing must be addressed. For example, modelling and design tools for thermal, mechanical and electrical characteristics in small 3D packages, including molded and additive manufacturing methods are needed.

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

1.2.4.3.3 Key focus areas of technologies, manufacturing and integration processes

- Integration processes, technologies and platforms:
  - Robust heterogeneous 3D integration of sensors, actuators, electronics, communication, RF front-end components, energy supply into systems.
  - Rapid prototyping and manufacturing technologies (additive manufacturing, 2D and 3D additive technologies, etc.).
  - Hybrid integration of heterogeneous components into several types of platforms.
  - Integration towards low vertical form factor (<100 µm) and the miniaturization of external matching networks through integration.
  - Embedding of power sources (batteries, energy harvesting transducers, supercaps, etc.) into a package (PwrSiP) and on a chip (PwrSoC).
  - Use of flexible Si-substrates for 3D form factors and for flexible electronics.
  - Integration of quantum systems: Manufacturing and integration technologies for superconducting, photonic and Silicon quantum components, sensors and systems.
  - Integration with biological and molecular systems, including fluidics e.g. for biosensors
  - Photonic system integration based on silicon photonics (and other substrates), multi-domain integration to photonic systems, including RF, MEMS/NEMS, sensors, etc.; electro-optic co-packaging.
  - Enabling electronic-photonic systems by heterogeneous integration (III-V, ferroelectrics, ultra-low-loss waveguide materials).
  - System self-diagnosis and health monitoring features.

- Manufacturing and equipment:
  - Automation and customization in component, module and system integration for large-scale manufacturing, including Industry 4.0 techniques, design for manufacturing based on production data techniques, and lot-size-1 manufacturing.
  - Manufacturing and testing tools (including tests, inspection) for components, modules and systems, enabling zero-defect integration.
  - Submicron LAE fabrication processes and equipment (printing technologies in general, nanoimprinting, reverse offset printing, etc.) and automated manufacturing equipment for flexible electronics, including testing tools for electrical and non-electrical properties.
  - Interconnections processes and tools for flexible and stretchable devices and integration tools for structural electronics (in glass, plastics, laminates, etc.).
  - Heterogeneous integration processes and equipment for integrated photonics, including high-precision component placement and bonding, as well as low-loss fiber coupling.

1.2.4.4 Major Challenge 4: sustainability and recyclability

1.2.4.4.1 State of the art

As increased integration will cause the borders between components, modules and systems to become blurred, and more diverse and complex materials are used at each level, the dismantling of systems into their constituent components at the end of their useful life will become increasingly difficult. Many industrial ECS products have life time extending decades, thus the environmental regulations for recyclability cannot be known at the time of product design in detail. Incineration is traditionally the only "recovery" strategy used to dispose of an integrated system once it is discarded.

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

2.1 2.3

In 2019, world-wide e-waste exceeded 50 million tons, and it is forecasted to grow to 70 million tons in 2030[27]. Given the increasing burden of improperly dealt with e-waste and considering that a significant part of CO_2 emissions arises from the fabrication of the ECS themselves, extending product life time is important for reducing environmental load. This needs to be addressed by designs that enable repair or replacement of faulty components instead of replacing the full module or system. To fight obsolescence, hardware and software upgrades should be supported, even in field conditions. Reducing CO_2 emissions during the life time of the system requires minimizing the power consumption at component, module and system levels while in operation by using low-power hardware and software technologies.

1.3 2.1

27 *Forti V., Baldé C.P., Kuehr R., Bel G. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/ United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.*

1.2.4.4.2 Vision and expected outcome

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

- Upstream considerations and design for repair, upgradeability, dismantling, materials separation and recycling.
- Non-fossil, recyclable, biodegradable and compostable materials, without releasing any dangerous materials or having other negative impact on environment.
- Life time extension and system health monitoring, self-monitoring and healing.
- Increasing energy efficiency of ECS, during manufacturing and life time, and end-of-life.
- (predictive) maintenance, repair, upgrading, reconfiguring, recharging, retrofitting and re-use in second life, including ecosystems and tools to support these actions.
- Sustainability and reducing energy consumption and environmental footprint of the manufacturing and integration processes.

The development of integration processes based on new design tools will allow the dismantling of components, and the recycling of components and recovery of materials (urban mining) is essential. Therefore, system design techniques need rethinking to use multifunctional components and modules, and design for component separation and recyclability is generally required, in selection of materials and in integration technologies. Recycling technologies, as well as new approaches to second life of ECS and re-use in new application, must be advanced. For example, with the electrification of cars, the recycling and re-use of battery packs, modules, and individual cells, and finally, materials recovery from the cells, becomes more and more important.

1.1 2.3

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

1.2.4.4.3 Key focus areas of sustainability and recyclability

- Sustainable integration, manufacturing and use of ECS:
  - Modular design for reparability and maintenance and updating. Condition monitoring for usage as well as for health.
  - Increasing the sustainability and power efficiency to reduce greenhouse gas emissions of the integration and manufacturing process.
  - Increasing power efficiency of the ECS during life time by using low-power techniques.
  - Condition monitoring and predictive maintenance as tools to extend life time of ECS, including associated pertinent physics of failure models.
  - Assessment of environmental impact ECS in design stage, as a tool for sustainable ECS, using life time assessment (LCA) or similar framework.

- Recyclability of components, modules and systems:
  - Design tools for optimized use for materials.
  - Use of recyclable, biodegradable, compostable, non-fossil materials.

- Designing and developing integration processes that allow module dismantling, component recycling and material recovery (urban mining).
- Recycling technologies (e.g. for precious metals), second-life scenarios, repair, re-purposing and re-use approaches.
- Breakthroughs in recycling process and solutions for energy storage components, such as batteries.
- Solutions for full recycling energy storage components.

1.2.5 TIMELINE

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

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 1: physical and functional integration	**Topic 1.1:** sensing, imaging and actuation	• Integration for multifunctional sensors based on MEMS/ NEMS and MOEMS • Photonic sensing; imaging sensing; Lidar / radar systems • Selective gas-sensing; fluidics • Disease monitoring and diagnostics platforms (in vitro, wearables) • Quantum principles
	Topic 1.2: communications	• Real-time, low-latency, low-power for edge and IoT devices • Photonics communications • Reduction of EMI • High-speed 5G and beyond 5G connectivity
	Topic 1.3: energy and thermal management	• Energy harvesters and storage • Low power components • Energy autonomous systems • Thermal management at different integration levels including advanced and active cooling systems
	Topic 1.4: information processing	• Security and privacy • Explainable AI, edge computing (HW and SW) • Hybrid modelling (physical and data-driven)
Major Challenge 2: materials for integration	**Topic 2.1:** materials for active components and functional materials	• Functional materials (piezo, ceramics, polymers, metamaterials) • New materials and inks for flexible electronics • Photonic materials • Replacement materials to comply with RoHS and minimize CRM dependence
	Topic 2.2: materials for packaging, integration substrates and for protective purposes	• Materials for additive manufacturing • Protective coatings and barrier materials • Non-fossil, bio-compatible substrate and housing materials • Materials for chip interconnection; ACA, flip chip etc. • Materials enabling recycling and repair • Self-cleaning materials • Replacement materials to comply with RoHS and minimize CRM dependence • Thermal interface materials
	Topic 2.3: material properties	• Database of material properties for simulation and reliability

MID-TERM (2027-2031)	LONG TERM (2032 – 2036)
• MEMS/NEMS • Micro-optics, MOEMS • Photonic sensing • Hyperspectral imaging • Selective detection of allergens, residues • Fluidics • Disease monitoring and diagnostic platforms (in vitro, wearables) • Drug delivery • Quantum principles (also at room temperature)	• Advanced MEMS/NEMS • Advanced photonics • Convergence of sensing principles (e.g. thermal, optical cameras with lidar/radar) • Advanced fluidics • Multifunctional healthcare support systems (wearables, implants) • Quantum principles (also at room temperature)
• Quantum key distribution • Advanced interconnect photonics at component as well as at system-level • Beyond 5G and 6G communications, including non-terrestrial networks • THz communication	• Quantum internet and cryptography • Beyond 6G • THz communication
• Energy harvesters and storage • Low/zero power components and systems • solution for thermal management in integrated photonics	• CO_2-neutrality and circular economy for ECS
• Integration of information processing close to data acquisition • Hardware solutions for security and privacy • Neuromorphic computing • AI in the edge computing • Quantum simulation and quantum computing for the data-analysis (in the cloud)	• Low-power AI • Neuromorphic computing • Quantum computing • Quantum simulation

• Functional materials (piezo, ceramics, polymers, glass, metamaterials) • Organic and bio-compatible materials • Photonic materials • Materials for quantum principles	• Materials for advanced MEMS, NEMS (including wearables and implants) • Materials for advanced photonics • Materials for quantum principles
• Multifunctional coatings • Self-cleaning and self-healing materials • Compostable and biodegradable substrate and housing materials • Materials for quantum technology integration in cryogenic temperatures	• CO_2-neutrality and circular economy for ECS, with sustainable materials
• Database for simulation and reliability • Material by design approach	• Database for simulation and reliability

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 3: technologies, manufacturing and integration processes	**Topic 3.1:** integration processes, technologies and platforms	• Integration for complexity: Hybrid integration of heterogeneous components into several types of platforms • System health monitoring and self-diagnosis • Integration of biological and molecular functions, integration with fluidics • Photonics integration with RF, sensors; electro-optic co-packaging • Integration with Flexible, structural and 3D conformable electronics • Integration of quantum systems: superconducting, photonic, Silicon technologies
	Topic 3.2: manufacturing and equipment	• I4.0 for manufacturing optimization • Additive manufacturing and rapid prototyping technologies • Improved automation and customization in integration for smaller lots • Interconnection processes and equipment for heterogeneous integration in flexible electronics, integrated photonics
Major Challenge 4: sustainability and recyclability	**Topic 4.1:** sustainable integration and use of ECS	• Designing for reparability, including modular approach, upgrades and maintenance • Condition monitoring and predictive maintenance • Increasing the energy efficiency and environmental footprint of components, systems and modules
	Topic 4.2: recyclability of components, modules and systems	• Use of recyclable materials • Design and processes for Component dismantling and materials separation, Life cycle analysis as tool for design

MID-TERM (2027-2031)	LONG TERM (2032 – 2036)
• Integration for harsh environments, and implantable electronics • System health monitoring and self-diagnosis, self-healing	• Maximum functional integration in minimum volume/ footprint Advanced photonics • Biological-electronics hybrid systems • Stretchable electronics • Quantum SiP
• I4.0 for manufacturing optimization, Zero-defect integration • Automation and customization in integration for smaller lots. • Additive manufacturing and rapid prototyping technologies	• Automation and customization in integration, lot one. • Automated Interconnection processes and equipment for heterogeneous integration in flexible electronics, integrated photonics
• Reducing energy consumption and CO_2 footprint of integration processes and ECS systems • Processes for re-use and second life	• CO_2-neutral ECS economy
• Use of compostable and biodegradable materials • Improved recycling and material recovery processes • Breakthroughs in recycling processes, for including energy storage components	• Circular economy of ECS • Solutions for full recycling and material recovery of ECS, including energy storage components

1.2.6
SYNERGY WITH OTHER THEMES

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

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

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

1.3

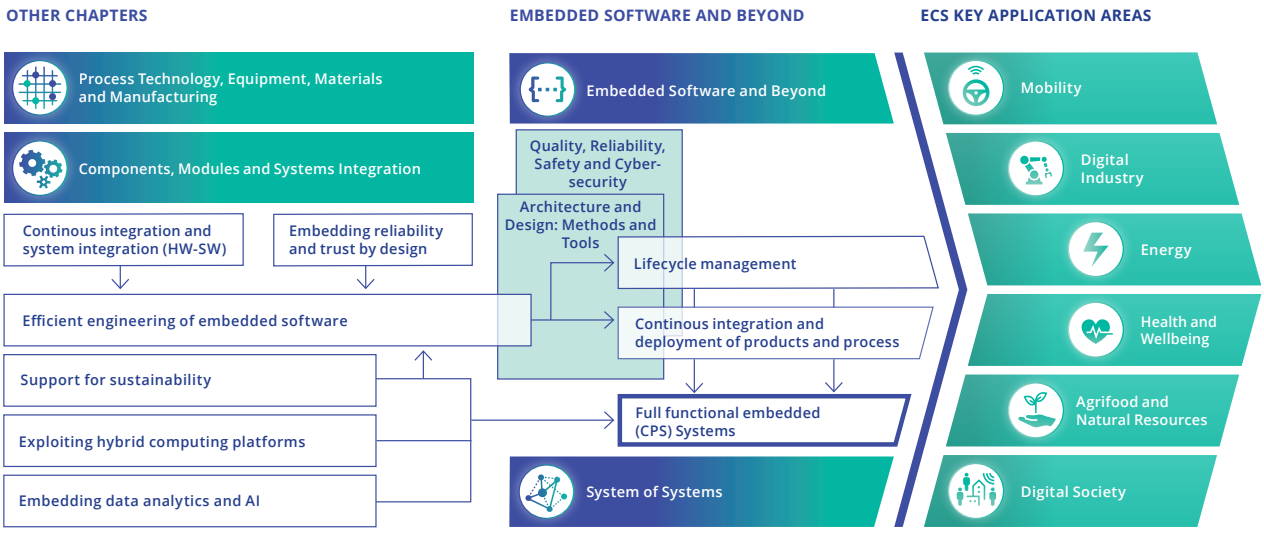
Foundational Technology Layers

EMBEDDED SOFTWARE AND BEYOND

1.3.1 INTRODUCTION

The Artemis/Advancy report[28] states that "the investments in software technologies should be on at least an equal footing with hardware technologies, considering the expected growth at the higher level of the value chain (Systems of Systems, applications and solutions)". According to the same report, embedded software technology and software engineering tools are part of the six technology domains for embedded intelligence. Embedded intelligence is the ability of a system or component to reflect on its own state (e.g. operational performance, usage load, environment), and as such is a necessary step towards the level of digitalisation and sustainability that is aimed for. In this context, embedded intelligence supports the Green Deal initiative, as one of the tools for reaching sustainability.

Embedded software enables Embedded and Cyber-Physical Systems (ECPS) in a way that they can play a key role in solutions for digitalisation in almost every application domain (cf. Chapters 3.1-3.6). The reason for this Chapter being entitled **Embedded Software and Beyond** is to stress that embedded software is a key component of system's internal intelligence, it enables systems to act on external events, and it enables inter-system communication.



Positioning of the Embedded Software and Beyond Chapter in the ECS-SRIA **F.12**

Figure F.12 illustrates the role and positioning of the **Embedded Software and Beyond** Chapter in the ECS-SRIA. The Chapter on **Components Modules and System Integration**, is focused on functional hardware components and systems that compose the embedded and cyber-physical systems (CPS), considered in this Chapter. While the System of Systems (SoS) Chapter is based on independent, fully functional systems, products and services (which are also discussed in this Chapter), they are also the constituents of SoS

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

solutions. The **Architecture and Design: Methods and Tools** Chapter, examines engineering processes, methods and tools, while this Chapter focuses more on the engineering aspects of **Embedded Software and Beyond**. For the discussion of safe, trustworthy, and explainable AI in the context of embedded intelligence this Chapter is also linked to the **Quality, Reliability, Safety and Cybersecurity** Chapter.

From a functional perspective, the role of Embedded and Cyber-Physical Systems (ECPS) in complex systems is becoming increasingly dominant (in cars, trains, airplanes, health equipment, etc.) because of the new software-enabled functionalities they provide (including autonomy). In these systems, most of the innovations nowadays come from software. ECPS are also required for the interconnection and interoperability of SoS (smart cities, air traffic management, etc). Owing to all these factors, ECPS are an irreplaceable part of the strive towards digitalisation of our society.

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

1.3.2 SCOPE

The scope of the challenges existing in embedded software engineering for ECPS includes:

- Interoperability.
- Complexity.
- Software quality (safety, security, reliability, dependability, sustainability, and, ultimately, trustworthiness).
- Lifecycle (maintainability, extendibility).
- Efficiency, effectiveness, and sustainability of software development.
- Dynamic environment of ECPS.
- Maintenance, integration, and extendibility of legacy software solutions.

To enable ECPS functionalities and their required level of interoperability, the engineering process will be progressively automated and will need to be integrated in advanced SoS engineering covering the whole product during its lifetime. Besides enabling new functionalities and their interoperability, it will need to cover non-functional requirements (safety, security, reliability, dependability, sustainability, and, ultimately, trustworthiness) visible to end users of ECPS, and also to satisfy quality requirements important to engineers

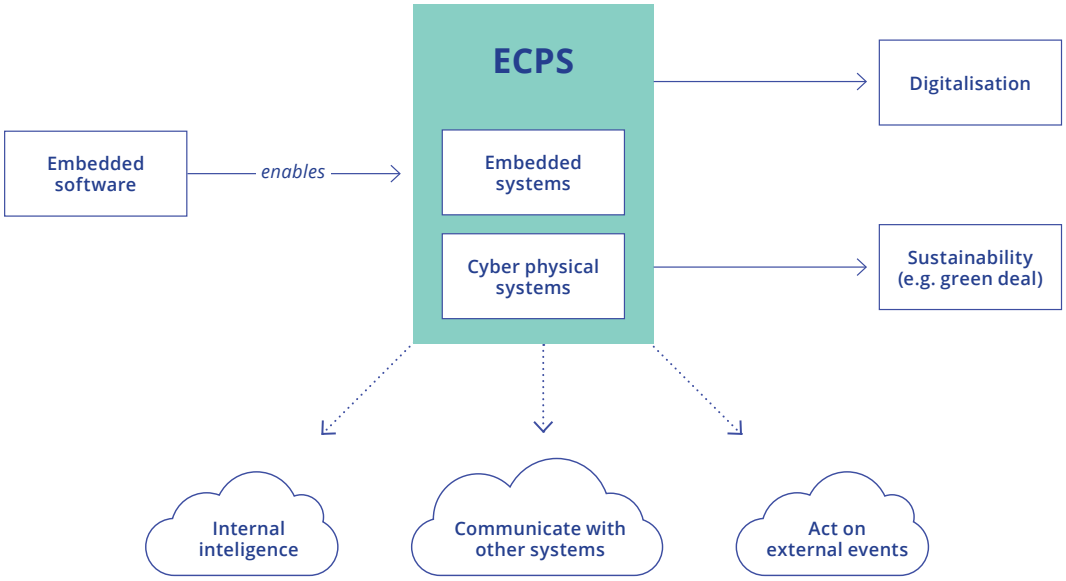
of the systems (evolution, maintenance, etc.). This requires innovative technologies that can be adapted to the specific requirements of ECPS and, subsequently, SoS.

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

Producing industrial software, and embedded software in particular, is not merely a matter of writing code: to be of sufficient quality, it also requires a strong scientific foundation. Modern software used in products such as cars, airplanes, robots, banks, healthcare systems, and the public services comprises millions of lines of code. To produce this type of software, many challenges have to be overcome. Even though software in ECPS impacts everyone everywhere, the effort required to make it reliable, maintainable and usable for longer periods is routinely underestimated. As a result, every day there are news articles about expensive software bugs and over budget or failed software development projects. Currently, there is no clearly reproducible way to develop such software solutions and simultaneously manage their complexity. Also, there exist big challenges with correctness and quality properties of software, as human wellbeing, economic prosperity, and the environment depend on it. There is a need to guarantee that software is maintainable and usable for decades to come, and there is a need to construct it efficiently, effectively and sustainably. Difficulties further increase when legacy systems are considered: information and communications technology (ICT) systems contain crucial legacy components at least 30 years old, which makes maintenance difficult, expensive, and sometimes even impossible.

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

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



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

F.13 *Importance of Embedded Software for Cyber physical systems and its roles.*

1.3.3
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

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

Considering their role in digitalisation solutions, ECPS represent a key technology to ensure the continuity of any kind of digital industrial and societal activity, especially during crises, and have an indirect but significant impact on the resilience of economic systems. Without ECPS, data would not be collected, processed, shared, secured/protected, transmitted for further analysis, etc. Embedded software allows for the practical implementation of a large set of such activities, providing the features required by the applications covered in this SRIA, where it becomes a technology enabler. The efficiency and flexibility of embedded software, in conjunction with the hardware capabilities of the ECPS, allows for embedded intelligence on the edge (edge AI), opening unprecedented opportunities for many applications that rely on the human presence

(automated driving, security and surveillance, process monitoring, etc.). Moreover, digitalisation platforms exploit embedded software flexibility and ECPS features to automate their remote management and control through continuous engineering across their entire lifecycle (provisioning, bugs identification, firmware and software updates, configuration management, etc). It is the requirement of embedded software to improve sustainability of these platforms.

Open source software and licenses

The definition of Open Source (OS) in software community implies that source code is distributed under a license in which the copyright holders grant the power to run, access, modify and re-distribute the software to anyone and for any purpose, thus enabling the development to happen under an open, collaborative model. Throughout the years, the Open Source Software (OSS) development model has gained more and more popularity around the globe. Nowadays, Open Source components are the core building blocks of application software in most innovative domains, providing developers with an ever-growing selection of off-the-shelf possibilities that they can use for assembling their products faster and more efficiently.

Open Source allows to use (freely), study (in complete transparency), improve and share (collaboratively) developed code. To achieve this, Open Source licenses exist that are compliant with the OS definition, which allow the software to be freely used, modified and shared.

The license spectrum ranges from permissive licenses (e.g., MIT, BSD, Apache) to proprietary licenses which typically don't allow modification or distribution of the software. In between, there are the "Copyleft Licenses". In contrast to permissive licenses, these are considered protective or reciprocal as they impose more constraints on the users or integrators of the software. Within this share of the spectrum we find both strong (e.g. GPL, AGPL) and weak (e.g. EPL, MPL) copyleft licenses. The strength of the copyleft governing a work is an expression of the extent to which the copyleft provisions can be efficiently imposed on all kinds of derived works. Weak copyleft licenses require users to redistribute their changes to the software under the same license, but are considered more business friendly as they typically allow the use of a different license (including sometimes proprietary licenses) when embedding the software in a larger product or solution.

Application breakthroughs

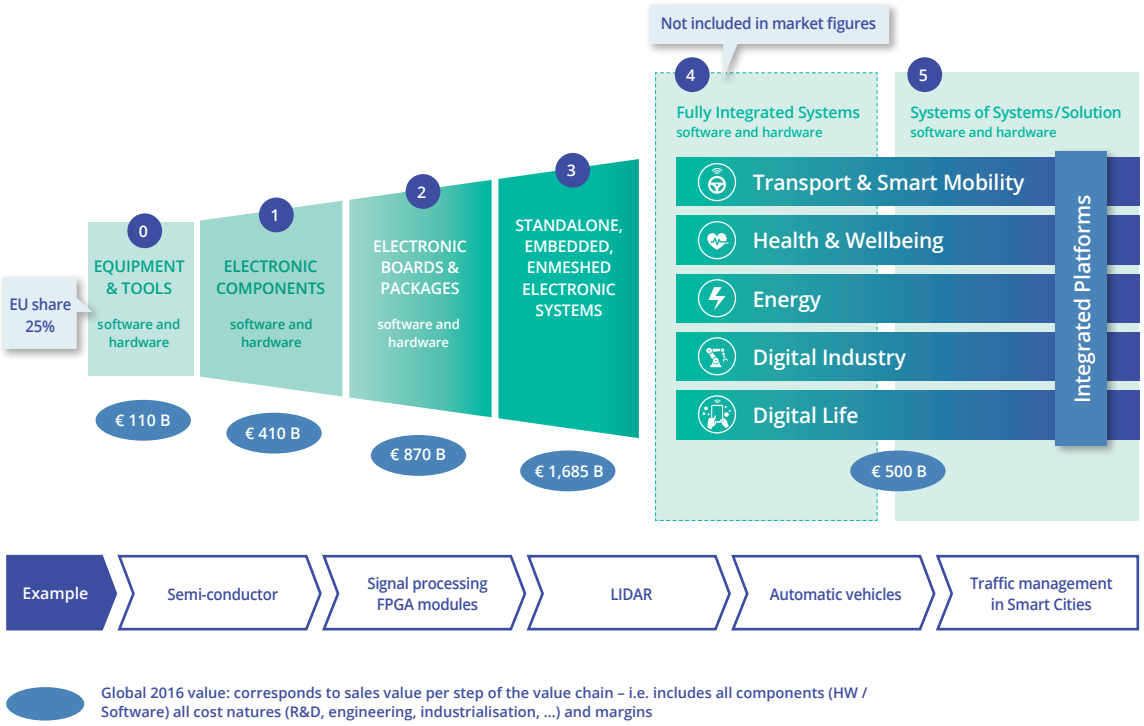
Embedded software significantly improves the functionalities, features, and capabilities of ECPS, increasing their autonomy and efficiency, and exploiting their resources and computational power, as well as bringing to the field functionalities that used to be reserved only for data centres, or more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

Following a similar approach, it has been possible to extend the functionalities of mobile phones and smart watches, which today can count steps, keep track of walked route, monitor health, inform users about nearby restaurants, etc., all based on a few extra hardware sensors and a myriad of embedded software applications. The trend is to replace specialised hardware application with software running on generic computing hardware and supported by application-specific hardware, such as AI accelerators, neural chips,

etc. This trend is also contributing to the differentiation of the value creation downstream and upstream, as observed in the Advancy report [29] (see *Figure F.14*).

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

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



F.14 *Advancy (2019)[30] report: value creation*

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

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

1.3.4
STRATEGIC ADVANTAGE FOR THE EU

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

European industry that is focused on ECS applications spends about 20% of its R&D efforts in the domain of embedded digital technologies, resulting in a cumulative total R&D&I investment of €150 billion for the period 2013–20. The trend in product and solutions perspective estimates a growth from €500 billion to €3.100–11.100 billion[31], which will be greatly determined by embedded software (30%).

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

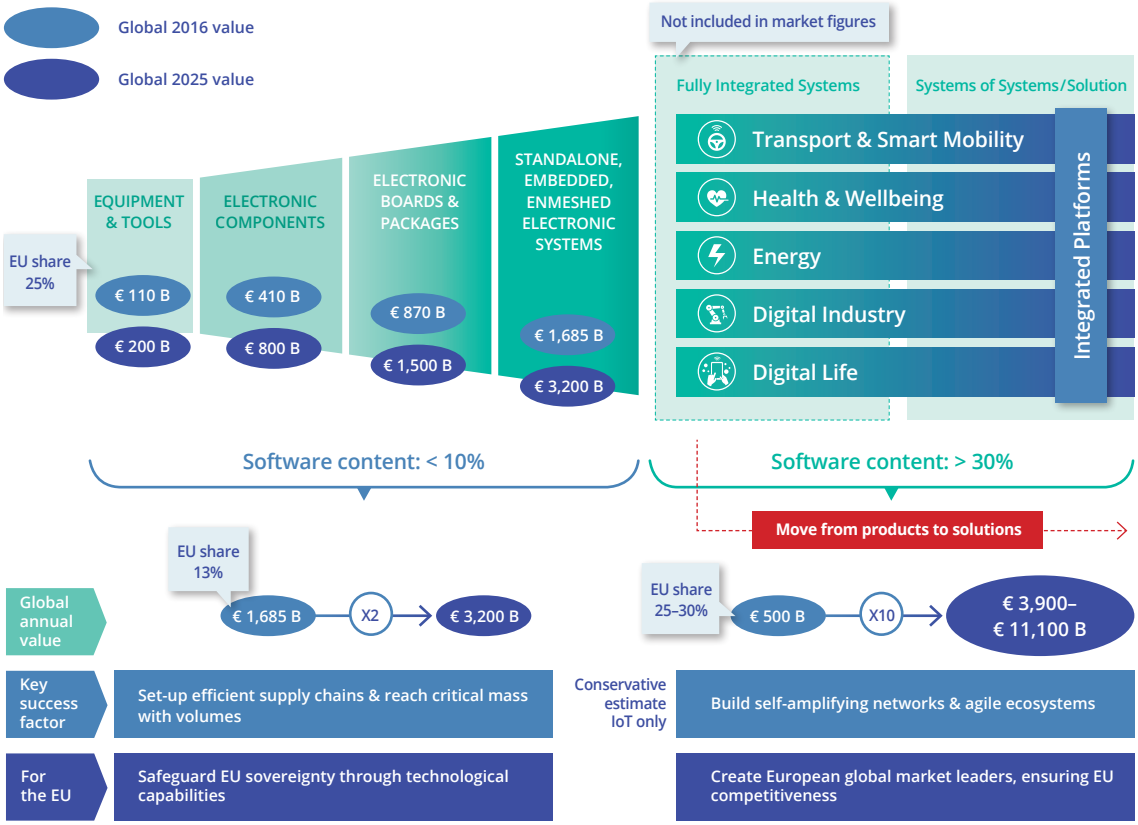
The current employment levels in the embedded intelligence market in Europe is estimated to be 9.1 million, of which 1.1 million are jobs in the embedded software area, with €15 billion being expected to be allocated to collaborative European R&D&I projects in embedded software and beyond technologies.

1.3.5
MAJOR CHALLENGES

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

- **Major challenge 1:** efficient engineering of embedded software.
- **Major challenge 2:** continuous integration and deployment.
- **Major challenge 3:** lifecycle management.
- **Major challenge 4:** embedding data analytics and artificial intelligence.
- **Major challenge 5:** support for sustainability by embedded software.
- **Major challenge 6:** software reliability and trust.

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



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

F.15 *Global and European value chain 2016–25 (Source: Embedded Intelligence: Trends and Challenges, A Study by Advancy [32], Commissioned by ARTEMIS Industry Association, March 2019).*

1.3.5.1 Major Challenge 1: efficient engineering of embedded software

1.3.5.1.1 State of the art

Embedded software engineering is frequently more a craft than an engineering discipline, which results in inefficient ways of developing embedded software. This is visible, for instance, in the time required for the integration, verification, validation and releasing of embedded software, which is estimated to exceed 50% of the total R&D&I expenses[33]. Embedded software can be classified in two major categories:

- Low level software: embedded software that is allowed to "use" hardware functionalities (e.g. the battery management software in a car, or the image-capturing algorithms of an x-ray source). This category of software often follows the design of the hardware.

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

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

- Embedded software determining ECPS functionalities and aware of the contact with other parts of the system, such as in medical image processing, right up to completely embedded applications or autonomous driving software.

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

2.3

1.3.5.1.2 Vision and expected outcome

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

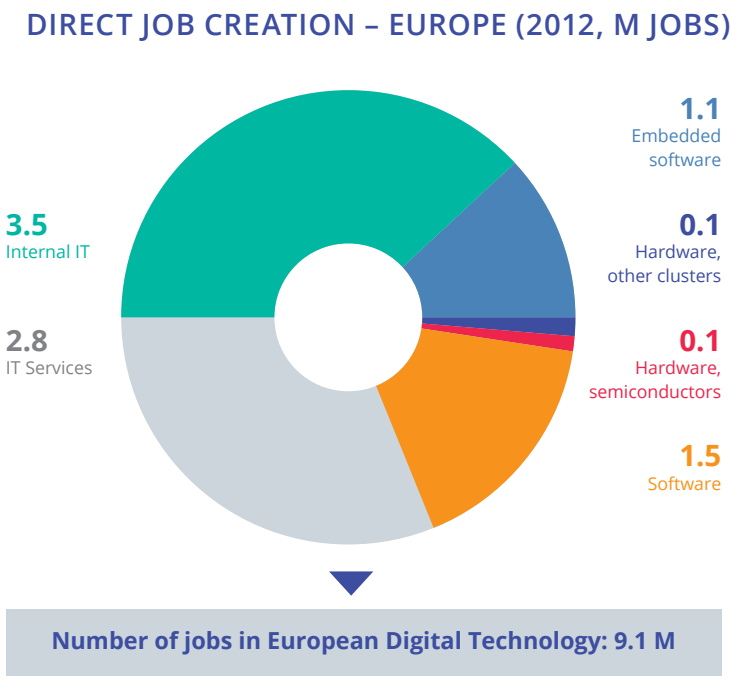
(A) From embedded software engineering to cyber physical systems engineering

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

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

2.3 2.4

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



F.16 *Direct job creation – Europe (2012, m jobs) Source: EU, IDC, Destatis, Roland Berger*

(B) Software architectures for optimal edge computing

At the moment, Edge computing lacks proper definition and, including many different types of managed and unmanaged devices, this leads to uncertainty and difficulties on how to efficiently and effectively use software architectures, including aspects as resource, device, and network management (between edge devices as well between edge and fog/cloud), security, useful abstractions, privacy, security, reliability, and scalability.

Additionally, automatic reconfiguration, adaptation and re-use face a number of challenges. These challenges are caused by diversity of edge devices and wide range of requirements in terms of Quality of Service (e.g., low latency, high throughput). Finally, sustainability and reliability are difficult to be ensured when trying to prioritize between Quality of Service on the edge and end-to-end system Quality of Service.

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

2.1

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

Since edge devices need to be self-contained, edge software architectures need to support, from one side, virtual machine-like architectures, and from the other side they need to support the entire software lifecycle. The fact that there are many different types of edge devices would also require an interoperability standard

to ensure that they can work together. Innovations in this field should focus on, amongst others, software hardware co-design, virtualisation and container technologies and new standard edge software architecture (middleware).

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

(C) Integration of embedded software

2.3

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

(D) Using abstraction and virtualisation

2.3

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

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

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

(E) Resolving legacy

1.4 2.3

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

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

1.3.5.1.3 Key focus areas

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

- Model-based software engineering:
  - Model-based software engineering enabling systems to become part of SoS.
  - Model inference to enable re-use of existing subsystems in SoS.
  - Model-based testing that takes the re-use of uncontrolled systems into account.
  - Embedded software architectures to enable SoS.
- Constraint environments:
  - Knowledge-based leadership in design and engineering.
  - Resource planning and scheduling (including multi-criticality, heterogeneous platforms, multicore, software portability).
  - Simulating and the impact of using open source.
  - Design for software evolution over time, while catering for distinct phases.
  - Exploiting hybrid compute platforms, including efficient software portability.
- Software technology:
  - Virtualisation as tool for efficient engineering.
  - Interface management enabling systems to become part of SoS.
  - Technology for safe and dependable software ecosystems.
  - Artificial intelligence-based tools to support software engineering efforts.
- SW engineering tools:
  - Middleware controlling embedded (mobile) hardware compilers, with links to new hardware.
  - Added value of, and embedding AI in, software architecture and design.
  - Programming languages for developing large-scale applications for embedded systems.
  - Models & digital twins, also at run-time for maintenance and sustainability.

1.3.5.2 Major Challenge 2: continuous integration and deployment

1.3.5.2.1 State of the art

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

1.4 2.3

One aspect of the problem relates to the design of SoS[34], which are assumed to be composed of independent subsystems but over time have become dependent. Orchestration between the different subsystems, that may involve IoT as well, is an additional issue here. Another aspect relates to the certification of such systems that requires a set of standards. This applies especially for IoT and SoS and it is complicated by the introduction of AI into software systems. Although AI is a software-enabled technology, there are still many issues on the system level when it comes to its integration into software systems. It is particularly challenging to ensure their functional safety and security, and thus to certify such systems. Some of the existing initiatives that are moving towards certification include SAE J3016, which recommends a taxonomy and definitions for terms related to automated driving. Note, that AI may be applied as an engineering tool to simplify certification.

Finally, integration practices are part of the engineering processes. Although methodologies already exist to achieve this (such as DevSecOps and ChatOps), these mostly relate to software production. With ECPS, continuous integration becomes increasingly more complex, since the products into which the new software modules have to be integrated into are already sold and 'working in the field', often in many different variants (i.e. the whole car fleet of an OEM). Even in domains where the number of variant systems is small, retaining a copy of each system sold at the producing company in order to have an integration target is prohibitive. Thus, virtual integration using model-based design methods (including closed-box models for legacy components) and digital twins used as integration targets as well as for testing by physically accurate simulation are a mandatory asset for any system company. to manage the complexity of ECPS and their quality properties. System engineering employing model-based design and digital twins must become a regular new engineering activity.

1.3.5.2.2 Vision and expected outcome

Europe is facing a great challenge with the lack of platforms that are able to adopt embedded applications developed by individual providers into an ecosystem (cf. Reference Architectures and Platforms in Chapter 2.3). As (embedded) software systems evolve towards distributed computing, SoS and microservice-based architectural paradigms, it becomes even more important to tackle the challenges of integration at the higher abstraction levels and in a systematic way. Especially when SoS or IoT is involved, it is important to be able to separate the concerns over the subsystems. The main challenges here are to ensure the adequate functionality of integrated systems (which is partially solved by the microservices approach), while ensuring key quality properties such as performance, safety, and security (see also Major Challenge 6) (which is

1.4 2.3

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

becoming increasingly complex and neglected as we adopt approaches that facilitate only integration on the functional level). Instrumental for these challenges is the use of integration and orchestration platforms that standardise many of the concerns of the different parts in the SoS, some of which are connected via IoT. In addition, Automated engineering processes will be crucial to ease the integration of parts.

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

1.4 2.3

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

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

1.3.5.2.3 Key focus areas

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

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

- Evolvability of embedded software:
  - Technology, including automation of engineering and the application of integration and orchestration platforms, for keeping systems maintainable, adaptable and sustainable considering embedded constraints with respect to resources, timing and cost.
  - Certification of safety-critical software in CPSs.

1.3.5.3 Major Challenge 3: lifecycle management

1.3.5.3.1 State of the art

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

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

1.3.5.3.2 Vision and expected outcome

2.3

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

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

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

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

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

1.3.5.3.3 Key focus areas

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

- Rejuvenation of systems:
  - Software legacy and software rejuvenation (technical debt).
  - Design for X (test, evolvability and updateability, diagnostics, adaptability, etc).
  - Continuous platform-agnostic integration, deployment and migration.
  - End-of-life and evolving off-the-shelve/open source (hardware/software).
- Digital twinning:
  - Virtualisation as means for dealing with legacy systems.
  - Virtualisation and virtual integration testing (using Digital Twins and specialized design methods, like e.g.., contract based design, for guaranteeing safe and secure updates (cf. Architecture and Design: Methods and Tools Chapter 2.4).
  - Approaches to reduce re-release/re-certification time, i.e. model based design, contract based design, modular architectures, etc.
  - Distinct core system versus applications and services.
  - Design for X (test, evolvability and updateability, diagnostics, adaptability, etc).
- Managing complexity over time:
  - Interplay between legacy software and new development approaches.
  - Vulnerability of connected systems.
  - Continuous certification of updates in the field (reduce throughput time).
  - Diagnostics of systems in the field.
- Managing configurations over time:
  - Enable tracking system configurations over time.
  - Create a framework to manage properties like composability and system orchestration.

1.3.5.4 Major Challenge 4: embedding data analytics and artificial intelligence

1.3.5.4.1 State of the art

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

2.1

2.4

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

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

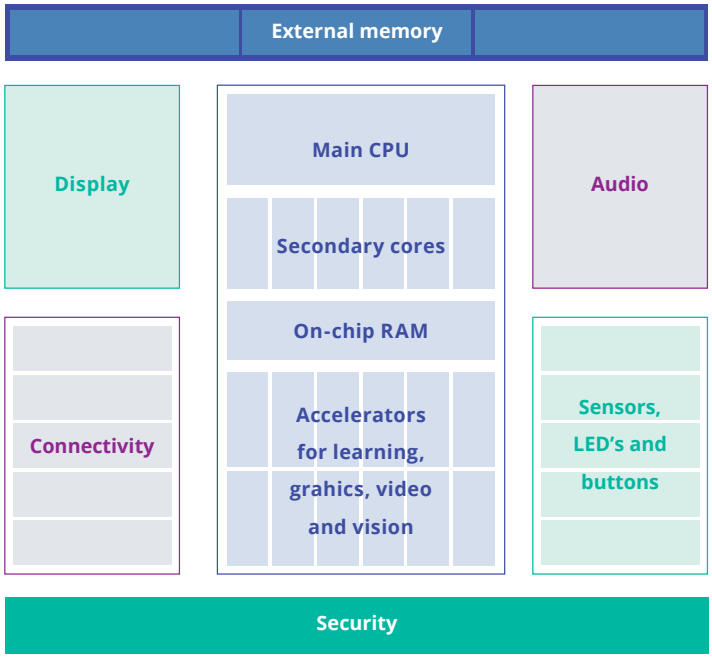
2.1

Once developed (on servers), a neural network has to be tuned for its embedded target by pruning the network topology using less precision for operations (from floating point down to 1-bit coding) while preserving accuracy. This was not a concern for the "big" AI development environment providers (e.g., Tensorflow, PyTorch, Caffe2, Cognitive Toolkit) until recently. This has led to the development of environments designed to optimise neural networks for embedded architectures[35], but Google, Apple, Facebook, Amazon and Microsoft (GAFAM) and Baidu, Alibaba, Tencent, Xiaomi (BATX) are now increasingly aware of the move towards the Edge. For example, Google's Tensorflow Lite is now dedicated for targeting embedded devices. The Google Assistant will also work locally on smartphones due to a "completely new speech recognition and language understanding models, bringing 100GB of models in the cloud down to less than half a gigabyte"[36], allowing real-time performance, lower latency and the ability to work even without a connection. NVIDIA's TensorRT has the same goal of optimising the inference phase for running on embedded GPUs.

35 *Such as N2D2, https://github.com/CEA-LIST/N2D2*

36 *https://www.blog.google/products/assistant/ next-generation-google-assistant-io/*

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



F.17 *Data analytics and Artificial Intelligence require dedicated embedded hardware architectures*

1.3.5.4.2 Vision and expected outcome

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

2.4

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

2.3

1.3.5.4.3 Key focus areas

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

- Federated learning:
  - Create federated learning at the edge in heterogeneous distributed systems (analysis, modelling and information gathering based on local available information).
  - Federated intelligence at the edge (provide context information and dependability based on federated knowledge).
- Embedded Intelligence:
  - Create a software AI framework to enable reflecting and acting on the systems own state.
  - Dynamic adaption of systems when environment parameters and sensors like IoT devices are changing.
- Data streaming in constraint environments:
  - Feed streaming data into low-latency analysis and knowledge generation (using context data to generate relevant context information).
- Embedding AI accelerators:
  - Accelerators and hardware/software co-design to speed up analysis and learning (patter analysis, detection of moves (2D and 3D) and trends, lighting conditions, shadows, etc).
  - Actual usage-based learning applied to accelerators and hardware/software co-design (automatic adaptation of parameters, adaptation of dispatch strategies, or use for new accelerators for future system upgrades).

1.3.5.5 Major Challenge 5: support for sustainability by embedded software

1.3.5.5.1 State of the art

The complete power demand in the whole ICT market currently accounts from 5% to 9% of the global power consumption[37]. The ICT electricity demand is rapidly increasing and it could go up to nearly 20% in 2030[3]. Compared to estimated power consumption of future large data centres, embedded devices may seem to be a minor problem. However, when the devices powered by batteries still have a significant environmental impact. Energy efficient embedded devices produce less hazardous waste and last longer time without need to be replaced.

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

1.1 1.2

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

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

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

1.3.5.5.2 Vision and expected outcome

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

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

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

2.3

1.2 2.1

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

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

1.3.5.5.3 Key focus areas

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

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

1.3.5.6 Major Challenge 6: software reliability and trust

1.3.5.6.1 State of the art

Two emerging challenges for reliability and trust in ECPS relate to computing architectures and the dynamic environment in which ECPS exist. The first challenge is closely related to the end of Dennard scaling[38]. In the current computing era, concurrent execution of software tasks is the main driving force behind the performance of processors, leading to rise of multicore and manycore computing architectures. As the number of transistors on a chip continues to increase (Moore's law is still alive), industry has turned to a heavier coupling of software with adequate computing hardware, leading to heterogeneous architectures. The reasons for this coupling are the effects of dark silicon[39] and better performance-to-power ratio of heterogeneous hardware with computing units specialised for specific tasks achieves. The main challenges for using concurrent computing systems in embedded systems remain: (i) hard-to-predict, worst-case execution time; and (ii) testing of concurrent software against concurrency bugs[40].

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

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

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

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

On the level of systems composed from embedded devices, the most important topics are the safety, security, and privacy of sensitive data. Security challenges involve: (i) security of communication protocols between embedded nodes, and the security aspects on the lower abstraction layers; (ii) security vulnerabilities introduced by a compiler[41]; and (iii) hardware-related security issues[42]. It is necessary to observe security, privacy and reliability as quality properties of systems, and to resolve these issues on a higher abstraction level by design[43].

2.3 2.4

1.3.5.6.2 Vision and expected outcome

European industry today relies on developed frameworks that facilitate production of highly complex embedded systems (for example, AUTOSAR in the automotive industry). However, such frameworks are exclusive to enterprises that can afford to invest heavily into their systems, ensuring system quality properties such as safety, security and reliability. But beyond that, platforms with these qualities is exactly what is needed for powering national digital infrastructures.

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

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

2.3

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

Apart from techniques that enable the testing and verification of developed systems and their parts, it is necessary to provide technologies that ensure reliability and correctness of system development. These activities consider providing tools and means for collaboration when developing such complex software

41 V. D'Silva, M. Payer and D. Song, "The Correctness-Security Gap in Compiler Optimization," 2015 IEEE Security and Privacy Workshops, 2015, pp. 73-87, https://doi.org/10.1109/SPW.2015.33

42 Moritz Lipp, Vedad Hadžić, Michael Schwarz, Arthur Perais, Clémentine Maurice, and Daniel Gruss. 2020. Take A Way: Exploring the Security Implications of AMD's Cache Way Predictors. In Proceedings of the 15th ACM Asia Conference on Computer and Communications Security (ASIA CCS '20). Association for Computing Machinery, New York, NY, USA, 813–825. DOI:https://doi.org/10.1145/3320269.3384746

43 Dalia Sobhy, Leandro Minku, Rami Bahsoon, Tao Chen, Rick Kazman, Run-time evaluation of architectures: A case study of diversification in IoT, Journal of Systems and Software, Volume 159, 2020, 110428, ISSN 0164-1212, https://doi.org/10.1016/j.jss.2019.110428

systems – especially modelling approaches for capturing correctness criteria for dynamic SoS, against which it is then necessary to perform testing and verification.

1.3.5.6.3 Key focus areas

2.3 2.4

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

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

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

- Reliable software on new hardware (multi-core systems, GPUs, heterogeneous computing, field-programmable gate arrays (FPGAs), distributed computing architectures, including edge, fog and cloud processing):
  - Code coverage of reliability tooling and porting.
  - Validation and verification through simulation and mock-up based approaches for handling concurrency.
  - Embedding reliability on a software system architecture level.
- Robustness against unexpected uses:
  - Trustworthy, secure, safe, privacy-aware.
  - Testing self-adapting systems using simulation.
- Security and privacy as a service:
  - To become part of the software architecture.
  - Means and techniques for continuous system monitoring and self-monitoring.

1.3.6 TIMELINE

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

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 1: efficient engineering of embedded software	**Topic 1.1:** modelling-based software engineering	• Model-based software engineering enabling systems to become part of SoS
	Topic 1.2: constraint environments	• Resource planning and scheduling • Design for software evolution over time
	Topic 1.3: software technology	• Virtualisation as tool for efficient engineering • Technology for safe and dependable software ecosystems
	Topic 1.4: software engineering tools	
Major Challenge 2: continuous integration of embedded software	**Topic 2.1:** continuous integration	• DevOps modelling • Virtualisation
	Topic 2.2: verification and validation	• Virtualisation of test platform
	Topic 2.3: evolvability of embedded software	• Adaptable embedded software
Major Challenge 3: lifecycle management of embedded software	**Topic 3.1:** rejuvenation of existing systems	• Software legacy and software rejuvenation • Design for rejuvenating systems in a later phase
	Topic 3.2: digital twinning	• Virtualisation as tool for dealing with legacy systems
	Topic 3.3: managing complexity over time	• Diagnostics of systems in the field
Major Challenge 4: embedding data analytics and AI	**Topic 4.1:** federated learning	• Create federated learning at the edge in heterogeneous distributed systems
	Topic 4.2: data streaming in constraint environments	• Feed streaming data into low-latency analysis and knowledge generation
	Topic 4.3: embedding AI accelerators	• Accelerators and hardware/software co-design to speed up analysis and learning

MEDIUM TERM (2027-2030)	LONG TERM (2031-2036)
• Model inference to enable re-use of existing subsystems in SoS	• Model-based testing taking re-use of uncontrolled SoS into account
• Embedded software architectures to enable SoS	• Exploiting hybrid computer platforms, including efficient software portability
• Interface management enabling systems to become part of SoS	• Develop new software architectures for edge computing • Artificial intelligence to assist and support efforts in software engineering
• Middleware controlling dynamically embedded (mobile) hardware solutions • Compilers and link to new hardware	• Programming languages for developing large-scale applications for embedded SoS
• Simulation on a virtual platform	• Digital twin • Model-based engineering based on digital twins
• Model-based testing	• Integration & orchestration platforms for IoT and SoS
• Dynamical embedded software	• Autonomous embedded software • Autonomous processes (IoT & edge embedded HW/SW co-design)
• End-of-life and evolving off-the-shelve/open source solutions	• The cloud-for-edge continuum - “Write once, run anywhere” on this computing continuum • Composability, properties contracts and orchestration systems • Interoperability: must be ensured in integration platforms
• Enabling secure updates and extending useful life	• Distinct core system versus applications and services • SW updates, device management, and data management
• Continuous certification	• Interplay between legacy
• Federated intelligence at the edge	• Safe, trustworthy & explainable AI • AI is playing several key roles in innovation, e.g. as a tool for SW development/engineering • Embedded intelligence
• Actual usage based learning applied for accelerators and hardware/software co-design	• Use of AI in autonomous systems

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 5: Green Deal and embedded software	**Topic 5.1:** green-aware software	
	Topic 5.2: green-aware hardware	• Integration of green-aware in software integration
	Topic 5.3: extending lifetime of products and services	• Rejuvenation technologies
Major Challenge 6: embedding reliability and trust	**Topic 6.1:** reliability of software and new hardware	• Code coverage of reliability tooling and porting • Simulation and mock-up based approaches for handling concurrency
	Topic 6.2: robustness (trustworthy, secure, safe, privacy- aware)	• Trustworthy, secure, safe, privacy-aware • Testing self-adapting systems using simulation
	Topic 6.3: security and privacy as a service	• Design for security and privacy as a service

MEDIUM TERM (2027-2030)	LONG TERM (2031-2036)
• Design for green-aware products	
• Design for extending lifetime	• Digital twins that support green deal and enable sustainability(e.g. contain power models)
• Embed reliability on software architecture level	• Use of quantum computing • IoT digital twin simulation • Validation and verification through simulation and mock-up based approaches for handling concurrency
• Define a maturity model for robustness of embedded software and beyond	
• Architecture for security and privacy as a service	

1.3.7
SYNERGY WITH OTHER THEMES

Opportunities for joint research projects, including groups outside and within the ECS community, can be expected in several sections of the Application chapters, the chapters in the technology value stack and with cross sectional chapters. There are strong interactions with the **System of Systems** Chapter. In the System of Systems Chapter, a reasoning model for system architecture and design is one of the main challenges. Part of system architecture and design is the division in which the system functions will be solved in hardware, and which will be solved in Embedded Software and Beyond. Embedded Software can be divided into two parts: software enabling the hardware to perform, and software implementing certain functionalities. Furthermore, there are connections with the cross-technology chapters, **Artificial Intelligence, Edge Computing and Intelligence on the Edge, Architecture and Design: Methods and Tools, and Quality, reliability, safety and cybersecurity**. With respect to AI, using AI as a technology and software components powered by AI in embedded solutions will be part of the **Embedded Software and Beyond** Chapter, while innovating AI will be part of the **AI, Edge Computing and Intelligence on the Edge** Chapter, and discussing its quality properties will be part of the Quality, reliability, safety and cybersecurity. With respect to the **Architecture and Design: Methods and Tools** Chapter, all methods and tools belong there, while Embedded Software and Beyond focuses on development and integration methodologies. The challenges of preparing useful embedded solutions will be part of the **System of Systems** Chapter and the **Embedded Software and Beyond** Chapter. The embedded software solutions for new computing devices, such as quantum computing, will be part of the **Long-Term Vision** Chapter.

1.4

Foundational Technology Layers

SYSTEM OF SYSTEMS

1.4.1 SCOPE

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

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

According to the definition, SoS[44] must satisfy five characteristics: (i) the operational independence of constituent systems; (ii) the managerial independence of constituent systems; (iii) geographical distribution; (iv) emergent behaviour; and (v) evolutionary development processes. A system that does not satisfy these characteristics is not considered a SoS.

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

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

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

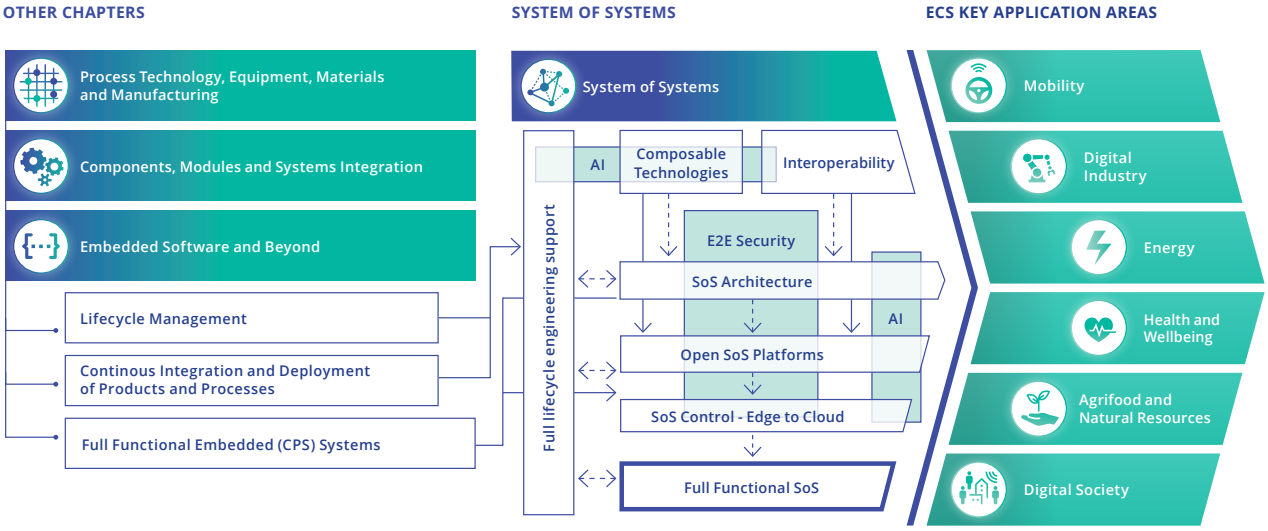
that single charging stations and vehicles cannot independently provide. Application areas of SoS are very diverse, covering most industrial and societal domains.

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

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

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

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



Structure: System of Systems

F.18

1.4.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

There is a very strong market pull[45] for systems of embedded and cyber physical systems in supply chains, smart grids, smart cities, etc, and there is also a similar situation for very complex system such as autonomous vehicles, distributed EV-Charging infrastructures, lithography machines, operation theatres, etc.

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

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

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

45 *Embedded Intelligence: Trends and challenges, Artemis report, 2019*

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

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

1.4.2.1 Application breakthroughs

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

3.4

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

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

3.1

- Achieving the Green Deal for mobility with the 2 Zero goals of –37.5% CO2 by 2030.
- Increased road safety through the CCAM programme.
- Competitiveness of the European industrial mobility digitalisation value chain.
- Ensuring inclusive mobility for persons and goods by providing mobility access to everyone, with a focus on special needs.

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

3.3 3.5

- Significant reduction and recovery of losses (application and SoA-related).
- Increased functionality, reliability, and lifetime (incl. sensors & actuators, ECS HW/SW, semiconductor power devices, artificial intelligence, machine learning, monitoring systems,etc.).
- Management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility. Grid stabilization through e-vehicle charging.
- Energy supply infrastructure for e-mobility, digital live, and industry 4.0.
- "Plug and play integration" of ECS into self-organised grids and multi-modal systems, real- time digital twin capability in component and complete system design (to simulate system behaviour).

- Safety and security issues of self-organised grids and multi-modal systems through smart edge devices and high-level IT security (resilient communications and trustworthy AI).
- Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.
- Energy technologies in the circular economy approach: predictive and condition-based maintenance with repair and recycle capabilities.
- Aligning with standardization of our energy systems.

3.3 3.5

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

- Intelligent control room systems to enable correlations between machine malfunctions and load parameters to be detected immediately, thereby enabling maintenance work to be carried out early and on schedule, with a reduction in costly downtimes.
- Food industry imposes specific requirements (e.g. in food processing) that may take advantage of smart (bio-)sensing for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
- AI/machine learning (ML) and big data models must be devised and used to offer further intelligent decision-making and, whenever possible, should be employed directly at-the-edge for greater energy efficiency.
- IIoT systems can provide the flexibility to tailor-make new products to help cope with ever-demanding diets.
- Remotely piloted autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, to improve efficiency.
- Smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced) – e.g. weather/climate information for predictive models providing risk assessments and decision support for IPM.
- IoT devices specialising in pests and disease measurements, such as insect traps and other systems based on image recognition or AI models.
- Large-scale and high-precision measurements of plant growth, architecture and composition.
- Winning the global platform game on various application sectors (that are currently strong) and in building effectively and, at a high level, outperforming applications and systems for industrial and business needs.
- Preparing for the 5G and beyond era in communications technology, especially its manufacturing and engineering dimension.
- Solving IoT cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive.
- Interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management that allows for the (semi)autonomous deployment and operation of a large number of devices.
- Decision support for AI, modelling and analytics in the cloud and also in edge/fog settings.

3.6

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

- Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
- AI into the design, manufacturing, production and deployment processes, productivity can be improved.

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

1.4.3 STRATEGIC ADVANTAGE FOR THE EU

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

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

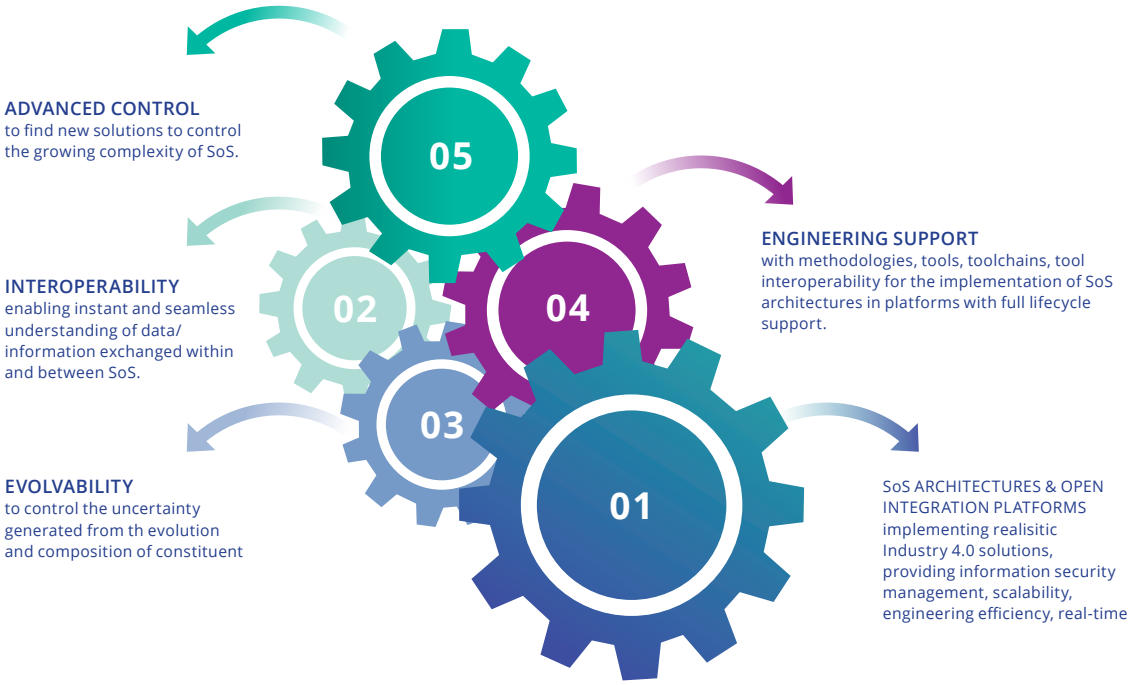
Similar situations can be identified in healthcare technology and in the electronics and components sectors, where world-leading companies provide very complex products and services. These can be internally regarded as a SoS or system of cyber-physical systems (SoCPS). It is obvious that these products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

SoS have been originally conceived and studied in the defence domain, but they are (and will be) vital infrastructure for many other vertical domains, including transportation, energy, healthcare and wellbeing, natural resource management, agriculture, disaster response, consumer products, finance, media, etc. In all these verticals, the shared enabling technology is represented by open SoS platforms that can play a central role in digitalisation solutions to orchestrate entire supply chains, manage assets, production, operations, processes, marketing and sales, and also in ensuring business continuity and resilience during global crises. The market for open SoS platforms is still very new, and several aspects still need to be completely constructed. Nevertheless, IoT platforms, which currently represent the larger subset of the SoS platforms market, is a very rapidly growing market: a recent study indicated that IoT platform revenues already amounted to US

$55 billion in 2019 and estimated have to reached US $66 billion by 2020, with an annual growth of 20%[46]. With the impact of IoT and its evolution towards SoS, the current and future expectations of the market justify investment in SoS research and innovation[47].

The Advancy report on embedded intelligence very clearly points to the SoS market pull for the complete ECS value chain, with market growth being projected at €3.4–10.6 trillion[48]. Rapid EU advancement in the SoS area is therefore critical to the whole ECS value chain.

FIVE MAIN DIRECTIONS FOR INNOVATION



Fine Main Directions of Innovation (source: Eurotech).

F.19

46 *The Internet of Things: Consumer, Industrial & Public Services 2020-2024, Juniper Research, 2020/05/05*

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

48 *Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.*

1.4.4 MAJOR CHALLENGES

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

- **Major Challenge 1:** SoS architecture and open integration platforms.
- **Major Challenge 2:** SoS interoperability.
- **Major Challenge 3:** evolvability of SoS composed of embedded and cyber-physical systems.
- **Major Challenge 4:** system of embedded and cyber-physical systems - SoECPS – engineering.
- **Major Challenge 5:** control in SoS composed of embedded and cyber-physical systems.
- **Major Challenge 6:** SoS monitoring and management.

1.4.4.1 Major Challenge 1: SoS architecture and open integration platforms

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

1.4.4.1.1 State of the art

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

Current industrial state of the art are a couple of major commercial and proprietary information/communications/control/technology platforms offering industrial solutions for complex automation solutions from companies like e.g. Schneider Electric[49], Siemens[50], Bosch[51], Emerson[52], ABB[53], Advantech[54]. These proprietary digital platforms, at various levels, support design, implementation and operation of SoS architectures tailored for dedicated solutions in sectors including e.g. manufacturing, water and wastewater, minerals and mining, oil and gas, energy sectors, smart cities.

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

49 *https://ecostruxure.schneider-electric.com/*

50 *https://www.plm.automation.siemens.com/global/en/webinar/iiot-the-next-big-digital-disruption/31921*

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

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

53 *https://ability.abb.com/*

54 *https://www.advantech.com/resources/ news/advantech-launches-30-iiot-solutions- through-the-co-creation-model-and-the- wise-paas-platform-and-announces-a- large-scale-showcase-in-november*

To take the next step, Europe and other regions have invested in a number of open SoS integration frameworks and platforms. A summary of these is shown in *Figure F.21*[55].

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

Open architectures and reference implementations such as e.g. the IMC-AESOP approach[56], Eclipse Arrowhead[57], Eclipse Basyx[58], FiWare[59], PERFoRM30[60] are providing a link to standardisation activities in national and international innovation platforms. Such standardisation activities are e.g. DIN Specification 91345[61] "Reference Architecture Model for Industry 4.0" (RAMI 4.0), the "Industrial Internet Architecture" (IIA), the "High Level Architecture of the Alliance for Internet of Things Innovation", the "NIST Big data Reference Architecture", to name just a few. A complementary overview of such high-level architecture frameworks is shown in *Figure F.20*[62].

55 *Industrial Frameworks for Internet of Things: A Survey, IEEE System journal 2020*

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

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

58 *https://www.eclipse.org/basyx/*

59 *https://www.fiware.org/*

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

61 *https://www.en-standard.eu/din-spec-91345-reference-architecture-model-industrie-4-0-rami4-0/*

62 *On devising an architecture framework for system-of-systems, Bedir Tekinerdogan, SiSoS@ECSA '16: Proceedings of the International Colloquium on Software-intensive Systems-of-Systems at 10th European Conference on Software Architecture, November 2016 Article No.: 4 Pages 1–6 https://doi.org/10.1145/3175731.3175732*

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

F.20 *SoS architecture panorama.*

Europe has a strong investment in large projects that have delivered open platforms for the implementation of solutions based on SoS platforms[63]. Considering the platforms referred to in Figure *Figure F.21*, Eclipse Arrowhead, AUTOSAR, FiWare and BaSys have all been developed with substantial European leadership and partnership.

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

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

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

F.21 *Open SoS integration frameworks and platforms*[64]

Security takes on a new dimension in the case of SoS. In this Chapter, security is taken to be the ability to prevent leaking information and to prevent the taking over of control of the SoS by agents not being part of the SoS, but also the guarantee that no hostile party can prevent the sharing of essential information between the systems comprising the SoS. Several security aspects require attention. First, the level of security of each individual system requires attention: the lower bound to security of a SoS is determined by the system with the lowest security level, and by the link with the lowest security level between systems ("weakest link in the chain"). This is covered in section 2.4 ("Quality, Reliability, Safety and Cybersecurity") at the system level.

2.4

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

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

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

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

1.4.4.1.2 Vision and expected outcome

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

This requires new and improved platform technologies comprising:

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

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

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

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

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

- security and trust,
- safety,
- stability,
- composability,
- evolution,
- interoperability,
- engineering tools and procedures,
- advanced control,
- energy consumption.

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

This requires new and improved platform technologies comprising:

- robust design- and run-time integration and orchestration of functionalities at the edge,
- platform support for multi-level security, security management scalability, engineering,
- efficiency, real-time performance, closed loop and digital control, QoS, distributed intelligence and other key application area requirements, 2.3 2.4
- interoperability to legacy SoS technology,
- interoperability to existing and emerging IoT and SoS technologies and platforms,
- a high degree of autonomous operation and failure mitigation,
- enabling SoS flexibility.

1.4.4.1.3 Key focus areas

The key focus is how SoS architectures and their open implementation platforms can enable and leverage important and necessary aspects while also enabling efficient adaptation to specific application solutions.
To support EU strategic autonomy, a small number of SoS architectures and integration platforms should be driven by EU-based ecosystems. Important features that such platforms should provide include:

- a robust support for the integration of a wide range of solutions in diverse fields of applications,
- integration platform and associated engineering tools and toolchains that support the complete engineering process in both design- and run-time, including SoS critical aspects such as e.g. security, safety and risk mitigation, 2.3
- suitable and adaptable engineering processes, with associated training material for solution engineering.

1.4.4.2 Major Challenge 2: SoS interoperability

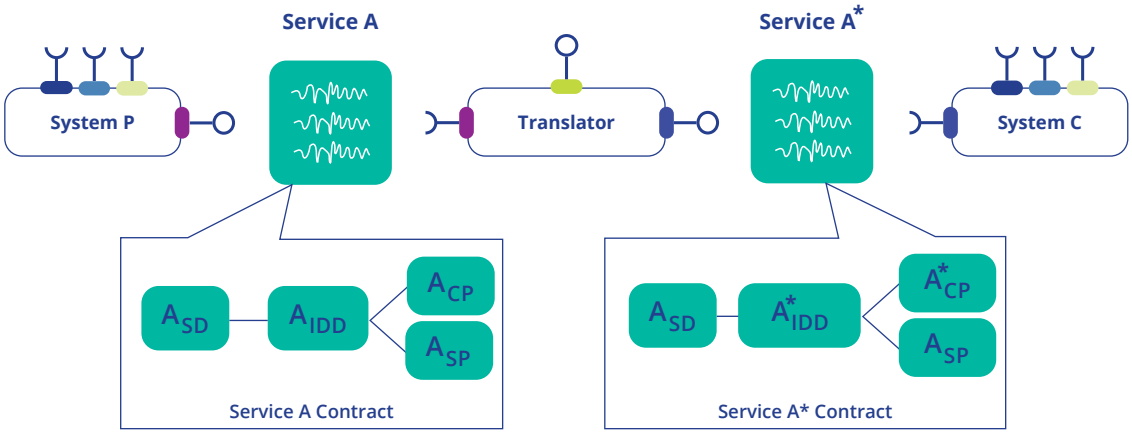
SoS interoperability enables instant and seamless understanding of information exchanged within and between networked and distributed systems.

1.4.4.2.1 State of the art

Interoperability in the SoS domain is a rising problem for cost-effective engineering and operation of systems of embedded and cyber-physical systems (see *Figure F.22*).

There is currently no industrial solution to this problem. Academia and industry are experimenting with approaches based on, for example, ontologies[65], machine learning[66] and open semantic frameworks[67]. No clear winning approach can be identified based on current research results.

INFORMATION INTEROPERABILITY



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

F.22

1.4.4.2.2 Vision and expected outcome

To enhance EU leadership and sovereignty in the field of systems of embedded and cyber-physical systems, autonomous information translation for understanding is a necessity. Some integration platforms already focus on protocol and information interoperability[68]. To enable the cost- and time- efficient engineering of solution integration and extension, their updates and upgrades over the lifecycle is crucial. Therefore, integration platforms have to provide mechanisms for dynamic and instant information translation across the ontologies and semantics used the individual constituent systems of the SoS.

1.4.4.2.3 Key focus areas

2.3

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

- Translation between standardised data models (e.g. ISO 103030, ISO 15926, BIM, etc.).
- Translation between different implementations of standardised data models.
- Automated data model translation.
- Autonomous data model translation.

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

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

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

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

- Efficient and flexible engineering procedures.
- Engineering tools that support the complete engineering process in both design- and run-time.
- Support for key automation requirements.
- Automated engineering.

1.4.4.3 Major Challenge 3: evolvability of SoS composed of embedded and cyber-physical systems

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

1.4.4.3.1 State of the art

Evolvability and composability is a multi-dimensional key aspect of SoS evolution, one that affects their architectures, properties, functionalities and behaviours from different perspectives (evolvability, trust, interoperability, scalability, availability, resilience to failures, etc.). Primarily, composability must ensure the persistence of the five major attributes that characterise a SoS (see Maier, 1998[69]). Vertical (hierarchical) composability provides the most common way to build a SoS that is typically structured in a hierarchical stack composed of adjacent layers. Vertical composability has to deal with the different abstraction levels of the stack layers, adopting aggregation and de-aggregation solutions as references to compose the constituent systems of the SoS. Architectural composability, on the other hand, is fundamental for SoS design, specifically when critical requirements such as trust or safety must be satisfied (see Neumann 2004[70], for an extensive report on trustworthy composable architectures).

In the hierarchical structure of a SoS, the constituent systems that are at the same level typically compose horizontally (in parallel or serially), potentially generating competing chains of constituent systems. Serial composability represents a critical issue for all properties that are not automatically transitive, such as trust. Indeed, the inclusion of AI in embedded and cyber-physical systems increases the required level of trust, as well as the uncertainty of the results of the composition process (see, for example, Wagner, 2015[71]).

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

69 *Architecting Principles for Systems-of-Systems, Mark W. Maier, Systems Engineering journal, John Wiley & Sons 1998*

70 *Peter G. Neumann, "Principled Assuredly Trustworthy Composable Architectures", DARPA, Computer Science Laboratory SRI International EL-243, 333 Ravenswood Ave, Menlo Park, California 94025-3493, USA.*

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

1.4.4.3.2 Vision and expected outcome

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

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

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

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

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

1.3 2.1

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

2.4

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

2.3

1.4.4.3.3 Key focus areas

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

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

- Methods and tools for engineering evolvability of systems of embedded and cyber physical systems.
- Evolutionary architectures in systems of embedded and cyber-physical systems.
- Evolvable solutions for trust, availability, scalability, and interoperability.
- Evolvable solutions capable for managing resulting uncertainty emergent properties, functionalities and behaviours, including resilience to failures.
- Evolvability in systems of cyber-physical systems supported by virtual engineering (e.g. digital twins).
- Methods and tools to manage emergencies in embedded and composable systems of cyber-physical systems.
- Service-based vertical and horizontal evolvability to enable high-level, and potentially cross-domain, interoperability of embedded and cyber-physical systems.

1.4.4.4 Major Challenge 4: system of embedded and cyber-physical systems - SoECPS - engineering

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

1.4.4.4.1 State of the art

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

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

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

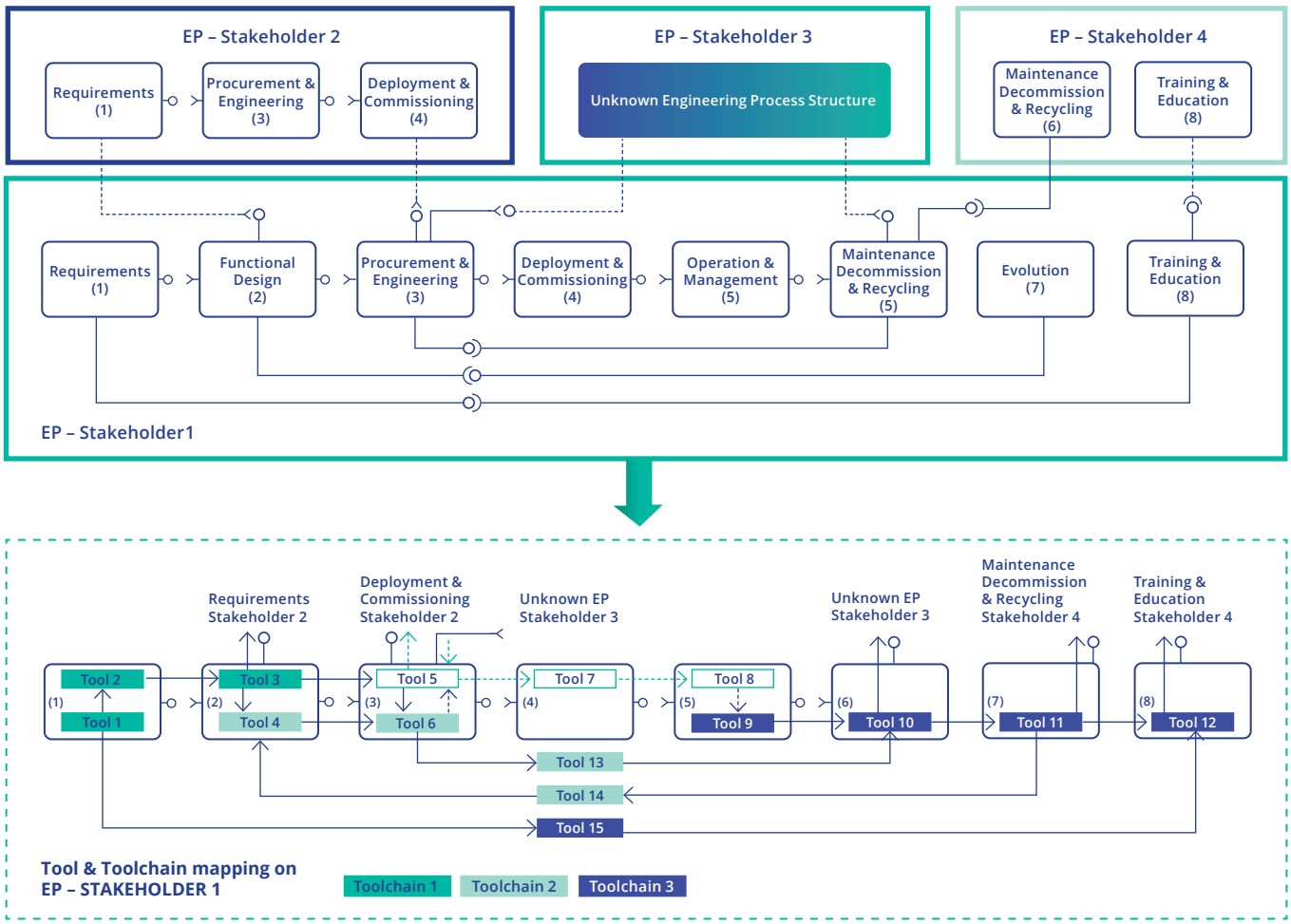
1.4.4.4.2 Vision and expected outcome

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

This is expected to lead to automated engineering processes and toolchains that can be integrated between multiple stakeholders, multiple brand and multiple technologies, supporting engineering efficiency, solution quality and sustainability, (*Figure F.23*)[72]:

- Flexible engineering procedures.
- Model-based engineering procedures and tool.
- Supported by interoperable and flexible toolchains.
- Integration of multi-stakeholder engineering processes.

2.3



Example of conceptual service-oriented view on the integration of multiple service-based engineering processes (EP) from different stakeholders, including the engineering process mapping with integrated toolchains and tools[24]

F.23

72 G. Urgese, P. Azzoni, J. v. Deventer, J. Delsing and E. Macii, "An Engineering Process model for managing a digitalised life-cycle of products in the Industry 4.0," NOMS 2020 – 2020 IEEE/IFIP Network Operations and Management Symposium, Budapest, Hungary, 2020, pp. 1-6, doi: 10.1109/NOMS47738.2020.9110365.

1.4.4.4.3 Key focus areas

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

2.3

- Efficient and flexible engineering processes.
- Model based engineering.
- Engineering tools supporting the complete engineering process along the system's lifecycle.
- Support for key automation requirements.
- Automated engineering.
- Automated testing validation and verification (TV&V).

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

1.4.4.5 Major Challenge 5: control in SoS composed of embedded and cyber-physical systems

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

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

1.4.4.5.1 State of the art

In alignment with the traditional architectures in "Control and Automation", automation, control and monitoring schemes in most SoS today are characterized by a hierarchical and centralised architecture, made up of layers of sensors and actuators, controllers, and associated computers that are distributed throughout the often complex, interconnected SoS. In terms of control, the atomic unit of a SoS can be found on the field level, where direct control of so-called agents takes place. This can be e.g. the control of a single generator

3.2

in a power plant, which itself is part of a smart grid. The actions of field control are directed by higher levels such as plant supervisory control, scheduling control or plant-wide optimisation.

1.4.4.5.2 Vision and expected outcome

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

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

1.4.4.5.3 Key focus areas

2.1 2.3

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

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

1.4.4.6 Major Challenge 6: SoS monitoring and management

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

1.4.4.6.1 State of the art

3.2 3.3

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

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

- status of operation,
- safety,
- real time performance,
- real time monitoring of sensors and actuators, incl. fault detection and isolation,
- validation of signals (using redundancies created by the data network of the SoS),
- control,

- maintenance,
- assets,
- security.

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

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

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

1.4.4.6.2 Vision and expected outcome

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

1.3 2.3

1.4.4.6.3 Key focus areas

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

- Monitoring and management strategies and architectural concepts in OT-IT environments.
- Methodologies and technologies for monitoring and management of multiple and interrelated SoS dimensions.
- Processes and technology for life cycle monitoring and management over SoS dimensions.

1.4.5 TIMELINE

The following table illustrates the roadmaps for System of Systems.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: SoS architecture and open integration platforms	**Topic 1.1:** Robust SoS integration platform capable of supporting a wide range of solutions in diverse fields of applications	Architectures and associated implementation platforms with sufficient granularity and engineering support for efficient implementation of real-world Industry 4.0 solutions
	Topic 1.2: integration platform and associated engineering tools and toolchains that support the complete engineering process in both design- and run-time, including SoS critical aspects such as security, safety and risk mitigation	Lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc.
	Topic 1.3: suitable and adaptable engineering processes with training material for solution engineering	Hardware and software tools and training material suited for training of professionals and students at university level
Major Challenge 2: SoS interoperability	**Topic 2.1:** Translation between standardised data models e.g. ISO 103030, ISO 15926, BIM, ...	Translation technologies enabling translation of standardised data models and demonstrated at TRL 5-6
	Topic 2.2: Translation between different implementations of standardised data models	Translation technologies enabling translation of different implementations of standardised data models and demonstrated at TRL 5-6
	Topic 2.3: automated data model translation	Technologies and tools for automating the engineering of data model translations
	Topic 2.4: autonomous data model translation	Technology and tools for enabling autonomous data model translation in run-rime
Major Challenge 3: evolvability of SoS composed of embedded and cyber-physical systems	**Topic 3.1:** methods and tools for engineering evolvability of systems of embedded and cyber- physical systems.	Persistence of operational independence, managerial independence, geographic distribution, emergent behavior and evolutionary development
	Topic 3.2: evolutionary architectures in systems of embedded and cyber-physical systems.	Modular and evolvable architectures.
	Topic 3.3: evolvable solutions for trust, availability, scalability, and interoperability.	Modular frameworks addressing trust, availability, scalability and interoperability-
	Topic 3.4: evolvable solutions capable for managing resulting uncertainty emerging properties, functionalities and behaviours, including resilience to failures	Technology frameworks supporting self-adaptability
	Topic 3.5: evolvability in systems of cyber-physical systems supported by virtual engineering (e.g. digital twins)	Virtualisation of IoT and edge services based on open SoS architectures and platforms

MEDIUM TERM (2027–2031)	LONG TERM (2032–2036)
Architectures and implementation platform with support for a wide set of autonomous operation e.g. M2M business execution	Architectures with support for self-X e.g. self-healing, self-extension etc.
Lifecycle support for extra-functional requirements, such as energy consumption, environmental impact that translates into maintainability, sustainability, etc.	Autonomous management of functional and non-functional dimensions
Model based engineering support proving partial engineering automation of solutions	Automated SW engineering for most solution engineering stages.
Fully autonomous translation	
Full cross-domain interoperability	
Fully automated information translation	
Fully autonomous translation	
Full predictable and controllable composition of functional and extra-functional properties	Full predictable and controllable composition of functional and extra-functional properties, also covering dynamically recombining SoS
Evolvability and composability by design	Automated evolvability and composability analysis in design time and run-time
Modular frameworks and open integration platforms addressing e.g. trust, availability, scalability, interoperability	Open modular frameworks and integration platforms addressing e.g. trust, availability, scalability, interoperability, evolvability, composability
Failures resilience at SoS level	Automated manegement of uncertainty and resilience to failures.
Automated virtualisation of IoT and edge services based on open SoS architectures and platforms	Dynamic and scalable virtualisation of IoT and edge services based for run-time optimisation on open SoS architectures and platforms

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
	Topic 3.6: methods and tools to manage emergencies in embedded and composable systems of cyber-physical systems.	Technology frameworks supporting emergency self-adaptability
	Topic 3.7: service-based vertical and horizontal evolvability to enable high-level, and potentially cross-domain, evolvability of embedded and cyber-physical systems	Open services enabling technology and data evolvability cross-domain
Major Challenge 4: system of embedded and cyber-physical systems - SoECPS - engineering	**Topic 4.1:** efficient and flexible engineering processes	SoA-inspired engineering processes, toolchains and tools
	Topic 4.2: model based engineering	Partial automated generation of SoS software using model based engineering
	Topic 4.3: engineering tools supporting the complete engineering process along the system's lifecycle	Engineering tools enabling run-time engineering
	Topic 4.4: support for key automation requirements	SoS engineering process and tools partial support for fundamental automation requirements like e.g. real time, security, safety
	Topic 4.5: automated engineering	Automation of SoS software engineering from requirements to deployment
	Topic 4.6: automated testing validation and verification (TV&V)	Automated and runtime SoS TV&V for parts of the engineering process
Major Challenge 5: control in SoS composed of embedded and cyber-physical	**Topic 5.1:** tools for control system analysis of SoS	Technologies and tool for design time control analysis in SoS environments
	Topic 5.2: considering humans, environment and the economy in the loop	Technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact
	Topic 5.3: support in SoS control design	Technologies and tool for efficient and robust control design in SoS environments
	Topic 5.4: dynamic optimisation of communication effort, control architecture	Technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation
	Topics 5.5: control system testing, validation and verification (TV&V)	Technologies and tools enabling design time and run-time TV&V in complex SoS solutions.

MEDIUM TERM (2027–2031)	LONG TERM (2032–2036)
Automated technology and tools supporting emergency self-adaptability	Autonomous technology and tools supporting emergency self-adaptability
Open services and integration platforms enabling technology and data evolvability cross-domain	Open services and integration platforms enabling automated technology and data evolvability cross-domain
Engineering support for SoS emergent behaviours	Engineering support for emergent behaviours of very large SoS
Full automated generation of SoS software using model based engineering	Model based engineering support providing engineering automation for very complex SoS solutions
Multi-stakeholders and multi-domains automated engineering process	Highly automated solution engineering in a multi-stakeholders and multi-domains SoS environment
SoS engineering process and tools full support for fundamental automation requirements like e.g. real time, security, safety	
Technologies and tool for highly automated design time control analysis in SoS environments	Technologies and tool for autonomous run-time control analysis in SoS environments
Automated runtime SoS TV&V for the entire engineering process	Autonomous runtime SoS TV&V
Automated technologies and tool for efficient and robust control design in SoS environments	Autonomous technologies and tool for efficient and robust control design in SoS environments
Automated technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact	Autonomous technologies and tools enabling control optimisation based on human behaviour, environmental and economic impact
Automated technologies and tool for efficient and robust control designed TV&V in SoS environments	Autonomous technologies and tools for efficient and robust control run-time design and TV&V in SoS environments
Model based technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation	Fully automated run-time technologies and tool enabling dynamic optimisation of SoS control architecture enabling communication and energy consumption minimisation
Model based technologies and tools enabling design time and run-time TV&V in complex SoS solutions	Automated technologies and tools enabling design time and run-time TV&V in complex SoS solutions

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 6: SoS monitoring and management	**Topic 6.1:** monitoring and management strategies and architectural concepts in OT-IT environments	Real time monitoring and management of evolving OT.IT environments
	Topic 6.2: methodologies and technologies for monitoring and management of multiple and interrelated SoS dimensions	Functional, security and safety interrelations monitoring and management
	Topic 6.3: processes and technology for life cycle monitoring and management over SoS dimensions	Approaches to life cycle monitoring and management for multiple SoS dimensions. Like e.g. functionality, security and safety

MEDIUM TERM (2027–2031)	LONG TERM (2032–2036)
Scalable monitoring architecture applicable to large scale SoS	SoS integration platforms including scalable, and manageable monitoring capabilities
Manageable monitoring architecture of multiple SoS dimensions	SoS management based on multi-dimensional monitoring
SoS monitoring architecture along its life cycle	SoS integration platforms supporting SoS monitoring and management evolution along its life cycle

2.1
EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

2.2
CONNECTIVITY

2.3
ARCHITECTURE AND DESIGN: METHODS AND TOOLS

2.4
QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

2

Strategic Research and Innovation Agenda 2022

CROSS-SECTIONAL TECHNOLOGIES

2.1

Cross-Sectional Technologies

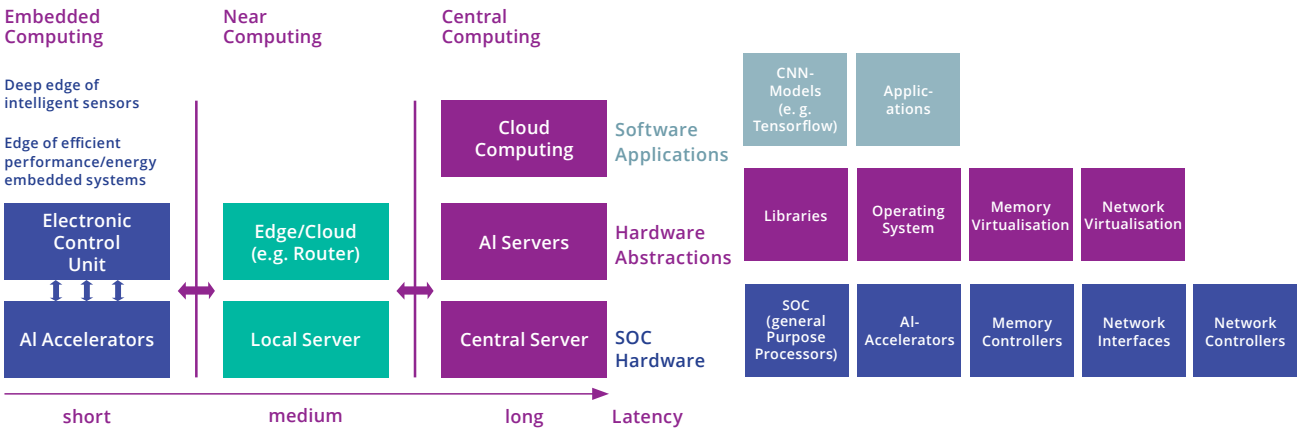
EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

2.1.1 SCOPE

2.1.1.1 Introduction

Our world is drastically changing with the deployment of digital technologies that provide ever increasing performance and autonomy to existing and new applications at a constant or decreasing cost but with a big challenge concerning energy consumption. Distributed computing systems have diverse architectures and in addition tend to form a continuum between extreme edge, fog, mobile edge[73] and cloud. Nowadays, many applications need computations to be carried out on spatially distributed devices, generally where it is most efficient. This trend includes edge computing, edge intelligence (e.g. Cognitive CPS, Intelligent Embedded Systems, Autonomous CPS) where raw data is processed close to the source to identify the insight data as early as possible bringing several benefits such as reduce latency, bandwidth, power consumption, memory footprint, and increase the security and data protection.

THE CONTINUUM OF COMPUTING AND RELATIONS.



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

F.24

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

One of the mainstream uses of AI is to allow an easier and better interpretation of the data (unstructured data such as image files, audio files, or environmental data) coming from the physical world. The use of AI in the edge will contribute to automate complex and advanced tasks, and represents one of the most important

73 Multi-access Edge Computing standardization (ETSI/ISG)

innovations being introduced by the digital transformation. For instance, its contribution in the recovery from Covid-19 pandemic as well as its potential to ensure the required resilience in future crises[74].
This Chapter focuses on computing components, and more specifically Embedded architectures, Edge Computing devices and systems using Artificial Intelligence at the edge. These elements rely on process technology, embedded software, constraints of quality, reliability, safety, and security. They also rely on system composition (systems of systems) and design and tools techniques to fulfil the requirements of the various application domains.

Furthermore, this Chapter focuses on the trade-off between performances and power consumption reduction, and managing complexity (including security, safety and privacy[75]) for Embedded architectures to be used in different applications areas, which will spread Edge computing and Artificial Intelligence use and its contribution to the European sustainability.

2.1.1.2 Positioning edge and cloud solutions

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

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

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

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

In this Chapter, **Edge Computing** is described as a paradigm that can be implemented using different architectures built to support a distributed infrastructure of data processing (data, image, voice, etc.) as close as possible to the points of collection (data sources) and utilization. In this context, the edge computing distributed paradigm provides computing capabilities to the nodes and devices of the edge of the network

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

75 Security, safety and privacy will be covered in the Chapter about "Quality, reliability, safety and security"

(or edge domain) to improve the performance (energy efficiency, latency, etc.), operating cost, reliability of applications and services, and contribute significantly to the sustainability of the digitalization of the European society and economy. Edge computing performs data analysis by minimizing the distance between nodes and devices and reducing the dependence on centralized resources that serve them while minimizing network hops. Edge computing capabilities include a consistent operating approach across diverse infrastructures, the ability to perform in a distributed environment, deliver computing services to remote locations, application integration, orchestration. It also adapts service delivery requirements to the hardware performance, and develops AI methods to address applications with low latency and varying data rates requirements – in systems typically subject to hardware limitations and cost constraints, limited or intermittent network connections.

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

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

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

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

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

The **meta-edge** integrates processing units, typically located on-premises, implemented with high-performance embedded computing units, edge machine vision systems, edge servers (e.g., high-performance

CPUs, GPUs, FPGAs, etc.) that are designed to handle compute-intensive tasks, such as processing, data analytics, AI-based functions, networking, and data storage.

This classification is closely related to the distance between the data source and the data processing, impacting overall latency. A high-level rough estimation of the communication latency and the distance from the data sources are as follows. Micro edge the latency is below 1ms, and the distances from zero to max 15 m, deep edge with distances under 1 km and latency below 2-5 ms, meta edge latencies under 10 ms and distances under 50 km, beyond 50 km the fog computing, MEC concepts are combined with near edge 10-20 ms 100 km, far edge 20-50ms 500 km and cloud and data centres more than 50 ms and 1000 km.

	LATENCY	DISTANCE
Micro-edge	Below 1ms	From 0 cm to 15 m
Deep-edge	Below 2-5 ms	Below 1km
Meta-edge	Below 10 ms	Below 50 km
Fog	10-20 ms	Up to 50 km
MEC76 + near edge	10-20 ms	100 km
Far edge	20-50 ms	200 km
Cloud/data centers/HPC	More than 50 -100 ms	1000 km and beyond

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

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

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

76 Multi-access Edge Computing (ETSI/ISG)

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

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

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

2.1.1.3 Positioning Embedded Artificial Intelligence

Thanks to the fast development in Machine Learning during the last decade, Artificial Intelligence is nowadays widely used. However, it demands huge quantity of data treatments, especially for supervised learning, to get accurate results level. According to the application complexity, neuronal deep learning architectures are becoming more and more complex and demanding in terms of calculations time. As a result, the huge AI success, its perversive deployment and its computing costs, the worldwide energy consumed will be increased dramatically to levels that will be unsustainable in the near future.

Nevertheless, Artificial Intelligence remains a very efficient tool for several applications (e.g., image recognition and classifications, natural language understanding, complex manufacturing optimization, supply chain improvements, etc.) where pattern detection and process optimization can be done.

As a side effect, data collection is exploding with high heterogeneity levels, coming from numerous and very various sensors. On top, the bandwidth is limited towards Data Center and all data do not need to be always treated in the Cloud.

Naturally, systems are evolving from a centralized to a distributed architecture. Artificial Intelligence is, then, a crucial element that allows soft and optimized operation of distributed systems. Therefore, it is increasingly more embedded in the various network nodes even till the very edge.

Such powerful tool allows Edge Computing to be more efficient in treating the data locally, while also minimizing the necessary data transmission to the upper upper network nodes. Another advantage of Embedded Artificial Intelligence is its capacity to self-learn and adapt to the environment through the data collected. Today’s learning techniques are still mostly based on supervised learning, but semi-supervised, self-supervised, unsupervised or federative learning techniques are being developed.

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

2.1.1.4 Scope of the Chapter

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

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

The technological aspects, at system level (PCB, assembly, system architecture, etc.), and embedded and application software are not part of this Chapter as they are covered in other Chapters.

Therefore, this Chapter should ideally cover mainly the elements foreseen to be used to compose AI or Edge systems:

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

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

1.1 1.2

- **Security infrastructure** (e.g. Secure Enclave) with placeholder for customer-specific secure elements (PUF, cryptographic IPs...). Security requirements are dealt with details in the corresponding Chapter.
- **Field connectivity IPs** (see connectivity Chapter, but the focus here is on field connectivity) (all kinds, wired, wireless, optical), ensuring interoperability.
- Integration using chiplet and interposer interfacing units will be detailed in the technology Chapter.
- And all other elements such as coherent cache infrastructure for many-cores, scratchpad memories, smart DMA, NoC with on-chip interfaces at router level to connect cores (coherent), memory (cache or not) and IOs (IO coherent or not), SerDes, high speed peripherals (PCIe controllers and switches, ...), trace and debug hardware and low/medium speed peripherals (I2C, UART, SPI...).

However, the Chapter will not detail the challenges for each of these elements, but only the generic challenges that will be grouped in 1) Edge computing and 2) Embedded Artificial Intelligence domains.
In a nutshell the main recommendation is a paradigm shift towards distributed low power architectures/ topologies:

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

2.1.1.5 State of the Art

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

Impact of AI and embedded intelligence in sustainable development

AI and particularly embedded intelligence, with its ubiquity and its high integration level having the capability "to disappear" in the environment, is significantly influencing many aspects of our daily life, our society, the environment, the organizations in which we work, etc. AI is already impacting several heterogeneous and disparate sectors, such as companies' productivity[77], environmental areas like nature resources and biodiversity preservation[78], society in terms gender discrimination and inclusion[79, 80], smarter transportation systems[81], etc. just to mention a few examples. The adoption of AI in these sectors is expected to generate both positive and negative effects on the sustainability of AI itself, of the solutions based on AI and on their users[82 83]. It is difficult to extensively assess these effects and there is not, to date, a comprehensive analysis of their impact on sustainability. A recent study[84] has tried to fill this gap, analysing AI from the perspective of 17 Sustainable Development Goals (SDGs) and 169 targets internationally agreed in the 2030 Agenda for Sustainable Development[85]. From the study it emerges that AI can enable the accomplishment of 134 targets, but it may also inhibit 59 targets in the areas of society, education, health care, green energy production, sustainable cities and communities.

From a technological perspective AI sustainability depends, at first instance, on the availability of new hardware[86] and software technologies. From the application perspective, automotive, computing and healthcare are propelling the large demand of AI semiconductor components and, depending on the application domains, of components for embedded intelligence and edge AI. The research and industry organizations are trying to provide new technologies that lead to sustainable solutions redefining traditional processor architectures and memory structure. We already saw that computing near, or in-memory, can lead to parallel and high-efficient processing to ensure sustainability.

The second important component of AI that impacts sustainability concerns software and involves the engineering tools adopted to design and develop AI algorithms, frameworks and applications. The majority of AI software and engineering tools adopts an open-source approach to ensure performance, lower development costs, time to market, more innovative solutions, higher design quality and software engineering sustainability. However, the entire European community should contribute and share the engineering efforts

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

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

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

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

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

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

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

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

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

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

at reduced costs, improving the quality and variety of the results, increasing the security and robustness of the designs, etc.

Sustainability through open technologies extends also to open data, rules engines[87] and libraries. The publication of open data and datasets is facilitating the work of researchers and developers for ML and DL, with the existence of numerous images, audio and text databases that are used to train the models and become benchmarks[88]. Reusable open- source libraries[89] allow to solve recurrent development problems, hiding the technical details and simplifying the access to AI technologies for developers and SMEs, maintaining a high-quality results, reducing time to market and costs.

Eventually, open-source initiatives (being so numerous, heterogeneous, and adopting different technologies) provide a rich set of potential solutions, allowing to select the most sustainable one depending on the vertical application. At the same time, open-source is a strong attractor for applications developers as it gathers their efforts around the same kind of solutions for given use cases, democratizes those solutions and speeds up their development. However, some initiatives should be developed, at European level, to create a common framework to easily develop different types of AI architectures (CNN, ANN, SNN, etc). This initiative should follow the examples of GAFAM. GAFAM have greatly understood it and elaborated business models in line with open source, representing a sustainable development approach to support their frameworks[90]. It should be noted that open-source hardware should not only cover the processors and accelerators, but also all the required infrastructure IPs to make an Embedded architectures, and be sure that all IPs are interoperable and well documented, are delivered with a verification suite and need to be maintained constantly to keep up with errata from the field and to incorporate newer requirements. The availability of automated SoC composition solutions, allowing to build Embedded architectures design from IP libraries in a turnkey fashion, is also a desired feature to quickly transform innovation into PoC (Proof of Concept) and to bring productivity gains and shorter time-to-market for industrial projects.

The extended GAFAM (Google, Amazon, Facebook, Apple, Microsoft) and the BAITX also have large in-house databases required for the training and the computing facilities. In addition, almost all of them are developing their chips for DL (e.g. Google with its line of TPUs) or made announcement that they will. The US and Chinese governments have also started initiatives in this field to ensure that they will remain prominent players in the field.

It will be a challenge for Europe to be in this race, but the emergence of AI at the edge, and its know-how in embedded systems, might be winning factors. However, the competition is fierce and the big names are in with big budgets and Europe must act quickly, because US and Chinese companies are already also moving in this "intelligence at the edge" direction (e.g. with Intel Compute Stick, Google's Edge TPU, Nvidia's Jetson Nano and Xavier, etc.).

Recently, the attention to the identification of sustainable computing solutions in modern digitalization processes has significantly increased. Climate changes and initiative like the European Green Deal[91] are generating more sensitivity to sustainability topics, highlighting the need to always consider the technology

87 E.g. Clips, Drools distributed by red Hat, DTRules by Java, Gandalf on PHP

88 A few examples are ImageNet (14 million images in open data), MNIST or WordNet (English linguistic basis)

89 E.g. Nvidia Rapids, Amazon Comprehend, Google NLU Libraries

90 See e.g. DL networks with Tensorflow at Google, PyTorch / Caffe at Facebook, CNTK at Microsoft, Watson at IBM, DSSTNE at Amazon

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

impact on our planet, which has a delicate equilibrium with limited natural resources[92]. The computing approaches available today, as cloud computing, are in the list of the technologies that could potentially lead to unsustainable impacts. A recent study[93] has clearly confirmed the importance that edge computing plays for sustainability but, at the same time, highlighted the necessity of increasing the emphasis on sustainability, remarking that "research and development should include sustainability concerns in their work routine" and that "sustainable developments generally receive too little attention within the framework of edge computing". The study identifies three sustainability dimensions (societal, ecological and economical) and proposes a roadmap for sustainable edge computing development where the three dimensions are addressed in terms of security/privacy, real-time aspects, embedded intelligence and management capabilities.

Market perspectives

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

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

From another side, PWC expects that the market for AI-related semiconductors to grow to more than US$30bn by 2022. The market for semiconductors powering inference systems will likely remain fragmented because potential use cases (e.g. facial recognition, robotics, factory automation, autonomous driving, and surveillance) will require tailored solutions. In comparison, training systems will be primarily based on traditional CPUs, GPUs, FPGAs infrastructures and ASICs.

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

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

AI components vendors

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

Qualcomm has launched the fifth generation Qualcomm AI Engine, which is composed of Qualcomm Kyro Central Processing Unit (CPU), Adreno Graphics Processing Unit (GPU), and Hexagon Tensor Accelerator (HTA). Developers can use either CPU, GPU, or HTA in the AI Engine to carry out their AI workloads. Qualcomm launched also Qualcomm Neural Processing Software Development Kit (SDK) and Hexagon NN Direct to facilitate the quantization and deployment of AI models directly on Hexagon 698 Processor.

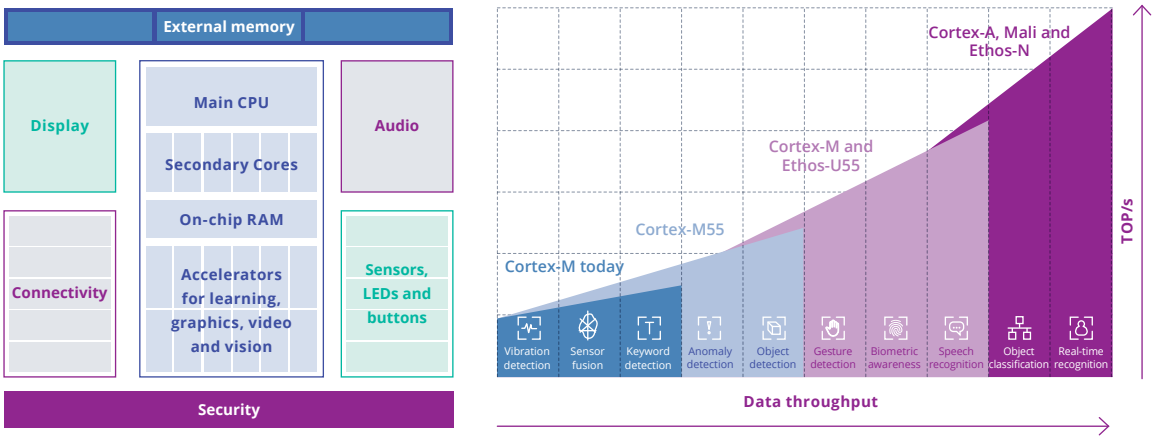
Huawei and MediaTek incorporate their Embedded architectures into IoT gateways and home entertainment, and Xilinx finds its niche in machine vision through its Versal ACAP SoC. NVIDIA has advanced the developments

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

93 Hamm, Andrea & Willner, Alexander & Schieferdecker, Ina. (2020). Edge Computing: A Comprehensive Survey of Current Initiatives and a Roadmap for a Sustainable Edge Computing Development. 10.30844/wi_2020_g1-hamm.

based on the GPU architecture, NVIDIA Jetson AGX platform a high performance SoC that features GPU, ARM-based CPU, DL accelerators and image signal processors.

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



F.25 *Example of architecture of a modern SoC (from Paolo Azzoni, see also Chapter 1.3) / Arm's Cortex-M55 and Ethos-U55 Tandem. Provide processing power for gesture recognition, biometrics, and speech recognition applications (Source: Arm).*

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

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

2.1.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

Driven by Moore's Law over the last 40 years[94], computing and communication brought important benefits to society. Complex computations in the hands of users and hyper-connectivity have been at the source of significant innovations and improvements in productivity, with a significant cost reduction for consumer products at a global level, including products with a high electronic content, traditional products (e.g. medical and machinery products) and added value services.

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

They will also enable synergies between domains: e.g., self-driving vehicles with higher reliability and predictability will directly benefit medical systems, consumer smart bracelets or smart watches for lifestyle monitoring reduce the impact of health problems[95] with a positive impact on the healthcare system costs, first-aid and insurance services are simplified and more effective thanks to cars location and remote control functionalities.

1.3 3.4

These computing solutions introduce new security improvements and threats. Edge Computing allows a better protection of personal data, being stored and processed only locally, and this ensures the privacy rights required by GDPR. But at the same time, the easy accessibility to the devices and new techniques, like AI, generates a unique opportunity for hackers to develop new attacks. It is, then, paramount to find interdisciplinary trusted computing solutions and develop appropriate counter measures to protect them in case of attacks. For example, Industry 4.0 requires new architectures that are more decentralized, new infrastructures and new computational models that satisfy high level of synchronization and cooperation of manufacturing processes, with a demand of resources optimization and determinism that cannot be provided by solutions that rely on "distant" cloud platforms or data centres[96], ensure low-latency data analysis, that are extremely important for industrial application[97].

2.4

3.3

These computing solutions have also to consider the man in the loop: especially with AI, solutions ensuring a seamless connection between man and machine will be a key factor. Eventually, a key challenge is to keep the environmental impact of these computing solutions under control, to ensure the European industry sustainability and competitiveness.

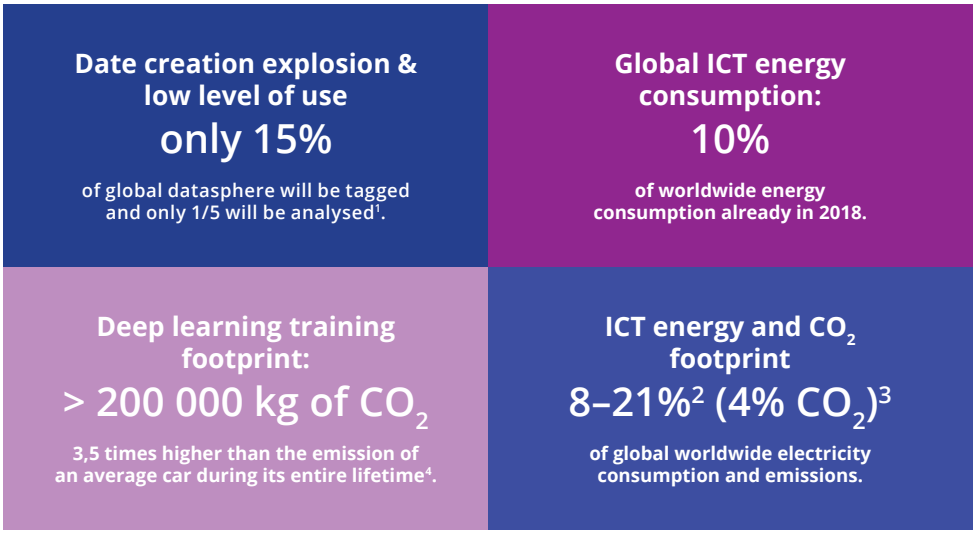
94 *Moore's law is diminishing, however including Ai and accelerator at the edge might increase Moore's law duration, see https://www.synopsys.com/glossary/what-is-sysmoore.html*

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

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

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

The following figure illustrates an extract of the challenges and expected market trend of Edge Computing and AI at the edge:



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

F.26 *Challenges and expected market evolution.*

AI introduces a radical improvement to the intelligence brought to the products through microelectronics and could unlock a completely new spectrum of applications and business models. The technological progress in microelectronics has increased the complexity of microelectronic circuits by a factor of 1000 over the last 10 years alone, with the integration of billions of transistors on a single microchip. AI is therefore a logical step forward from the actual microelectronics control units and its introduction will significantly shape and transform all vertical applications in the next decade.

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

1.4
2.2

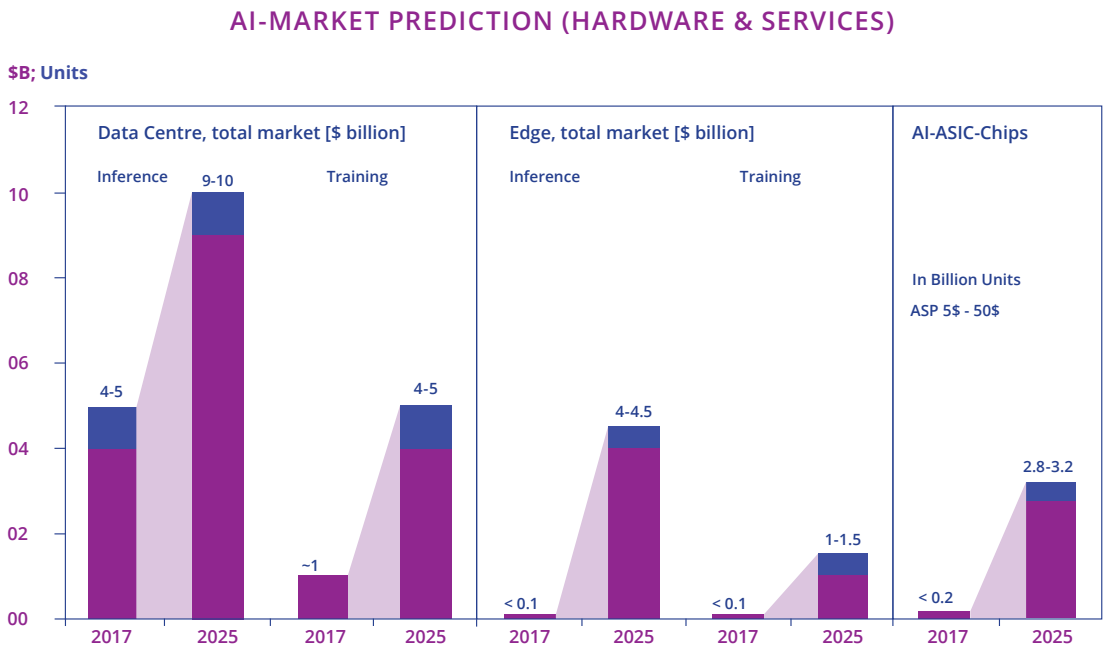


Illustration of an extract of the challenges and the expected market trend for AI and edge computing AI-Market prediction (Hardware & Services) (Source: Tractica, May 2019, McKinsey & Company)

F.27

2.1.3
APPLICATIONS BREAKTHROUGHS

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

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

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

energy management policies are key for systems where AI techniques are part of processing sensor data and power management policies are needed to extend the battery life of the entire system.

2.3 2.4

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

To achieve intelligent sensors with online learning capabilities, semiconductor technologies alone will not suffice. Neuroscience and information theory will continue to discover new ways[98] of transforming sensory data into knowledge. These theoretical frameworks help model the cortical code and will play an important role towards achieving real intelligence at the extreme edge.
AI systems use the training and inference for providing the proper functions of the system, and they have significant differences in terms of computing resources provided by the AI chips. Training is based on past data using datasets that are analysed, and the findings/patterns are built into the AI algorithm. The AI hardware used for training needs to provide computation accuracy, support sufficient representation accuracy, e.g., floating-point or fixed-point with long word-length, large memory bandwidth, memory management, synchronization techniques to achieve high computational efficiency and fast write time and memory access to a large amount of data[99].

Reinforcement learning (RL) is a booming area of machine learning and is based on how agents ought to take actions in an environment in order to maximize the notion of cumulative reward. Recent work[100] develops systems that were able to discover their own reward function from scratch. Similarly, Auto-ML allows to determine a "good" structure for a DL system to be efficient in a task. But all those approaches are also very compute demanding.

The inference is the application of the learned algorithm to the real devices to solve specific problems based on present data. The AI hardware used for inference needs to provide high speed, energy efficiency, low cost, fixed-point representation, efficient reading memory access and efficient network interfaces for the whole hardware architecture. The development of AI-based devices with increased performance, and energy efficiency allows the AI inference "at the edge" (embedded intelligence) and accelerate the development of middleware allowing a broader range of applications to run seamlessly on a wider variety of AI-based circuits. Companies like Google, Gyrfalcon, Mythic and Syntiant are developing custom silicon for the edge. As an example, Google is releasing Edge TPU, a custom processor to run TensorFlow Lite models on edge devices.

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

- Various processing, especially concerning AI functionalities, will be moved to local devices, such as voice and environment recognition, allowing privacy preserving functionalities.
- The Artificial Intelligence of Things will be enabled by AI.

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

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

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

1.4

3.4

- Federated functionalities will emerge (increasing the functionality of a device by using capabilities, resources, or neighbouring devices).
- Connected functionalities will also show up: this will extend the control and automation of a single system (e.g. a truck, a car) to a network of systems (e.g. a truck platoon), resulting in networked control of a cyber-physical system. The benefit of this is generally better performance and safety. It will also set the foundation for autonomous machines (including vehicles).
- The detection of events by camera and other long-range sensors (radar, lidar, etc) will come into action. Retina sensors will ensure low power operation of the system. Portable devices for blind people will be developed.
- The possibilities for disabled people to move their arms and legs comes into reach, as AI-conditioned sensors will directly be connected to the brain.
- The use of voice commands will be drastically increased, improving the human machine interface with reliable understanding of natural language.

2.1.4 STRATEGIC ADVANTAGE FOR THE EU

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

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

In this context, Europe must secure the knowledge to build AI-systems, design AI-chips, procure the AI-software ecosystem, and master the integration task into its products, and particularly into those products, where Europe has a lead today.

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

A potential approach could be to:

- To rely on existing application domains where we are strong (e.g. automotive, machinery, chemistry, energy, ...).
- Promoting to keep, catch-up and get all expertise in Europe that are required to build competitive Edge Computing systems and Embedded Intelligence, allowing us to develop solutions that are adapted to the European market and beyond. All the knowledge is already present in Europe,

but not structured and focused and often the target of non-European companies. The European ecosystem is rich and composed of many SMEs, but with little focus on common goals and cooperation.

- Open-source Hardware can be an enabler or facilitator of this evolution, allowing this swarm of SMEs to develop solutions more adapted to the diversity of the market.
- Data-based and knowledge-based modelling combined into hybrid modelling is an important enabler.
- Particular advantage will be cross-domain and cross-technology cooperation between various European vendors combining the best hardware and software know-how and technologies .
- Cooperation along and across value chains for both hardware and software experts will be crucial in the field of smart systems and the AI and IoT community.

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

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

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

AI optimized hardware components such as CPUs, GPUs, FPGAs, ASICs accelerators and neuromorphic processors are becoming more and more important. European solutions exist, and the knowledge on how to build AI-systems is available mainly in academia. However, more EU action is needed to bring this knowledge into real products in view to enhance the European industry with its strong incumbent products. Focused action is required to extend the technological capabilities and to secure Europe’s industrial competitiveness. A promising approach to prevent the dependence on closed processing technologies, relies on Open Hardware initiatives (Open Compute Project, RISC-V, OpenCores, OpenCAPI, etc.). The adoption of an open ecosystem approach, with a globally and incrementally built know-how by multiple actors, prevents that a single entity can monopolize the market or cease to exist for other reasons. The very low up-front cost of open hardware/ silicon IP lowers the barrier of innovation for small players to create, customize, integrate, or improve Open

IP to their specific needs. Thanks to Open Hardware freely shared, and to existing manufacturing capabilities that still exist in Europe, prototyping facilities and the related know-how, a new wave of European start-ups could come to existence, building on top of existing designs and creating significant value by adding the customization needed for industries such as automotive, energy, manufacturing or health/medical. Another advantage of open-source hardware is that the source code is auditable and therefore inspected to ensure quality (and less prone to attack if correctly analysed and corrected).

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

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

2.1.5 MAJOR CHALLENGES

2.1.5.1 For Edge Computing

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

1. Increasing the energy efficiency of computing systems:
    a. Processing data where it is created.
    b. Co-design: algorithms, HW, SW and topologies.
2. Managing the increasing complexity of systems:
    a. Balanced mechanisms between performance and interoperability.
    b. Realizing self-X, self-optimize, reconfiguration and self-management.
    c. Using AI techniques to help in complexity management.
3. Supporting the increasing lifespan of devices and systems:
    a. HW supporting software upgradability.
    b. Improving interoperability (with the same class of application) and between classes, modularity and complementarity between generations of devices.
    c. Developing the concept of 2nd life for components.
    d. Implementation on the smallest devices, high quality data, meta-learning, neuromorphic computing and other novel hardware-architectures.
4. Ensuring European sustainability in Embedded architectures design.
    a. Open-source HW.
    b. Energy efficiency improvement.
    c. Engineering support to improve sustainable AI, edge computing and Embedded architectures.

2.1.5.2 For Embedded Intelligence

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

Ultimately, energy efficiency becomes the key criteria as digital world is taking more and more significant percentage of produced electricity.

Embedded Intelligence is then foreseen as a crucial element to allow a soft and optimized operation of distributed systems. It is a powerful tool to achieve goals as:

- Power energy efficiency by treating data locally and minimizing the necessary data sent to the upper node of network.
- Securing the data (including privacy) keeping them local.
- Allowing different systems to communicate each other and adapt over the time (increasing their lifetime).
- Increasing resilience by learning and becoming more secured, more reliable.
- Keeping systems always on and accessible towards a network continuum.

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

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

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

Third, self-learning techniques (Federative learning, unsupervised learning, ...) will be necessary for fast and automatic adaptation.

Last but not least, trust in AI is key for societal acceptance. Explainability of AI decision for critical systems is an important factor for AI adoption.

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

Summarizing, four Major Challenges have been identified:

- Increasing the energy efficiency:
  - Development of innovative (and heterogeneous) hardware architectures: e.g. Neuromorphic.
  - Avoiding to move large quantities of data: processing at the source of data, sparse data coding, etc. Only processing when it is required (sparse topology, algorithms, etc.).
  - Interoperability (with the same class of application) and between classes.
  - Scalable and Modular AI.
- Managing the increasing complexity of systems:
  - Development of trustable AI.
  - Easy adaptation of models.
  - Standardized APIs for hardware and software tool chains, and common descriptions to describe the hardware capabilities.
- Supporting the increasing lifespan of devices and systems:
  - Realizing self-X (unsupervised learning, transfer learning, etc.).
  - Update mechanisms (adaptation, learning, etc.).
- Ensuring European sustainability in AI:
  - Developing solutions that correspond to European needs and ethical principles.
  - Transforming European innovations into commercial successes.

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

2.1.5.3 Major Challenge 1: increasing the energy efficiency of computing systems

2.1.5.3.1 For Edge Computing

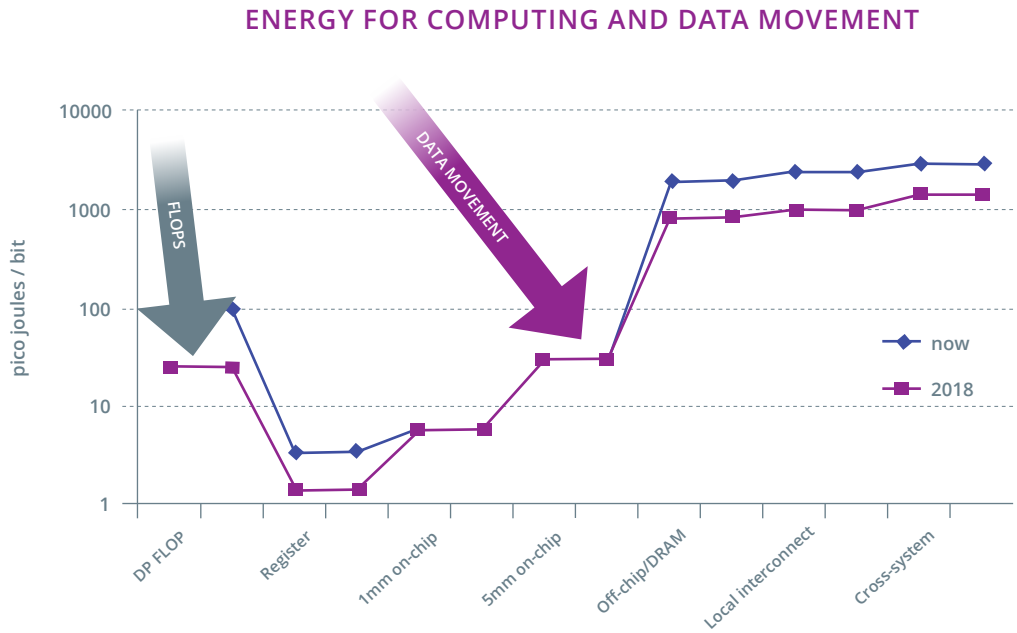
The advantages of using digital systems should not be hampered by their cost in terms of energy. For HPC or data centres, it is clear that the main challenge is not only to reach the “exaflops”, but to reach “exaflops” in a reasonable energy cost, which impacts the cooling infrastructure, the size of the “power plug” and globally the cost of ownership. At the other extremity of the spectrum, micro-edge devices should work for months on a small battery, or even by scavenging their energy from the environment (energy harvesting). Reducing the energy footprint of devices is the main charter for fulfilling sustainability and the “European Green deal”. Multimode energy harvesting (e.g. solar/wind, regenerative braking, dampers/shock absorbers, thermoelectric, etc.) offers huge potential for electrical vehicles and other battery-, fuel cells -operated vehicles in addition to energy efficiency design, real-time sensing of integrity, energy storage and other functions.

Power consumption should not be only seen just at the level of the device, but at the level of the aggregation of functions that are required to fulfil a task.

The new semiconductor technology nodes don’t really bring improvement on the power per device, Dennard’s scaling is ending and going to a smaller node does not anymore lead to a large increase of the operating frequency or a decrease of the operating voltage. Therefore, dissipated energy per surface, the power density of devices is increasing rather than decreasing. Transistor architectures, such as FinFet, FDSOI, nanosheets mainly reduce the leakage current (i.e. the energy spent by an inactive device). However, transistors made

on FDSOI substrates achieve the same performance than FinFet transistors at a lower operating voltage, reducing dynamic power consumption.

In addition, comes the memory wall. Today's limitation is not coming from the pure processing power of systems but more from the capacity to bring data to the computing nodes within a reasonable power budget fast enough.



F.28 *Energy for compute and data movement*

Furthermore, the system memory is only part of a broader Data Movement challenge which requires significant progress in the data access/storage hierarchy from registers, main memory (e.g. progress of NVM technology, such as the Intel's 3D-xpoint, etc.), to external mass storage devices (e.g. progress in 3D-nand flash, SCM derived from NVM, etc.). In a modern system, large parts of the energy is dissipated in moving data from one place to another. For this reason, new architectures are required, such as **computing in or near memory**, neuromorphic architectures (also where the physics of the NVM - PCM, CBRAM, MRAM, OXRAM, ReRAM, FeFET, etc. - technology can be used to compute) and lower bit count processing are of primary importance.

1.1 1.2

Power consumption can be reduced by local treatment of collected data, not only at circuit level, but also at system level or at least at the nearest from the sensors in the chain of data transfer towards the data centre (for example: in the gateway). Whereas the traditional approach was to have sensors generate as much data as possible and then leave the interpretation and action to a central unit, future sensors will evolve from mere data-generating devices to devices that generate semantic information at the appropriate conceptual level. This will obviate the need for high bit rates and thus power consumption between the sensors and the central unit. In summary, raw data should be transformed into relevant information (what is really useful) as early as possible in the processing continuum to improve the global energy efficiency:

- Only end or middle points equipment are working, potentially with low or sleeping consumption modes.
- Data transfer through network infrastructures is reduced. Only necessary data is sent to the upper level.
- Usage of computing time in data centres is also minimized.
- The development of benchmarks and standardization for HW/SW and data sets could be an appropriate measure to reduce power consumption. Hence, energy consumption evaluation will be easy and include the complete view from micro-edge to cloud.

2.1.5.3.2 Key focus areas

To increase the energy efficiency of computing systems, especially in the field of systems for AI and Edge Computing requires the development of innovative hardware architectures at all levels with their associated software architectures and algorithms:

- At technology level (FinFet, FDSOI, silicon nanowires or nanosheets), technologies are pushing the limits to be Ultra-low power. On top, advanced architectures are moving from Near-Memory computing to In-Memory computing with potential gains of 10 to 100 times. Technologies related to advanced integration and packaging have also recently emerged (2.5D, chiplets, active interposers, ...) that open up innovative design possibilities, particularly for what concerns tighter sensor-compute and memory-compute integration.

1.1 1.2

- At device level, several type of circuit architectures are currently running, tested, or developed worldwide. The list is moving from the so-known CPU to some more and more dedicated accelerators integrated in Embedded architectures (GPU, DPU, TPU, NPU, ...) providing accelerated data processing and management capabilities, which are implemented very variously going from fully digital to mixed or full analog solutions:

1.2

  - Fully digital solutions have addressed the needs of emerging application loads such as AI/DL workloads using a combination of parallel computing (e.g., SMP and GPU) and accelerated hardware primitives (such as systolic arrays), often combined in heterogeneous Embedded architectures. Low-bit-precision (8 bit integer or less) computation as well as sparsity-aware acceleration have been shown as effective strategies to minimize the energy consumption per each elementary operation in regular AI/DL inference workloads; on the other hand, there remain many challenges in terms of hardware capable of opportunistically exploiting the characteristics of more irregular mixed-precision networks. Applications, including AI/DL also require further development due to their need for more flexibility and precision in numerical representation (32 or 16 bit floating point), which puts a limit to the amount of hardware efficiency that can be achieved on the compute side.
  - Avoiding to move data: this is crucial because the access energy of any off-chip memory is currently 10-100x more expensive than access to on-chip memory. Emerging non-volatile memory technologies such as MRAM, with asymmetric read/write energy cost, could provide a potential solution to relieve this issue, by means of their greater density at the same technology node. Near-Memory Computing (NMC) and In-Memory Computing (IMC) techniques move part of the computation near or inside memory, respectively, further offsetting this problem. While IMC in particular is extremely promising, careful optimization at the system level is required to really take advantage of the theoretical peak efficiency potential.
  - Another way is also to perform invariant perceptive processing and produce semantic representation with any type of sensory inputs.

- At system level, micro-edge computing near sensors (i.e integrating processing inside or very close to the sensors or into local control) will allow Embedded architectures to operate in the range of 10 mW to 100 mW with an estimated energy efficiency in the order of 100s of GOPs/Watt up to a few TOPs/Watt in the next 5 years. This could be negligible compared to the consumption of the sensor (for example, a Mems microphone can consume a few mA). On top, the device itself can go in standby or in sleep mode when not used, and the connectivity must not be permanent. Devices currently deployed on the edge rarely process data 24/7 like data centres: to minimize global energy, a key requirement for future edge Embedded architectures is to combine high performance "nominal" operating modes with lower-voltage high compute efficiency modes and, most importantly, with ultra-low-power sleep states, consuming well below 1 mW in fully state-retentive sleep, and less than 1-10 uW in deep sleep. The possibility to leave Embedded architectures in an ultra-low power state for most of the time has a significant impact on the global energy consumed. The possibility to orchestrate and manage edge devices becomes fundamental from this perspective and should be supported by design. On the contrary, data servers are currently always on even if they are loaded only at 60% of their computing capability.

- At data level, memory hierarchies will have to be designed taking into account the data reuse characteristics and access patterns of algorithms, which strongly impact load and store access rate and hence, the energy necessary to access each memory in the hierarchy. For example (but not only), weights and activations in a Deep Neural Network have very different access patterns and can be deployed to entirely separate hierarchies exploiting different combinations of external Flash, DRAM, non-volatile on-chip memory (MRAM, FRAM...) and SRAM.

- At tools level, HW/SW co-design of system and their associated algorithms are mandatory to minimize the data moves and optimally exploit hardware resources, particularly if accelerators are available, and thus optimize the power consumption.

The challenge is not only at the component level, but also at the system and even infrastructure level: for example, the Open Compute Project was started by Facebook with the idea of delivering the most efficient designs for scalable computing through an open-source hardware community.

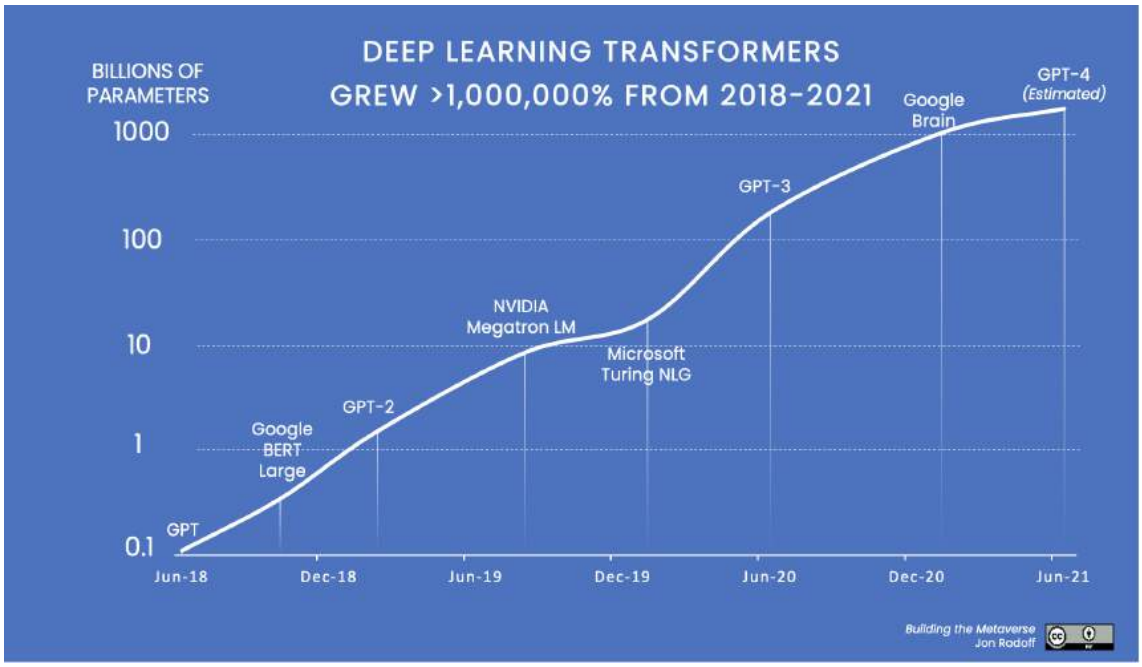
2.1.5.3.3 For Embedded Intelligence

Training AI models can be very energy-demanding. As an example, according to a recent study[101], the model training process for natural-language processing (NLP, that is, the sub-field of AI focused on teaching machines to handle human language) could end emitting as much carbon as five cars in their lifetimes[102]. However, if the inference of that trained model is executed billions of times (e.g., by billion users' smartphones), its carbon footprint could even offset the training one. Another analysis[103], published by the OpenAI association, unveils a dangerous trend: "since 2012, the amount of compute used in the largest AI training runs has been increasing exponentially with a 3.5 month-doubling time (by comparison, Moore's law had a 2-years doubling period)". These studies reveal that the need for computing power (and associated power consumption) for training AI models is dramatically widening. Consequently, the AI training processes need to turn greener and more energy-efficient.

101 https://arxiv.org/pdf/1906.02243.pdf

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

103 https://openai.com/blog/ai-and-compute/



Evolution of the size of the most advanced deep learning networks for Natural Language Processing, from https://www.reddit.com/r/singularity/comments/nzz8ek/ezra_klein_interviews_open_ai_ceo_sam_altman/.

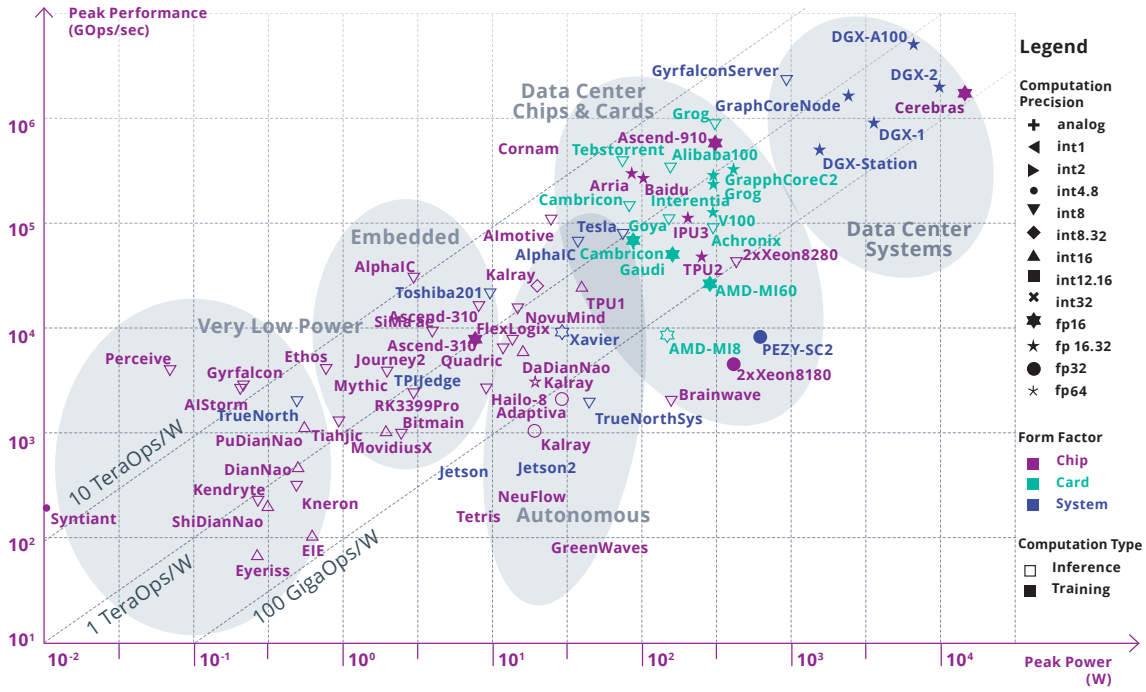
F.29

For a given use-case, the search for the optimal solution should meet multi-objective trade-offs among accuracy of the trained model, its latency, safety, security, and the overall energy cost of the associated solution. The latter means not only the energy consumed during the inference phase but also considering the frequency of use of the inference model and the energy needed to train it.

In addition, novel learning paradigms such as transfer learning, federated learning, online/continual/incremental learning, local and context adaptation, etc., should be preferred not only to increase the effectiveness of the inference models but also as an attempt to decrease the energy cost of the learning scheme. Indeed, these schemes avoid retraining models from scratch all the times or reduce the number and size of the model parameters to transmit back and forth during the distributed training phase.

Although significant efforts have been focused in the past to enable ANN-based inference on less powerful computing integrated circuits with lower memory size, today, a considerable challenge to overcome is that non-trivial DL-based inference requires significantly more than the 0.5-1 MB of SRAM, that is the typical memory size integrated on top of microcontroller devices. Several approaches and methodologies to artificially reduce the size of a DL model exist, such as quantizing the neural weights and biases or pruning the network layers. These approaches are fundamental also to reduce the power consumption of the inference devices, but clearly, they cannot represent the definitive solution of the future.

We witness great development activity of computing systems explicitly supporting novel AI-oriented use cases, spanning different implementations, from chips to modules and systems. Moreover, as depicted in the following figure, it covers large ranges of performance and power, from high-end servers to ultra-low power IoT devices.



F.30 *Landscape of AI chips according to their peak power performance [104].*

To efficiently support new AI-related applications, for both, the server and the client on the edge side, new accelerators need to be developed. For example, DL does not usually need a 32/64/128-bit floating point for its learning phase, but rather variable precision including dedicated formats such as bfloats. However, a close connection between the compute and storage parts are required (Neural Networks are an ideal "compute in memory" approach). Storage also needs to be adapted to support AI requirements (specific data accesses, co-location compute and storage), memory hierarchy, local vs. cloud storage.

Similarly, at the edge side, accelerators for AI applications will particularly require real-time inference, in view to reduce the power consumption. For DL applications, arithmetic operations are simple (mainly multiply-accumulate) but they are done on data sets with a very large set of data and the data access is therefore challenging. In addition, clever data processing schemes are required to reuse data in the case of convolutional neural networks or in systems with shared weights. Computing and storage are deeply intertwined. And of course, all the accelerators should fit efficiently with more conventional systems.

Finally, new approaches can be used for computing Neural-Networks, such as analogue computing, or using the properties of specific materials to perform the computations (although with low precision and high dispersion, but the Neural Networks approach is able to cope with these limitations).

Besides DL, the "Human Brain Project", a H2020 FET Flagship Project which targets the fields of neuroscience, computing, and brain-related medicine, including, in its SP9, the Neuromorphic Computing platform SpiNNaker and BrainScaleS. This Platform enable experiments with configurable neuromorphic computing systems.

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

2.1.5.3.4 Key focus areas

The focus areas rely on Europe is a leader in embedded systems, CPS, components for the edge (e.g., sensors, actuators, embedded microcontrollers), and applications in automotive, electric, connected, autonomous, and shared (ECAS) vehicles, railway, avionics, and production systems. Leveraging AI in these sectors will improve the efficient use of energy resources and increase productivity.

However, running computation-intensive ML/DL models locally on edge devices can be very resource-intensive, requiring, in the worst-case, high-end processing units to be equipped in the end devices. Such stringent requirement not only increases the cost of edge intelligence but can also become either unfriendly or incompatible with legacy, non-upgradeable devices endowed with limited computing and memory capabilities. Fortunately, inferring in the edge with the most accurate DL model is not a standard requirement. It means that, depending on the use case, different trade-offs among inference accuracy, power consumption, efficiency, security, safety, and privacy can be met. This awareness can potentially create a permanently accessible AI continuum. Indeed, the real game-changer is to shift from a local view (the device) to the "continuum" (the whole technology stack) and find the right balance between edge computation (preferable whenever possible, because it does not require data transfer) and data transmission towards cloud servers (more expensive in terms of energy). The problem is complex and multi-objective, meaning that the optimal solution may change over time, needing to consider changing cost variables and constraints. Interoperability/compatibility among devices and platforms is essential to guarantee efficient search strategies in this search space.

AI accelerators are crucial elements to improve efficiency and performances of existing systems (to the cost of more software complexity, as described in the next challenge, but one goal will be to automatize this process). For the training phase, the large amount of variable precision computations requires accelerators with efficient memory access and large multi-computer engine structures. In this phase, it is necessary to access large storage areas containing training instances. However, the inference phase requires low-power efficient implementation with closely interconnected computation and memory. In this phase, efficient communication between storage (i.e., the synapses for a neuromorphic architecture) and computing elements (the neurons for neuromorphic) are paramount to ensure good performances. Again, it will be essential to balance the need and the cost of the associated solution. For edge/power-efficient devices, perhaps not ultra-dense technologies are required; cost and power efficiency matter perhaps more than raw computational performances.

Other architectures (neuromorphic) need to be further investigated and to find the sweet use case spot. One key element is the necessity to save the neuronal network state after the training phase as reinitializing after switch-off will increase the global consumption. The human brain never stops.

It is also crucial to have a co-optimization of the software and hardware to explore more advanced trade-offs. Indeed, AI, and especially DL, require optimized hardware support for efficient realization. New emerging computing paradigms such as mimicking the synapses, using unsupervised learning like STDP (Spike-timing-dependent plasticity) might change the game by offering learning capabilities at relatively low hardware cost and without needing to access large databases. Instead of being realized by ALU and digital operators, STDP can be realized by the physics of some materials, such as those used in Non-Volatile Memories.

Developing solutions for AI at the edge (e.g., for self-driving vehicles, personal assistants, and robots) is more in line with European requirements (privacy, safety) and know-how (embedded systems). Solution at the extreme edge (small sensors, etc.) will require even more efficient computing systems because of their low cost and ultra-low power requirements.

The Deep learning approach is based on the neural networks paradigm coming initially from the work of Mc Culloch and Pitts, where a neuron is a small computing element connected to its pairs by weights called synapses. It is a structure where computing and storage are naturally closely mixed. It is therefore important to address memories and topologies in such AI architectures. Sparsity of coding and of the neural network topology are important to reduce energy consumption, both by decreasing data communication and taking benefit of the sparsity of coding and of the topology.

2.1.5.4 Major Challenge 2: managing the increasing complexity of systems:

2.1.5.4.1 For Edge Computing

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

1.3 1.4
2.3

The complexity is the result of the incorporation of hardware, software and connectivity into systems, and their design to process and exchange data and information without addressing the architectural aspects. As such, architectural aspects such as optimizing the use of resources, distributing the tasks, dynamically allocating the functions, providing interoperability, common interfaces and modular concepts that allow for scalability are typically not sufficiently considered. Today's complexity to achieve higher automation levels in vehicles and industrial systems is best viewed by the different challenges which need to be addressed when increasing the number of sensors and actuators offering a variety of modalities and higher resolutions. These sensors and actuators are complemented by ever more complex processing algorithms to handle the large volume of rich sensor data. The trend is reflected in the value of semiconductors across different vehicle types. While a conventional automobile contains roughly $330 value of semiconductor content, a hybrid electric vehicle with a full sensor platform can contain up to $1000 and 3,500 semiconductors. Over the past decade, the cost contribution for electronics in vehicles has increased from 18% to 20% to about 40% to 45%, according to Lam Research. The numbers will further increase with the introduction of autonomous, connected, and electric vehicles which make use of AI-based HW/SW components.

This approach necessitates the use of multiple high-performance computing systems to support the cognition functions. Moreover, the current Electrical and Electronic (E/E) architectures impose that the functional domains are spread over separated and dedicated Electronic Control Units (ECU's). This approach hampers upscaling of the automation functionality and obstructs effective reasoning and decision making.

2.1.5.4.2 Key focus areas

The major recommendations at the Embedded architectures infrastructure level are:

- Improving interoperability of systems: this is mainly covered by design methodology, where tools should be able to build a system from IPs coming from various sources. That means also that the description of the IPs, even if they are proprietary (black box), should contain all the view required to smoothly integrate them together. This is also a requirement for open-source Hardware. This can be extended at the level of integration in 2.5D systems based on interposers and chiplets: an ecosystem will only proliferate and flourish if a large catalogue of chiplets (in this case) are available and easily connected. As infrastructure for Embedded architectures, the "common platform" initiated by the European Processor Initiative (EPI) is an example of a template that allows to build different ICs with minimum efforts.

- Facilitating the easy addition of modules to a system: what is done at the Embedded architectures level can also be promoted at the system levels, where reuse of existing core could simplify the design, but perhaps at a cost of more complex software.
- Developing common interfaces and standards: this a basic element if we want to increase the productivity by reuse and the efficiency by using interoperability.
- Using AI techniques to help complexity management: existing Embedded architectures are so complex that humans cannot understand all the interactions and corner cases. Tools and techniques using Operational Research or Artificial Intelligence can be used to explore the space of conception, and recommend optimum combinations and architectures. Automated Design Space Exploration is an emerging field, and AI is already used in backend tools by the major CAD tools providers (and by Google to design their TPUs).

2.3

Similarly, the solutions and recommendations for Edge devices are similar of those for embedded computing:

- Improving interoperability of systems.
- Facilitating the easy addition of modules to a system .
- Developing common interfaces and standards , standardized APIs for hardware and software tool chains.
- Using AI techniques to help complexity management.

2.1.5.4.3 For Embedded Intelligence

To still achieve the required increased level of automation in automotive, transportation and manufacturing, disruptive frameworks are being considered offering a higher order of intelligence. Several initiatives to deliver hardware and software solutions for increased automation are ongoing. Companies like Renesas, NVIDIA, Intel/Mobileye, and NXP build platforms to enable Tier1s and OEMs to integrate and validate automated drive functions. Still, the “vertical” distribution of AI functionality is difficult to manage across the traditional OEM/Tier-1/Tier-2 value chain. Due to the long innovation cycle associated with this chain, vertically integrated companies such as Tesla/Waymo currently seem to hold an advantage in the space of autonomous driving. Closed AI component ecosystems represent a risk as transparency in decision making could prove hard to achieve and sensor level innovation may be stifled if interfaces are not standardized. Baidu (Apollo), Lyft, Voyage and Comma.ai take a different approach as they develop software platforms which are open and allow external partners to develop their own autonomous driving systems through on-vehicle and hardware platforms. Such open and collaborative approach might be the key to accelerate development and market adoption.

Next generation energy- and resource-efficient electronic components and systems that are connected, autonomous and interactive will require AI-enabled solutions that can simplify the complexity and implement functions such as self-configure to adapt the parameters and the resource usage based on context and real time requirements. The design of such components and systems will require a holistic design strategy based on new architectural concepts and optimized HW/SW platforms. Such architectures and platforms will need to be integrated into new design operational models that consider hardware, software, connectivity and sharing of information (1) upstream from external sources like sensors to fusion computing/decision processes, (2) downstream for virtualization of functions, actuation, software updates and new functions, and (3) mid-stream information used to improve the active user experience and functionalities.

2.3

Still, it is observed that the strategical backbone technologies to realize such new architectures are not available. These strategical backbone technologies include smart and scalable electronic, components and systems (controllers, sensors, and actuators), the AI accelerator hardware and software, the security engines, and the connectivity technologies. A holistic end-to-end approach is required to manage the increasing

complexity of systems, to remain competitive and to continuously innovate the European electronic components and systems ecosystem. This end-to-end approach should provide new architecture concepts, HW/SW platforms that allow for the implementation of new design techniques, system engineering methods and leverage AI to drive efficiencies in the processes.

Based on the European's semiconductor expertise and in view of its strategic autonomy, we see an incentive for Europe to build an ecosystem on electronic components, connectivity and software AI, especially when considering that the global innovation landscape is changing rapidly due to the growing importance of digitalization, intangible investment and the emergence of new countries and regions. As such, a holistic end-to-end AI technology development approach enables the advances in other industrial sectors by expanding the automation levels in vehicles and industrial systems while increasing the efficiency of power consumption, integration, modularity, scalability, and functional performance.

The new strategy should be anchored into a new bold digitalization transformation as digital firms perform better and are more dynamic: they have higher labour productivity, grow faster, and have better management practices.

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

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

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

1.4 2.3

Europe can drive the development of scalable and connected HW/SW AI-based platforms. Such platforms will efficiently share resources across platforms and optimize the computation based on the needs and functions. As such, the processing resource will dynamically adjust the type, speed and energy consumption of processing resource depending on the instantaneous required functionality.
This can be extended at the different layers of the architecture by providing scalable concepts for hardware, software, connectivity, AI algorithms (inference, learning) and the design of flexible heterogenous architectures that optimize the use of computing resources.

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

2.1.5.4.4 Key focus areas

- Evolving the architecture, design and semiconductor technologies of AI-based components and systems, integration into IoT/IIoT devices semiconductor chips with application in automation, intelligent connectivity, enabling seamless interactions and optimized decision-making for semi-autonomous and autonomous systems.
- New AI-based HW/SW architectures and platforms with increased dependability, optimized for increased energy efficiency, low cost, compactness and providing balanced mechanisms between performance and interoperability to support the integration into various applications across the industrial sectors.
- Edge and deep-edge components, architectures, and interoperability concepts for AI edge-based platforms for data tagging, training, deployment, and analysis. Use and development of standardized APIs for hardware and software tool chains.
- Deterministic behaviours, low latency and reliable communications are also important for other vertical applications, such as connected cars, where edge computing and AI represent "the" enabling technology, independently from the sustainability aspects. The evolution of 5G is strongly dependent on edge computing and multi-access edge computing (MEC) developments.
- Developing new design concepts for AI born embedded systems to facilitate trust by providing the dependable design techniques, that enable the end-to-end AI systems to be scalable, make correct decisions in repetitive manner, provide mechanisms to be transparent, explainable, and able to achieve repeatable results and embed features for AI model's and interfaces' interpretability.
- Distributed edge computing architecture with AI models running on distributed devices, servers, or gateways away from data centres or cloud servers.
- Scalable hardware agnostics AI models capable of delivering comparable performance on different computing platforms, (e.g. Intel, AMD or ARM architectures).
- Seamless and secure integration at HW/SW embedded systems with the AI models integrated in the SW/HW and APIs to support configurable data integrated with enterprise authentication technologies through standards-based methods.
- Development of AI based HW/SW for multi-tasking and provide techniques to adapt the trained model to produce close or expected outputs when provided with a different but related set of data. The new solutions must provide dynamic transfer learning, by assuring the transfer of training instance, feature representation, parameters, and relational knowledge from the existing trained AI model to a new one that addresses the new target task.
- HW/SW techniques and architectures for self-optimize, reconfiguration and to self-manage the resource demands (e.g. memory management, power consumption, model selection, hyperparameter tuning for automated machine learning scenarios, etc.).
- Edge-based robust energy efficient AI-based HW/SW for processing incomplete information with incomplete data, in real time.
- End-to-end AI architecture including the continuum of AI-based techniques, methods and interoperability across sensor-based system, device-connected system gateway-connected system, edge processing units, on-premises servers, etc.
- Developing tools and techniques helping in the management of complexity, e.g. using AI methods.

2.1.5.5 Major Challenge 3: supporting the increasing lifespan of devices and systems

2.1.5.5.1 For Edge Computing

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

The first level of lifetime extension is clearly the upgrade to avoid replacing an object but instead improving its features and performance through either hardware or software update. This concept is not new as it is already applied in several industrial domains for dozens of years.

The second aspect of increasing lifetime is to reuse a system in an application framework less demanding in term of performance, power consumption, safety, etc.

2.1.5.5.2 Key focus areas

For re-using something in an environment for which it was not initially designed, it is key to be able to qualify the part in its new environment. To achieve this very challenging goal the main question is "what are the objective parameters to take into account to guarantee that the degraded part is compatible with its new working environment?"

- Intelligent reconfigurable concepts are an essential key technology for increasing the re-use and service life of hardware and software components. Such modular solutions on system level require the consideration of different quality or development stages of sensors, software, or AI solutions. If the resulting uncertainties (measurements, predictions, estimates by virtual sensors, etc.) are considered in networked control concepts, the interoperability of agents/objects of different generations can be designed in an optimal way.
- Distributed monitoring: continuous monitoring and diagnosis also play a crucial role for the optimization of product lifetime. Where a large amount of data is collected during daily life operation (e.g. usage, environment, sensor data), big data analysis techniques can be used to predictively manipulate the operational strategy, e.g. to extend service life. Similarly, an increase in power efficiency can be achieved by adjusting the calibration in individual agents. For example, consider a fuel cell electric vehicle where the operation strategy decisively determines durability and service life. Distributed monitoring collects data from various interconnected agents in real-time (e.g. a truck platoon, an aircraft swarm, a smart electricity distribution network, a fleet of electric vehicles) and uses these data to draw conclusions about the state of the overall system (e.g. the state of health or state of function). On the one hand, this allows to detect shifting behaviour or faulty conditions in the systems and to even isolate them by attributing causes to changes in individual agents in the network or even ageing of individual objects and components. Such detection should be accomplished by analysing the continuous data stream that is available in the network of agents. A statistical or model-based comparison of the individual objects with each other provides additional insights. Thus, for example, early failures of individual systems could be predicted in advance.
- Another essential factor for increasing the lifespan of products is the intelligent use and handling of real-world data from products that are already in use and from previous generations of these. On the one hand, this allows for an optimal adaptation of the operating strategy to, for example, regionally, seasonally, or even individually varying use patterns. On the other hand, the monitoring of all agents (e.g. fleet of vehicles) also enables very precise estimates and

1.3 1.4

predictions of certain conditions. This enables the detection of early failures of individual objects but also the timely implementation of countermeasures. Such approaches can be referred to as distributed monitoring.

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

2.1.5.5.3 For Embedded Artificial Intelligence

The novelty with AI systems is to upgrade while preserving, guaranteeing the same level of safety and performance. For previous systems based on conventional algorithmic approaches, the behaviour of the system could be evaluated offline in validating the upgrade with a predefined data set representative enough of the operating conditions, knowing that more than the data themselves, the way they are processed is important. In the case of AI, things are completely different, as the way data are processed is not typically immediately understandable but what is key are the data set themselves and the results they produce. In these conditions it is important to have frameworks where people could reasonably validate their modification, whether it is hardware or software, in order to guarantee the adequate level of performance and safety, especially for systems which are human life critical. Another upgrade-related challenge is that of designing systems with a sufficient degree of architectural heterogeneity to cope with the performance demands of AI and machine learning algorithms, but at the same time flexible enough to adapt to the fast-moving constraints of AI algorithms. Whereas the design of a new Embedded architectures or electronic device, even of moderate complexity, takes typically 1-3 years, AI models such as Deep Neural Networks are outdated in just months by new networks. Often, new AI models employ different algorithmic strategies from older ones, outdating fixed-function hardware accelerators and necessitating the design of hardware whose functionality can be updated.

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

Whatever the solution used to extend lifetime of systems, this cannot be achieved without a strong framework regarding standards and, even more important, for AI qualification framework of solutions. AI systems are new and show little standardization currently. Therefore, it is of high importance to devote effort to this aspect of AI-hardware and -software developments. Europe has a very diverse industrial structure, and this is a strength if all those players have early access to the standards frameworks for AI and its development vectors. Open access is therefore as important for the European AI ecosystem as the ability to upgrade and participate in the development of AI-interfaces. Another very important point is how we qualify an AI solution. Comparing to computing systems based on algorithm, where it exists a lot of tools and environment to detect and certify that a system has a given property thanks to static code analysis, formal proof, worst case

execution time, ... In case of AI, most of these solutions are not applicable as the performance of the system depends on the quality of datasets used for training and quality of data used during the inference phases.

For this reason, we suggest a strong and dedicated focus on upcoming AI-standards. Nevertheless, we need to keep in mind the strong business lever of standard and make sure that European companies will be able to build on top of standards and generate value at European level. For instance, android is open source but no way to make a competitive smartphone without a Google android license.

Interoperability, modularity, scalability, virtualization, upgradability is well known in embedded systems and are already widely applied. But they are brand new in AI and nearly non-existent in edge AI. On top, self-x (learning/training, configuration or reconfiguration, adaptation, ...) are very promising but still under research or low level of development. Federative learning and prediction on the fly will certainly take a large place in the future edge AI systems where many similar equipment collect data (Smartphone, electrical vehicles, ...) and could be improved and refreshed continuously.

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

1.2 1.3

At the application level, edge AI has a potential positive impact on ecologic sustainability: consider e.g. the application of AI to optimize and reduce the power consumption in manufacturing plants, buildings, households, etc. The potential impact is evident but, to ensure a real sustainable development and a real benefit, edge AI solutions will have to ensure that the costs savings are significantly larger than the costs required to design, implement and train AI.

3.2

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

1.4 2.3

2.1.5.5.4 Key focus areas

- Developing HW/SW architectures and hardware that support software upgradability and extension of software useful life. Software upgradability is necessary in nearly all systems now and hardware should be able to support future updates. AI introduces additional constraints compared to previous systems. Multiplicity of AI approaches (Machine learning, DL, semantic, symbolic, etc.), multiplicity of neural network architectures based on a huge diversity of neuron types (CNN, RNN, etc.), potential complete reconfiguration of neural networks for a same system (linked to a same use case) with a retraining phase based on an adapted set of data make upgradability much more complex. This this why HW/SW, related stacks, tools, data sets compatible with the Edge AI system must be developed in synergy. HW/SW plasticity is necessary whatever is the AI background principle of each system to make them as much as possible upgradable and interoperable and to extend the system lifetime. HW virtualization will help to achieve it as well as standardization. The key point is that lifespan extension, like power

management, are requirements which must be considered from day one of the design of the system. It is impossible to introduce them near the end without a strong rework.

- Standardization: standards are very difficult to define as they shouldn't be too restrictive to avoid limitation to innovation but not too open also to avoid plenty of objects compliant to the standard but not really interoperable because not supporting the same options of the same standard. For this reason, the concept of introducing standards early in the innovation process, must be complemented with a visionary perspective in view to expand the prospective standards for future expansions in function, feature, form, and performance.
- Re-use: one concept called the "2nd life" is actually the re-use parts of systems. Such re-use could be adapted to edge AI as far as some basic rules are followed. First, it is possible to extract the edge AI HW/SW module which is performing a set of functions. For example, this module performs classification for images, movements detection, sounds recognition, etc. Second, the edge AI module can be requalified and recertified downgrading its quality level. A module implemented in aeronautic systems could be reused in automotive or industrial applications. A module used in industrial could be reused in consumer applications. Third, an AI system may be re-trained to fit the "2nd life" similar use case, going for example from smart manufacturing to smart home. Last, business model will be affordable only if such "2nd life" use is on a significant volume scale. A specific edge AI embedded module integrated in tens of thousands of cars could be removed and transferred in a new consumer product being sold on the market.
- Prediction and improvements: prediction / improvements with pure analytics techniques is always difficult. Very often the analytic behaviours of some system parts is not known and then either approximate models are build-up or it is just ignored. Thanks to AI, the system will be able to evolve based on data collected during its running phase. AI techniques will allow better prediction method based on real data allowing the creation of aggregated and more pertinent indicators not possible with pure analytic approach.
- Realizing self-X (adaptation, reconfiguration, etc.): for embedded systems self-adaptation, self-reconfiguration has an enormous potential in many applications. Usually in self-reorganizing systems the major issue is how to self-reorganize while preserving the key parameters of a system (performance, power consumption, real time constraints, etc.). For any system, there is an operating area which is defined in the multi-dimensional operating parameter space and coherent with the requirements. Of course, very often the real operating conditions are not always covering the whole operating domain for which the system was initially designed. Thanks to AI, when some malfunctioning parts are identified it could then be possible to decide, relying on AI and the data accumulated during system operation, if it affects the behaviours of the system regarding its real operating conditions. If it is not the case, it could be considered that the system can continue to work, with maybe some limitations, but which are not vital regarding normal operation. It would then extend its lifetime "in place". The second case is to better understand the degraded part of a system and then its new operating space. This can be used to decide how it could be integrated in another application making sure that the new operating space of the new part is compatible with the operating requirements of the new hosting system.
- Self-learning techniques are promising. Prediction on Natural Language Understanding (NLU) on the fly or keyboard typing, predictive maintenance on mechanical systems (e.g. motors) are more and more studied. Many domains can benefit of the AI in mobility, smart building, communication infrastructure.
- Dynamic reconfiguration: a critical feature of the AI circuits is to dynamically change their functions in real-time to match the computing needs of the software, AI algorithms and the data available and create software-defined AI circuits and virtualize AI functions on different computing platforms. The use of reconfigurable computing technology for IoT devices with

AI capabilities allows hardware architecture and functions to change with software providing scalability, flexibility, high performance, and low power consumption for the hardware. The reconfigurable computing architectures, integrated into AI-based circuits can support several AI algorithms (e.g. convolutional neural network (CNN), fully connected neural network, recursive neural network (RNN), etc.) and increase the accuracy, performance and energy efficiency of the algorithms are integrated as part of software define functions.

- From the engineering perspective, leveraging open source will help developing European advanced solutions for edge AI (open source hardware, software, training datasets, open standards, etc.).

As a summary, intelligence at the edge sustainable engineering will have to face many challenges:

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

2.1.5.6 Major Challenge 4: ensuring European sustainability

2.1.5.6.1 For Edge Computing

One of the major challenges that need to be accounted for in the next few years is related to the design of progressively more complex electronic systems to support advanced functionalities such as AI and cognitive functionality. This is particularly challenging in the European landscape, which is dominated by small and medium enterprises (SMEs) with only some large actors that can fund and support larger-scale projects. To ensure European competitiveness and sustainability in advanced Embedded architectures it is therefore crucial to create an ecosystem, and the means, in which SMEs can cooperate and increase its level of innovation and productivity. This ecosystem needs to cover at the best all part of the value chain from concept to design till production. The definition of open industrial standards and a market of Intellectual Properties (IPs) are required to accelerate the design, competitivity and create a larger market. Open-source on Software, Hardware and tools can play an extremely important role in this regard, open-source solutions significantly allow to reduce engineering costs for licensing and verification, lowering the entry barrier to design innovative products.

2.1.5.6.2 Key focus areas

1.1 1.2 1.3 2.3

- Energy efficiency improvement:
  - New materials, new embedded non-volatile memories with high density and ultra-low power consumption, substrates and electronic components oriented to low and ultra-low power solutions.
  - 3D-based device scaling for low power consumption and high level of integration.
  - Strategies for self-powering nodes/systems on the edge.
  - Low and ultra-low power and interoperable communications components.

- Efficient cooling solutions.
- Improving sustainability edge computing:
  - Efficient and secure code mobility.
  - Open edge computing platforms, providing remote monitoring and control, security and privacy protection.
  - Solutions for the inclusion/integration of existing embedded computers on the edge.
  - Policies and operational algorithms for power consumption at edge computing level.
  - New benchmarking approach considering sustainability.
- Leveraging open source to help developing European advanced solutions on the edge:
  - Open source hardware (and its complete ecosystem of IPs and tools).
  - Open source software.
  - Europe must address the end to end value chain.
- Engineering support to improve sustainable edge computing:
  - Engineering process automation for full lifecycle support.
  - Edge devices security by design.
  - Engineering support for edge computing, verification and certification, addressing end-to-end edge solutions.

2.1.5.6.3 For Embedded Artificial Intelligence

First, as Embedded Artificial Intelligence is developing quickly and in many different directions for new solutions, it is crucial that an European ecosystem emerge gathering all steps of the the value chain. It has then to include the hardware, the software, the tools chain for AI development and the data sets in an trustable and certifiable environment. Both Edge Computing and Embedded Artificial Intelligence ecosystems are tied together.

Next, technology is strongly affected by sustainability that, very often, tips the scale between the ones that are promising, but not practically usable, and the ones making the difference. e.g. cloud computing, based on data centres, plays a fundamental element for the digitalization process. However, data centres consume a lot of resources (energy[105], water, etc.) and they are responsible for significant carbon emissions, during their entire lifecycle, and generate a lot of electronic and chemical waste.

Today, the percentage of worldwide electricity consumed by data centers is estimated to exceed the 3%, while the CO2 emissions are estimated to reach the 2% of worldwide emissions[106] [107], with cloud computing that is responsible for half of these emissions. A recent study predicts that, without energy efficient solutions, by 2025 eight data centres will consume 20% percent of the world's energy, with a carbon footprint rising to 5.5% of the global emissions. Data centres are progressively becoming more efficient, but shifting the computing on the edge, for example, allows to temporally reduce data traffic, data centres storage and processing. However, only a new computing paradigm could significantly reduce their environmental footprint and ensure sustainability. Edge Computing could contribute to reach this goal by the introduction of ultra-low and efficient computing solutions.

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

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

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

Indeed, from a wider perspective, digital transformation relies largely on other technologies that could significantly impact sustainability, including edge and fog computing, AI, IoT hyper connectivity, etc. In recent years, artificial intelligence and cloud computing have been the focus of the scientific community, environmental entities and public opinion for the increasing levels of energy consumption, questioning the sustainability of these technologies and, indirectly, their impact on corporate, vertical applications and societal sustainability. For example, devices are already producing enormous amounts of data and a recent study[108] estimates that by 2025 communications will consume 20% of all the world's electricity. This situation has been worsening with COVID-19 pandemic that generated a worldwide reduction of power consumption as a result of global lockdown restrictions but, at the same time, caused a huge spike in Internet usage: NETSCOUT measured an increase of 25-35% of worldwide Internet traffic in March 2020, just due to remote work, online learning and entertainment. This spike in Internet use provides a flavour of the implications of digitalization on sustainability. Reducing energy of computing and storage devices is a major challenge (see Major Challenge 1 on "Increasing the energy efficiency of computing systems").

Shifting to green energy is certainly a complementary approach to ensure sustainability, but the conjunction of AI and edge computing, the Edge AI, has the potential to provide sustainable solutions with a wider and more consolidated impact. Indeed, a more effective and longer-term approach to sustainable digitalization implies reconsidering the current models adopted for data storage, filtering, analysis, processing, and communication. By embracing edge computing, for example, it is possible to significantly reduce the amount of useless and wasteful data flowing to and from the cloud and data centres, with an architectural and structural more efficient solutions that permanently reduces the overall power consumption and bring other important benefits such as real-time data analysis reducing the amount of data to be stored and then a better data protection. The Edge Computing paradigm also makes AI more sustainable: it is evident that cloud-based machine learning inference is characterized by a huge network load, with a serious impact on power consumption and huge costs for organizations. Transferring machine learning inference and data pruning to the edge, for example, could exponentially decrease the digitization costs and enable sustainable businesses. To avoid this type of drawbacks, new AI components should be developed based on neuromorphic. architectures and considering the application areas, in some cases, this could bring to a more specialised and very efficient solutions.

Sustainability of Edge Computing and AI is affected by many technological factors, on which Europe should invest, and, at the same time, they have a positive impact on the sustainability of future digitalization solutions and related applications.

Currently, GAFAM already master these technologies and are progressively controlling the complete value chain associated with them. To follow this trend and aim at strategic autonomy, Europe has therefore to fill the technology gaps and address the value chain end to end, with a particular attention to SMEs (which generate a large part of European revenues) and leveraging on the cooperation between the European stakeholders in the value chain to develop successful products and solutions. From this perspective, European coordination to develop AI, edge computing and edge AI technologies is fundamental to create a sustainable value chain based on alliances and capable to support the European key vertical applications.

It will be a challenge for Europe to be in this race, but the emergence of AI at the edge, and its know-how in embedded systems, might be winning factors. However, the competition is fierce and the big names are in with big budgets and Europe must act quickly, because US and Chinese companies are already also moving in this "intelligence at the edge" direction.

108 Andrae, A., & Edler, T. (2015). On global electricity usage of communication technology: trends to 2030. Challenges, 6, 117–157.

1.2
2.3 2.4

2.1.5.6.4 Key focus areas

On top of the key focus area for Edge computing, Embedded Artificial Intelligence also requires:

- Energy-efficiency improvement:
  - New memories used to mimic synapses.
  - Advanced Neuromorphic components.
- Improving sustainability of AI:
  - Re-use and share of knowledge and models generated by embedded intelligence.
  - Energy- and cost-efficient AI training.
  - New benchmarking AI approach considering sustainability.
- Leveraging open source to help developing European AI advanced solutions on the edge:
  - Open-source training datasets.
  - Open Frameworks including AI tools.
  - Europe must address the end-to-end Embedded Intelligence value chain.
- Engineering support to improve sustainable AI:
  - Edge AI security by design.
  - Engineering support for AI verification and certification.
  - Education and support to deploy Edge AI.

2.1.6 TIMELINE

Short term: 2022-2026 - Medium 2027-2031 - Long term: beyond 2031

Legend:

- (EC): concern Edge Computing
- (eAI:) concern Embedded Artificial Intelligence

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 1: increasing the energy efficiency of computing systems	Processing data where it is created (EC and eAI)	• Development of algorithms and applications where processing is performed. • Moving processing towards edge when it is possible • New memory management
	Development of innovative hardware architectures (EC)	• Development of computing paradigms (e.g. using physics to perform computing). Use of other technologies than silicon (e.g. photonics) • New In-memory computing accelerators
	Development of innovative hardware architectures: e.g. neuromorphic (eAI)	• Development of neuromorphic based chips and support of this new computing model. • New In-memory computing accelerators for AI
	Developing distributed edge computing systems (EC)	• Development of Edge (ex: fog) type of computing (peer to peer)
	Developing distributed edge AI systems (eAI)	• Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning)
	Interoperability (with the same class of application) and between classes (EC and eAI)	• Create gateways between various solutions, beyond ONNX (for eAI) • Developing open architectures (for fast development) with maximum reuse of tools and frameworks • Interfaces standards (more than solutions) (could help explainability, with a move from black to grey boxes)
	Scalable and Modular AI (eAI)	• Using the same software development infrastructure from deep edge to edge and possibly HPC applications for AI developments • Use of similar building blocks from deep edge to edge AI devices
	Scalable and Modular systems (EC)	• Using the same software development infrastructure from deep edge to edge and possibly HPC applications. • Use of similar building blocks from deep edge to edge devices
	Co-design: algorithms, HW, SW and topologies (EC)	• Quick implementation and optimization of HW for the new emerging algorithms

MEDIUM TERM (2027-2031)	LONG TERM (BEYOND 2031)
• Development of hybrid architectures, with smooth integration of various processing paradigms (classical, neuromorphic, deep learning), including new OSs supporting multiple computing paradigms • Advanced memory management	• Dynamic instantiation of multi-paradigm computing resources according to the specifications of the task to be performed. Automatic interfacing, discovery, and configuration of resources
• Supporting tools integrating multiple computing paradigms. • Use of 2.5D, interposers and chiplets, with efficient interconnection network, e.g. using photonics) • Advanced In-memory computing accelerators	• Integration in the same package of multiple computing paradigms (classical, Deep Learning, neuromorphic, photonic, ...) • Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs
• Integration of neuromorphic and other computing within classical systems • Supporting tools integrating multiple AI computing paradigms.	• Integration in the same package of multiple computing paradigms (classical, Deep Learning, neuromorphic, photonic, ...) • Exploring potential use of quantum computing in Artificial Intelligence?
• Edge computing demonstrating high performance for selected applications	
• Federated learning or similar approach demonstrating high performance for selected applications	
• Common interface architecture, with dynamic binding: publishing of capabilities for each device/block, flexible data structure and data converters, dynamic interconnect. • Promoting European standard for interoperability cross application silos. • Interfaces publishing non-functional properties (latency, bandwidth, energy, ...)	• At all levels (from chips to systems), automatic interoperability, adaptation to the data structure and physical interface, considering the communication characteristics. (Mid-term? Automatic translator of data and data format) • Global reconfiguration of the resources to satisfy the functional and non-functional requirements (latency, energy, etc.)
• Scalable architecture (in 3 dimensions). Use of interposer and chiplets to build chips for various applications (for edge and for HPC applications) with the same AI hardware building blocks	• Linear and/or functional scalability of AI systems • Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs of AI systems
• Scalable architecture (in 3 dimensions). Use of interposer and chiplets to build chips for various applications (for edge and for HPC applications) with the same hardware building blocks	• Linear and/or functional scalability • Digital twin (Functionalities simulation) • Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs
• Tools allowing semi-automatic design exploration of the space of configurations, including variants of algorithms, computing paradigms, hardware performances, etc.	• Auto-configuration of a distributed set of resources to satisfy the application requirements (functional and non-functional)

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 2: managing the increasing complexity of systems	Balanced mechanisms between performance and interoperability (EC)	• Exposing the non-functional characteristic of devices/blocks and off-line optimization when combining the devices/blocks
	Development of trustable AI (eAI)	• Move to security Chapter
	Developing distributed edge computing systems (EC)	• See items above in Increasing the energy efficiency of computing systems
	Scalable and Modular AI (eAI)	• See items above in Increasing the energy efficiency of computing systems
	Easy adaptation of models (eAI)	• Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning) • Create a European training reference database for same class of applications/use cases network learning
	Easy adaptation of modules (EC)	• Easy migration of application on different computing platforms (different CPU – x86, ARM, Risc V- different accelerators)
	Realizing self-X Self-optimize, reconfiguration and self-management (EC)	• Add self-assessment feature to edge devices
	Using AI techniques to help in complexity management (EC and eAI)	• Using AI techniques for the assessment of solutions and decrease the design space exploration
Major Challenge 3: supporting the increasing lifespan of devices and systems	HW supporting software upgradability (eAI)	• Create a European training reference database for same class of applications/use cases network learning • European training benchmarks (Methods and methodologies) • Framework tools for HW/SW for fast validation and qualification • Interfaces standards compatible with most of AI approaches
	Realizing self-X Also partially in *Managing the increasing complexity of systems (eAI)*	• Unsupervised learning technics • Development of efficient and automated transfer learning: only partial relearning required to adapt to a new application (Ex: Federative learning)
	Improving interoperability (with the same class of application) and between classes, modularity and complementarity between generations of devices. (EC) Also partially in *Increasing the energy efficiency of computing systems*	• Developing open architectures (to fast develop) with maximum reuse of tools and frameworks • Interfaces standards (more than solutions) (could help explainability move from black to grey boxes)

MEDIUM TERM (2027-2031)	LONG TERM (BEYOND 2031)
• On-line (dynamic) reconfiguration of the system to fulfil the requirements that can dynamically change (Self-x)	• Drive partitioning through standards
• Move to security Chapter	• Move to security Chapter
• See items above in Increasing the energy efficiency of computing systems	• See items above in Increasing the energy efficiency of computing systems
• See also items above in Increasing the energy efficiency of computing systems • Data and learning driven circuits design	• See items above in Increasing the energy efficiency of computing systems
• Optimization of the Neural Network topology from a generically learned networks to an application specific one.	• Generic model based digital AI development system
• Use of HW virtualization • Automatic transcoding of application for a particular hardware instance (à la Rosetta 2)	• Generic model based digital development system
• Automatic reconfiguration of operational resources following the self-assessment to fulfil the goal in the most efficient way	• Modelling simulation tools for scalable digital twins
• Automatic generation of architecture according to a certain set of requirements (in a specific domain)	• Modelling simulation tools for scalable digital twins

• HW virtualization based on AI algorithms • Generic AI functions virtualization • European training standards (Compliance/Certification)	• Explainable AI
• HW virtualization based on AI algorithms • Generic AI functions virtualization	• Explainable AI
• Generic functions modules by class of applications/use cases + virtualization	

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022-2026)
Major Challenge 3: supporting the increasing lifespan of devices and systems	Improving interoperability of AI functions (with the same class of application) and between classes, modularity and complementarity between generations of devices. (eAI) Also partially in *Increasing the energy efficiency of computing systems*	• Developing open AI architectures (to quickly develop) with maximum reuse of tools and frameworks • Interfaces standards (more than solutions) (could help explainability of AI with a move from black to grey boxes) • Clarified requirements for embedded AI in industry
	Developing the concept of 2nd life for components (EC) (link with sustainability)	• Inclusion of existing embedded systems on the edge (huge market opportunity) • Library of generic set of functions (Standardization) • Basic data collection for predictive maintenance
Major Challenge 4: ensuring European sustainability in Edge computing and embedded Artificial Intelligence	Energy efficiency improvement (EC)	• Materials and electronic components oriented to low and ultralow power solutions • Low and ultra-low power communications • Strategies for self-powering nodes/systems on the edge • Efficient cooling solutions
	Improving sustainability of Edge computing (EC)	• Inclusion of existing embedded systems on the edge (huge market opportunity)
	Improving sustainability of embedded Artificial Intelligence (eAI)	• Energy and cost-efficient AI training
	Leveraging open source to help developing European AI advanced solutions on the edge (eAI)	• Open source software • Open source training datasets • Open edge computing platforms
	Engineering support to improve sustainable Edge computing (EC)	• Sustainability through engineering process automation • Continuous engineering across the product life cycle
	Engineering support to improve sustainable embedded Artificial Intelligence (eAI)	• Sustainability through engineering process automation • Continuous engineering across the product life cycle

MEDIUM TERM (2027-2031)	LONG TERM (BEYOND 2031)
• Generic AI functions modules by class of applications/use cases + virtualization	
• Generic set of functions for multi-applications/use cases • Global data collections for predictive maintenance by applications/use cases	• Standardize flow for HW/SW qualification of generic set of functions (including re-training) which are used in a downgraded application/use case

• 3D-based device scaling for low energy consumption	
• Efficient and secure code mobility	
• Reuse of knowledge and models generated by embedded intelligence	
• Open source hardware	
• Holistic development environment • Engineering support for verification and certification	
• Holistic development environment • Engineering support for AI verification and certification • Edge AI security by design	

2.1.7
SYNERGY WITH OTHER THEMES

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

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

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

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

2.2

Cross-Sectional Technologies

CONNECTIVITY

2.2.1 SCOPE

Connectivity and interoperability technologies in ECS enabling business and social benefits are tied to layers 1, 5, and 6 of the OSI model. The focus on these layers is motivated by the Major Challenges that characterise them (see *Figure F.31*).

2.2.1.1 Scope for OSI layer 1

The scope covers the following types of physical layer connectivity.

- Cellular:
  - Beyond 5G.
  - Early 6G investigation.
- Low power wide area:
  - Cellular: narrow band IoT, LTE, 6G, etc.
  - Non-cellular: SigFox, LoRa, M-Bus, etc.
- Low power short range:
  - Wireless: existing (Bluetooth, WiFi, etc) or innovative technologies (mmW, etc.).
  - Wired: covering both high-speed optical glass and plastic fibers, mmW plastic fibers, and copper interconnect (USB, DOCIS, etc.).
- High speed:
  - Wireless: point to point mmW and satellite communication (low earth orbit and geosynchronous equatorial orbits).
  - Wired: high-speed optical (400 Gb+, etc) and copper interconnect (Ethernet, etc.).

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

2.2.1.2 Scope for OSI layer 5 and 6

The scope addressed in this context is the interoperability from application to application relying on technologies at OSI layers 5 and 6. This interoperability covers the following underlying aspects:

- Protocols at all technology levels: Internet, operational and legacy.
- Security: such as protocol security, payload encryption, certificates, tokens and key distribution.
- Data semantics: supporting application to application understanding of transferred data/information.

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

F.31 *Major Challenges: OSI Model*

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

F.32 *Major Challenge: ensuring European leadership in terms of connectivity technologies*

2.2.2
TECHNOLOGY-ENABLED SOCIETAL BENEFITS

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

- Industrial competitivity: the industrial transition to Industry 4.0, with its massive usage of automation and digitalisation accompanied by AI-supported analytics, puts much higher demands on the availability and reliability of high-speed, secure, low or guaranteed latency connectivity. Given the large amount of legacy connectivity and emerging new connectivity, interoperability over technology generations and between application domains will become an enabler for competitivity. 3.3

- Healthcare improvement: connectivity has the potential to improve medical behaviour for patients and healthcare professionals, as well as the delivery of better medical services. Connected devices can transform the way healthcare professionals operate by allowing remote diagnosis and more efficient means of treatment. For example, patient information could be sent to hospitals via mobile and internet applications, thus saving travel time and service costs, and also substantially improving access to healthcare, especially for rural populations. Connectivity and associated devices and services could complement and improve existing medical facilities. From the citizen side, the monitoring of illnesses can also be enhanced by mobile and internet applications designed to remind patients of their treatments, and to control the distribution of medicinal stocks. 3.4

- Energy and environment: one of the projected impacts of digitalisation is an improved ability to optimise energy utilisation and minimise environmental footprints. Connectivity and interoperability are critical elements of the information and communications technology (ICT) infrastructure that is essential to allow such optimisation and minimisation. The size of the energy efficiency market was estimated at US $221 billion in 2015, which was 14% of the global energy supply investments (IEA, 2016b), divided between buildings (53%) transport (29%) and industry (18%) (IEA, 2016a). 3.2

- For autonomous and automated driving advanced connectivity solutions are needed with key characteristics ultra-high reliability, extremely low latency and high throughput solutions. Advanced edge solutions that will integrated AI/ML schemes over secure links will be also of paramount importance. 2.1 3.1

- Improve public services, social cohesion and digital inclusion: ICT technologies have long been recognised as promoting and facilitating social inclusion – i.e. the participation of individuals and groups in society's political, economic and societal processes. One way in which ICT technologies can expand inclusion is through effective public services that rely on ICT infrastructure, and through digital inclusion (i.e. the ability of people to use technology). These three aspects are deeply intertwined, and span dimensions as diverse as disaster relief, food security and the environment, as well as citizenship, community cohesion, self-expression and equality. Public 3.6

authorities can enhance disaster relief efforts by promoting the spread of information online and by implementing early warning systems. The internet also enables relief efforts through crowd-sourcing: for instance, during Typhoon Haiyan in the Philippines, victims, witnesses and aid workers used the web to generate interactive catastrophe maps through free and downloadable software, helping disseminate information and reduce the vulnerability of people affected by the disaster. Communities can also be strengthened by connectivity, thereby promoting the inclusion of marginalised groups.

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

3.4 3.6

2.2.2.1 Applications breakthroughs

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

- A shift in focus from acute, hospital-based care to early prevention.
- Strengthening where and how healthcare is delivered, supporting home-based care.
- Stronger participation of citizens in their own care processes, enhancing patient engagement.
- Supporting the clinical workforce and healthcare consumers to embrace technology-enabled care.
- Data communication technology for interoperability of wireless data infrastructure.

3.4

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

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

In the mobility application area, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding: 3.1

- Achieving the Green Deal for mobility, with the 2Zero goals of –37.5% CO2 by 2030.
- Increasing road safety through the CCAM programme.
- Strengthening the competitiveness of the European industrial mobility digitalisation value chain.

In the energy application domain, the provision of improved, robust, secure and interoperable connectivity will support breakthroughs regarding: 3.2

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

In the industry application domain, the provision of improved, robust, secure and interoperable connectivity will support closing gaps such as: 3.3

- Preparing for the 5G era in communications technology, especially its manufacturing and engineering dimension.
- Long-range communication technologies, optimised for machine-to-machine (M2M) communication, a large number of devices and low bit rates, are key elements in smart farming.
- Solving IoT cybersecurity and safety problems, attestation, security-by-design, as only safe, secure and trusted platforms will survive in the industry.
- Interoperability-by-design at the component, semantic and application levels.
- IoT configuration and orchestration management allowing for the (semi)autonomous deployment and operation of large numbers of devices.

In the digital society application domain, the provision of improved, robust, secure and interoperable connectivity will support the overall strategy regarding: 3.6

- Enabling workforce efficiency regardless of location.
- Stimulating social resilience in the various member states, providing citizens with a better work/life balance and giving them freedom to also have leisure time at different locations.
- Ubiquitous connectivity, giving people a broader employability and better protection against social or economic exclusion.
- Enabling European governments, companies and citizens to closer cooperation, and to develop reliable societal emergency infrastructures.

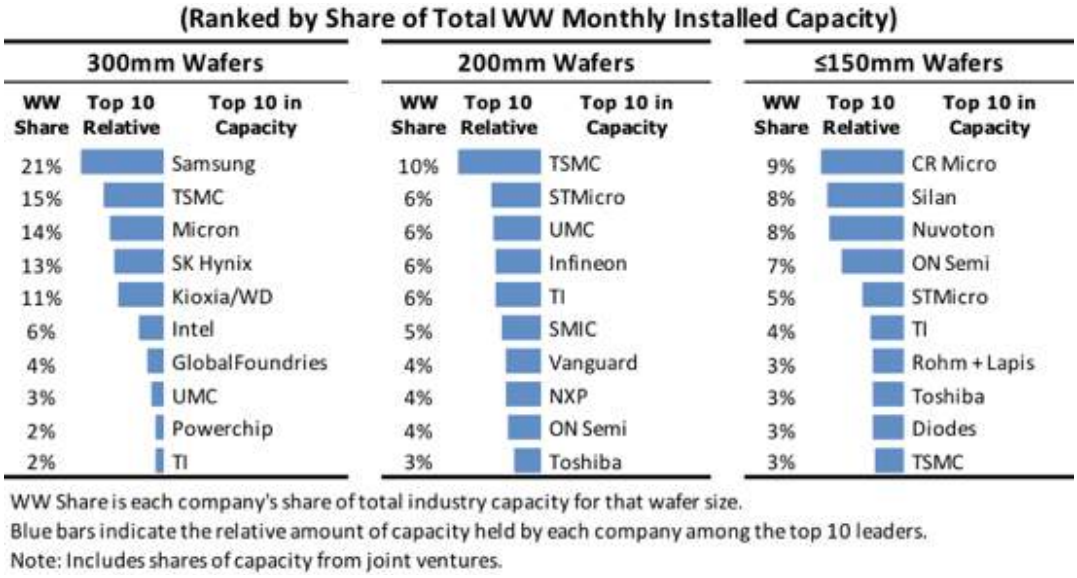
In the agrifood application domain, the provision of improved, robust, secure and interoperable connectivity will support innovations addressing the EU Green Deal regarding: 3.5

- Reducing the environmental impact related to transport, storage, packaging and food waste.
- Reducing water pollution and greenhouse gas emission, including methane and nitrous oxide.
- Reducing the European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agriculture and stopping biodiversity erosion.

2.2.3
STRATEGIC ADVANTAGE FOR THE EU

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

While Europe is just producing 9% of the overall electronic components (see *Figure F.33*), its market share is 19% on the market it serves today (industry-grade embedded segments, the wireless infrastructure market being a good example with Ericsson and Nokia). This figure is in line with Europe's GDP. Since Europe hardly addresses the consumer market, the European ecosystem requires a moderated manufacturing capacity mainly focused on mature or derivative technology. For example: automotive represents today only about 10%, but this is expected to increase in the coming years. The installed European semiconductor manufacturing capability to address Europe's key verticals is sized accordingly. As illustrated in *Figure F.33*, Europe has a strong presence on 200 mm facilities (with STMicroelectronics and Infineon among the top 5 leaders) which is in line with the technologies required by the European ecosystem and value chain.



F.33 *Installed capacity leaders in December 2020 by wafer size[109].*

Consequently, to strengthen Europe's position and enable European industry to capture new business opportunities associated with the connected world we live in, it is vital to support European technological leadership in connectivity-supporting digitization based on IoT and SoS technologies (for example, by being

109 https://www.icinsights.com/services/global-wafer-capacity/

at the forefront of new standard development for the current 5G initiative and the emerging SoS market). Moreover, to bring added value and differentiation compared to US and Asian competitors, European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report[110]).

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

- Automotive: the main driver here is the deployment of advanced driver-assistance systems (ADAS), which is a key opportunity for European semiconductor companies. Connectivity technology is consequently a Major Challenge since inter-sensor communication requires high bandwidth, reliability and very low latencies, and therefore innovative solutions will be necessary to prevent network overloads while meeting strict application and services requirements. A B5G and 6G networks with hierarchical architectures will be required to communicate in a reliable way with all the function domains of the car.
- Digital production: production of goods and services already involves a multitude of data obtained from various sources. Digitalisation demands a drastic increase of data sources, ranging from sensors and simulators to models. Such data will be used for control, analytics, prediction, business logics, etc., with receivers such as actuators, decision-makers, sales and customers. Obviously, this will involve a huge number of devices with software systems that are required to be interoperable, and possible to integrate for desired combined functionality. This demands seamless and autonomous interoperability between the devices and systems involved, regardless of the chosen technology. Connectivity technology plays an important role for all application areas of the ECS-SRIA.

3.1

3.3

2.2.4 MAJOR CHALLENGES

Five major challenges have been identified in the connectivity domain:

- **Major Challenge 1:** strengthening the EU connectivity technology portfolio to maintain leadership, secure sovereignty and offer an independent supply chain.
- **Major Challenge 2:** investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership.
- **Major Challenge 3:** autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics.
- **Major Challenge 4:** architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity.
- **Major Challenge 5:** network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures.

110 Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.

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

2.2.4.1.1 State of the art

1.1 1.2

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

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

From their side, European players (Infineon, NXP, ST, etc.) are strong on the analogue and RF front end module markets, mainly due to the availability of differentiated technologies developed and manufactured in Europe (for example, bipolar CMOS, BiCMOS, and RF silicon-on-insulator, SOI). Differentiated technologies are a key strength of the European ECS industry, especially when considering the connectivity market.
Consequently, to maintain Europe's leadership and competitiveness it is vital to ensure that European differentiated semiconductor technologies remain as advanced as possible. This is key to ensure that Europe secure's the market share in the connectivity market, and also strengthens its technology leadership by playing a major role in the development and standardisation of future connectivity technologies. This point is crucial to secure Europe sovereignty on the connectivity topic.

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

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

2.2.4.1.2 Vision and expected outcome

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

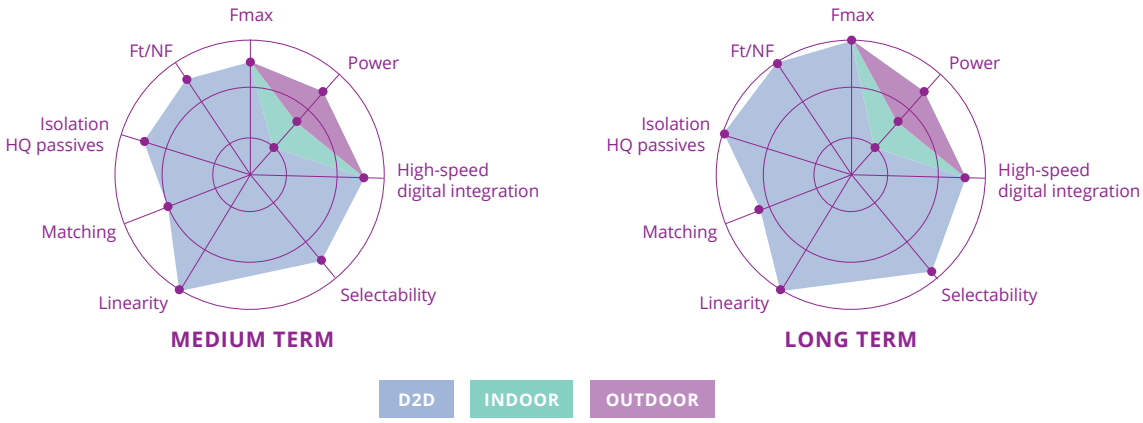
2.2.4.1.2.1 Strengthening Europe's differentiated technologies portfolio

As discussed above, Europe's differentiated semiconductor technologies are key assets that should be both preserved and improved upon to secure European leadership in connectivity. Consequently, dedicated

research should be encouraged, such as the technologies below (which are also promoted in the Chapter 1.1 on Process Technology, Equipment, Materials and Manufacturing).

- Advanced BiCMOS: targeting RF and sub THz (i.e., 100-300GHz) and THz front-end modules.
- RF SOI: targeting RF and mmW front-end modules.
- GaN: targeting the high-power infrastructure market.
- FD SOI: targeting power-efficient connectivity solutions.
- GaAs/InP: targeting mmW applications.

The main challenge will be in improving achievable performances. To illustrate this, we have extracted the medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID to serve as a connectivity roadmap (see *Figure F.34*). We can see that whatever the type of application (device-to-device, D2D, indoor, outdoor), the requirements in analogue RF will mainly consist of achieving Fmax and FT ~500 GHz in 2025 and 1 THz in 2030, while NFmin will be well below 1 dB in the medium term, to reach 0.5dB in the long term. The only parameter that differentiates the types of applications is the output power, which outdoors should reach between 36 and 40 dBm per PA by the end of the decade. The biggest challenge for silicon or hybrid-on-silicon substrate technologies is expected to be the frequency challenge. Technologies such as GaN/Si and RF SOI will deliver power but for applications operating at less than 100 GHz.



Medium-term (2025) and long-term (2030) solid state technology roadmap proposed by H2020 CSA project NEREID[111]. **F.34**

Note that the vision presented in *Figure F.34* also applies to packaging and printed circuit board (PCB) technologies. It is also worth noting that while Europe is playing a key role in innovative differentiated semiconductor technologies, there is very little R&D activity or few players in Europe on the packaging and PCB side. This point is clearly a weakness that should be addressed to strengthen Europe's connectivity technology portfolio.

111 https://www.nereid-h2020.eu/

2.2.4.1.2.2 Securing Europe's differentiated hardware technology manufacturing

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

1.1

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

2.2.4.1.2.3 Strengthening Europe's connectivity technology portfolio (hardware, internet protocols and software)

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

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

1.2

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

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

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

2.2.4.1.3 Key focus areas

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

- Innovative differentiated semiconductor technology development targeting connectivity application.
- Innovative packaging and PCB technology targeting connectivity application.
- Pilot line enablement to support the strengthening of European manufacturing capability.
- Innovative semiconductor equipment enablement.
- Innovative connectivity solution development targeting hardware, IP and software virtualisation.
- Enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc) to help European players capture higher value in the connectivity market.
- Ultra-low power transceivers will be needed, and low eco-footprint.
- Antenna and packages at mm-wave and THz, on-chip antennas.
- Meta-materials for antennas, meta-materials for intelligent reflective surfaces and meta-surfaces.

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

2.2.4.2.1 State of the art

1.1 1.2

Targeting connectivity solutions beyond 5G, R&D activity is today mainly focused on the three key challenges listed below.

2.2.4.2.1.1 Evaluating the advantage to use new spectrum (especially at mmW frequencies)

While to date the R&D evaluation has been focused on frequencies below 20 GHz, there is now some interest in assessing achievable performances with a higher frequency. For regulatory reasons, the 275 GHz – 325 GHz range holds promise as it enables the widest available bandwidth. As an illustration, to play a key role in preliminary 6G investigations, the US has facilitated their research on the 95 GHz – 3 THz spectrum over the coming decade. After a unanimous vote, the Federal Communications Commission (FCC) has opened up the "terahertz wave" spectrum for experimental purposes, creating legal ways for companies to test and sell post-5G wireless equipment.

2.2.4.2.1.2 Evaluating the opportunity to use new medium of propagation

Over the last few years, impressive results have been reported concerning high-speed millimetre wave silicon transceivers coupled to plastic waveguides. The state of art on the data rate is now at 36 Gb/s, with a short distance of 1 m in SiGe 55 mnm BiCMOS with 6pJ/b.meter working at 130 GHz. The maximum distance ever reported is 15 m, with 1.5 Gb/s data rate using 40nm CMOS at 120 GHz. In the 10 m distance – which, for instance, is the requirement for data centre applications – the state of the art is given by a data rate of 7.6 Gb/s at 120 GHz for 8m in 40nm CMOS, and a data rate of 6 Gb/s at 60 GHz for 12m in 65 nm CMOS. Although a 10 Gbps data rate, which is needed by data centres, seems feasible, questions remain over whether there is the required energy per bit to deliver this performance. Interesting technologies here is intelligent reflective surfaces and meta surfaces.

2.2.4.2.1.3 Exploring the benefits that AI could bring to connectivity technologies

While 5G is being deployed around the world, efforts by both industry and academia have started to investigate beyond 5G to conceptualise 6G. 6G is expected to undergo an unprecedented transformation that will make it substantially different from the previous generations of wireless cellular systems. 6G may go beyond mobile internet and will be required to support ubiquitous AI services from the core to the end devices of the network. Meanwhile, AI will play a critical role in designing and optimising 6G architectures, protocols and operations.

For example, two key 5G technologies are software-defined networking (SDN) and network functions virtualisation (NFV), which have moved modern communications networks towards software-based virtual networks. As 6G networks are expected to be more complex and heterogeneous, advanced softwarisation solutions are needed for beyond 5G networks and 6G networks. Selecting the most suitable computational and network resources and the appropriate dynamic placement of network functions, taking network and application performance as well as power consumption and security requirements, will be an important topic. By enabling fast learning and adaptation, AI-based methods will render networks a lot more versatile in 6G systems. The design of the 6G architecture should follow an "AI-native" approach that will allow the network to be smart, agile, and able to learn and adapt itself according to changing network dynamics.

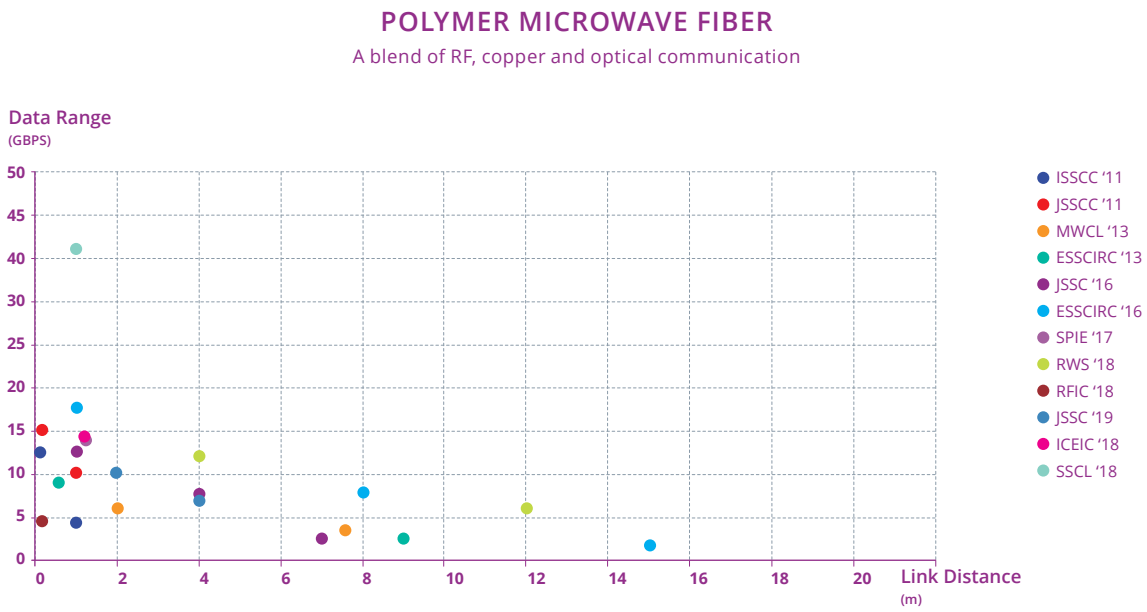
2.2.4.2.2 Vision and expected outcome

To address identified connectivity technology Major Challenge 2, we propose the vision described below, which can be summarised in the following three points (with associated expected outcomes).

2.2.4.2.2.1 Assess achievable connectivity performances using new spectrums

To maintain European leadership on connectivity technology and ensure sovereignty, the development of new electronics systems targeting connectivity applications in non-already standardised (or in the process of being standardised) spectrums should be supported. A special focus should be dedicated to the frequency bands listed below.

- SubTHz connectivity application in the 200 GHz – 300 GHz band: With THz communication being a hot topic in the international community, European activity in the spectrum > 300 GHz should be encouraged. These investigations should help Europe play a role in the development of the new technology and assess its relevance to future 6G standards.
- Unlicensed connectivity in the 6 GHz – 7 GHz band: As WiFi 6 is currently being deployed in the US in the 5 GHz – 6.2 GHz band (on April 23 2020, the FCC approved the opening of 1200 MHz of spectrum to IEEE 802.11ax), this spectrum allocation is also under discussion in Europe. It is vital for Europe to support investigation on this frequency band to ensure that the next generation of WiFi technology is accessible to European citizen and businesses (without any limitation compared to other countries).
- Investigation of <10 GHz spectrum for 6G: While 5G was initially thought to be mainly linked to the mmW spectrum (for example, at 28 GHz), most of the current deployment effort is happening in the new < 6 GHz frequency bands. To complement the investigation of the above-mentioned THz communication, the evaluation and development of innovative connectivity technology <10 GHz should be encouraged. This may secure European leadership in future 6G proposals and standardisation activities.



Polymer microwave fiber – A blend of RF, copper and optical communication
(Source: https://www.polymermicrowavefiber.com/ : PMF state of art by KUL Professor Patrick Reynaert)

F.35

2.2.4.2.2.2 Investigate new propagation medium to enable power-efficient and innovative connectivity technologies

New applications create the need for new connectivity technology. For example, autonomous driving requires very high-speed communication (currently 10 Gb/s and 40 Gb/s in the future) to connect all the required sensors to the central processing unit (CPU). While Ethernet is today perceived as the technology of choice, its deployment in cars is challenging since the electromagnetic interference (EMI) requirements of the automotive industry impose the use of shielded twisted pairs, which add cost and weight constraints. To address this need, intense R&D activity has been pursued over the last few years to assess the relevance of mmW connectivity using plastic waveguides (as described in the previous section). Consequently, the development of innovative connectivity solutions using new mediums of propagation should be encouraged to enable innovative connectivity technology and ensure European leadership and sovereignty.

2.2.4.2.2.3 Integrate AI features to make connectivity technology faster, smarter and more power-efficient

1.3 2.1

The use of new spectrums or propagation mediums is not the only way to boost innovative connectivity technology. As mentioned, 5G has underlined the role of software to promote virtualisation and reconfigurability, but those concepts may not be sufficient to address the challenges related to the more complex connectivity technology that may be developed (for example, 6G).

To address this challenge, Artificial Intelligence is now perceived as a strong enabler. Consequently, in coordination with the AI, Edge Computing and Intelligence on the Edge Chapter, the topics below should be supported.

- Investigate AI features at the edge: to improve the power efficiency of mobile devices by reducing the amount of data to be transmitted via the wireless network, the concept of AI at the edge (or edge AI) has been proposed. The idea is to locally process the data provided by the sensor using mobile device computing capability. Moreover, processing data locally avoids the problem of

streaming and storing a lot of data to the cloud, which could create some vulnerabilities from a data privacy perspective.

- Use AI to make the connectivity network more agile and efficient: the idea here is to move to an AI-empowered connectivity network to go beyond the concept of virtualisation and achieve new improvement in terms of efficiency and adaptability. For example, AI could play a critical role in designing and optimising 6G architectures, protocols and operations (e.g., resource management, power consumption, improve network performance etc.).

2.2.4.2.3 Key focus areas

To support the vision presented in the previous paragraph, we propose that efforts should be focused on the following key focus areas:

- Innovative connectivity system design using new spectrums (especially mmW).
- Investigation and standardisation activity targeting 6G cellular application in the frequency band < 10 GHz.
- Development of innovative connectivity technology using unlicensed frequency in the 6 GHz – 7 GHz band.
- Development of innovative connectivity system using new propagation mediums.
- Development of connectivity system leveraging the concept of edge AI.
- Evaluation of the AI concept to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability.

2.2.4.3 Major Challenge 3: autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics

2.2.4.3.1 State of the art

Europe has a very clear technology lead in automation and digitalisation technology for industrial use. The next generation of automation technology is now being pushed by Industry 4.0 initiatives backed by the EC and most EU countries. In the automotive sector, the autonomous car vision is the driver. Here, Europe again has a strong competitive position. In healthcare, the ageing population is the driver. Europe's position in this area is respectable but fragmented. Robust, dependable, secure and interoperable connectivity from application to application and prepared for interaction in System of Systems solution are fundamental to market success in these and other areas.

Interoperability is a growing concern among numerous industrial players. An example here is the formation of industrial alliances and associated interoperability project efforts. One of the directions chosen targets is to gather behind a few large standards. An example of this is showcased in *Figure F.36*.

To maintain and strengthen the European lead, advances in autonomous interoperability and associated efficient engineering capability are necessary. The game changers are:

- autonomous interoperability for SoS integration for efficient engineering at design-time and run-time,
- open interoperability frameworks and platforms,
- novel and advanced security solutions,
- standardisation of the above technologies.

ISO 15926 – Asset Standards worldwide (Source: Erik Molin, SEIIA)

F.36

2.2.4.3.2 Vision and expected outcome

To fully leverage this heterogeneous integration at the hardware level, software interoperability is a parallel challenge to provide application to application connectivity that allows for autonomous SoS connectivity, from IoT to back-end systems, enabling usage of available data for all areas of application. To do so, dedicated software tools, reference architecture and standardisation are key to supporting autonomous interoperability, thus enabling the provision of a widely interoperable, secure, scaleable, smart and evolvable SoS connectivity.

This challenge involves the interoperability of service or agent protocols, including encoding, security and semantics. Here, payload semantics interoperability is a primary focus, leading to architectures, technologies and engineering tools that support application to application integration of SoS for all areas of applications at design- time, in run-time and over life cycle. This will include e.g. translation between different standards used in domains where SoS interaction is necessary to reach business and societal objectives.

The objective here is for a technology that enables nearly lossless interoperability across protocols, encodings and semantics, while providing technology and engineering support foundations for the low-cost integration of very large, complex and evolvable SoS.

Expected achievements are:

- Open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, including 5G.
- Open source engineering and implementation frameworks for the de-facto standard SoS connectivity architecture.
- Architecture reference implementations with performance that meets critical performance requirements in focused application areas.

2.2.4.3.3 Key focus areas

The high-priority technical and scientific challenges in both design-time and run-time are:

- Semantics interoperability from application to application.
- Autonomous translation of protocols, encodings, security and semantics.
- Evolvable SoS connectivity architectures and technologies over time and technology generations.

2.2.4.4 Major Challenge 4: architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

2.2.4.4.1 State of the art

It is clear that the US is the leader when it comes to wired connectivity while Europe is the leader in cellular connectivity. The big potential game changer here is 5G and upcoming 6G. To advance the European position, the establishment of connectivity architecture, reference implementation and associated engineering frameworks supporting 5G/6G and other wireless technologies is required. The primary application markets should connect to European strongholds such as automation, digitalisation and automotive. The game changers are:

- Establishment of connectivity architecture standards with associated reference implementation and related engineering frameworks.
- SoS application to application connectivity being interoperable, secure, scalable, smart and evolvable.

2.2.4.4.2 Vision and expected outcome

The enabling of SoS connectivity is fundamental for capturing the emerging SoS market and its very high growth rate. Efficient engineering and the deployment of interoperable, secure, scaleable, smart and evolvable SoS connectivity will be key to this. This will help Europe lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

In certain domains such as automotive and industrial automation, Europe is the major player. Market studies[112] indicate very large to extreme growth in the SoS market over the next five years.
This will provide a very strong market pull for all technologies and products upstream. Here, connectivity interoperability is a very important component, enabling tailored SoS solutions and efficient engineering. The vision is to provide interoperable connectivity architecture, reference implementation and associated engineering support and frameworks spanning technologies from legacy to 5G and 6G and other wireless and wired technologies.

Expected achievements

- Open source implementation of reference architectures supporting interoperability, security scalability, smartness and evolvability across multiple technology platforms, including 5G and 6G.
- Open source engineering and implementation frameworks for the de-facto standard SoS connectivity architecture.
- Architecture reference implementations which meet critical performance requirements in focused application areas.

112 Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.

2.2.4.4.3 Key focus areas

The high-priority technical and scientific challenges are:

- SoS connectivity architecture as a de-facto standard.
- Reference implementation of de-facto SoS connectivity architectures.
- Engineering frameworks for de-facto standard SoS connectivity architecture.

2.2.4.5 Major Challenge 5: network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures

2.2.4.5.1 State of the art

Virtualisation of networks is a main trend for cellular networks. This has to be expanded to other wireless and wired connectivity technology. The game changers are:

- Technologies for network virtualisation across multiple layers and devices of different capabilities.
- Engineering tools and management methodologies for efficiently management virtualized network and service components.
- Intelligent, configurable generic hard platforms.

1.4 2.3

2.2.4.5.2 Vision and expected outcome

The enabling of virtualised networks is fundamental for capturing the emerging SoS market and its very high growth rate. Efficient engineering, deployment and management of connectivity is a key enabler for interoperable, secure, scalable, smart and evolvable SoS. This will help Europe lead in the establishment of connectivity architecture, reference implementation and associated engineering frameworks.

In certain domains such as automotive and industrial automation, Europe is the major player. Market studies[106] indicate very large to extreme growth in the SoS market over the next five years.

This will provide a very strong market pull for all technologies and products upstream. Here, virtualised connectivity is a very important component, enabling dynamic updates and rearrangements of SoS solutions. The vision is to provide virtualised connectivity across physical and mac layers spanning technologies from legacy to 5G and upcoming 6G.

Expected achievements:

- Open source implementation of reference architectures supporting virtualised connectivity across multiple technology platforms, including 5G, B5G and 6G.
- Open source engineering and management frameworks for virtualised connectivity across multiple technology platforms, including 5G, B5G and 6G.
- Reference implementations with performance that meets critical performance requirements in focused application areas.

2.2.4.5.3 Key focus areas

The high-priority technical and scientific challenges are:

- Virtual connectivity architecture supporting multiple technology platforms, including 5G, B5G and 6G.
- Reference implementation of virtual connectivity architecture.
- Engineering and management frameworks and tools for virtual connectivity architectures.

2.2.5 TIMELINE

The timeline for addressing the Major Challenges in this section is provided in the following table.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: strengthening EU connectivity technology portfolio	**Topic 1.1:** innovative differentiated semiconductor technology development targeting connectivity application	TRL 4–6
	Topic 1.2: innovative packaging and PCB technology targeting connectivity application	TRL 3–4
	Topic 1.3: pilot line enablement to support European manufacturing capability strengthening	TRL 4–6
	Topic 1.4: innovative semiconductor equipment enablement	TRL 3–4
	Topic 1.5:innovative connectivity solution development targeting hardware, IP and software items	TRL 3–4
	Topic 1.6: enable a European ecosystem that can support heterogeneous integration (multi-die system in a package, advanced assembly capability, advanced substrate manufacturing, etc) to help European players capture higher value in the connectivity market	TRL 4–6
Major Challenge 2: investigate innovative connectivity technology (new spectrums or mediums) and new approaches to improve the existing ones to maintain the EU's long-term leadership	**Topic 2.1:** innovative connectivity system design using new spectrums (especially mmW)	TRL 3–4
	Topic 2.2: investigation and standardisation activity targeting 6G cellular application in frequency band < 10 GHz	TRL 3–4
	Topic 2.3: development of innovative connectivity technology using unlicensed frequency in the 6 GHz – 7 GHz band	TRL 4–6
	Topic 2.4: development of innovative connectivity systems using new propagation mediums	TRL 3–4

MEDIUM TERM (2027–2031)	LONG TERM (2032–2037)
TRL 7–9	
TRL 5–6	TRL 7–9
TRL 7–9	
TRL 5–6	TRL 7–9
TRL 5–6	TRL 7–9
TRL 7–9	

TRL 5–6	TRL 7–9
TRL 5–6	TRL 7–9
TRL 7–9	
TRL 5–6	TRL 7–9

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 2: Investigate innovative connectivity technology (new spectrums or mediums) and new approaches to improve the existing ones to maintain the EU's long-term leadership	**Topic 2.5:** development of connectivity systems leveraging the concept of edge AI	TRL 4–6
	Topic 2.6: evaluation of the AI concept to be able to handle the complexity of future connectivity networks (for example, 6G), and to improve efficiency and adaptability	TRL 4–6
Major Challenge 3: autonomous interoperability	**Topic 3.1:** semantics interoperability	AI-supported translation of payload semantics based on a limited set of ontologies and semantics standards
	Topic 3.2: autonomous translation of protocols, encodings, security and semantics	Autonomous and dynamic translation between SOA-based services protocol, data encoding, data compression and data encryption
	Topic 3.3: evolvable SoS connectivity architectures and technologies over time and technology generations	TRL4–6
Major Challenge 4: architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	**Topic 4.1:** SoS connectivity architecture as a de facto standard	SoS connectivity architecture based on SOA established as a major industrial choice in the application domains of the SRIA
	Topic 4.2: reference implementation of de facto SoS connectivity architectures	Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (Chapter SoS) reference implementation
	Topic 4.3: e ngineering frameworks for de facto standard SoS connectivity architecture	Reference implementation of an engineering framework with associated tools for SoS connectivity

MEDIUM TERM (2027–2031)	LONG TERM (2032–2037)
TRL 7–9	
TRL 7–9	

General translation of payload semantics enabling application information usage	General translation of payload semantics enabling application information usage
Dynamic translation between major datamodel relevant for the ECSEL field of application	Autonomous and dynamic translation between a large set of data models relevant for the ECSEL field of application
TRL 5–7	TRL6–8

SoS connectivity architecture based on SOA established as the major industrial choice in the application domains of the SRIA	
Reference implementation of the SoS connectivity architecture becoming a natural part of the global SoS architecture (Chapter SoS) reference implementation at TRL 8–9	
Reference implementation of an engineering framework with associated tools for SoS connectivity at TRL 8	

2.3

Cross-Sectional Technologies

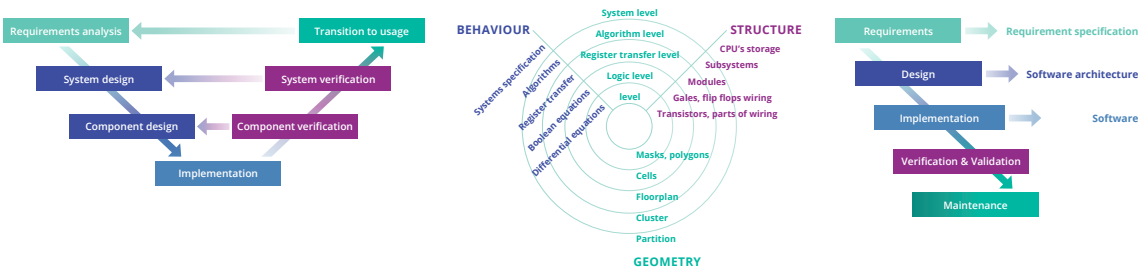
ARCHITECTURE AND DESIGN: METHODS AND TOOLS

2.3.1 SCOPE

To strengthen European industry's potential to transform new concepts and ideas cost- and effort-effectively into high-value and high-quality electronic components and systems (ECS)-based innovations and applications, two assets are essential: effective architectures and platforms at all levels of the design hierarchy; and structured and well-adapted design methods and development approaches supported by efficient engineering tools, design libraries and frameworks. These assets are key enablers to produce ECS-based innovations that are: (i) beneficial for society; (ii) accepted and trusted by end-users; and thus (iii) successful in the market.

Future ECS-based systems will be intelligent (using intelligence embedded in components), highly automated up to fully autonomous, and evolvable (meaning their implementation and behaviour will change over their lifetime), cf. Part 3. Such systems will be connected to, and communicate with, each other and the cloud, often as part of an integration platform or a system-of-system (SoS, see Chapter 1.4). Their functionality will largely be realised in software (cf. Chapter 1.3) running on high performance specialised or general-purpose hardware modules and components (cf. Chapter 1.2), utilising novel semiconductor devices and technologies (cf. Chapter 1.1). This Chapter describes needed innovations, advancements and extensions in architectures, design processes and methods, and in corresponding tools and frameworks, that are enabling engineers to design and build such future ECS-based applications with the desired quality properties (i.e. safety, reliability, cybersecurity and trustworthiness, cf. Chapter 2.4, which handles coping with these quality requirements from a design hierarchy point of view, whereas here a process oriented view is taken). The technologies presented here are therefore essential for creating innovations in all application domains (cf. Part 3); they cover all levels of the technology stack (cf. Part 1), and enable efficient usage of all cross-cutting technologies (cf. Part 2).

Traditionally, there is a huge variety of design processes and methods used in industry, such as processes based on the V-Model in systems and software design, based on Gajsky and Kuhn's diagram (Y-chart) in hardware design, based on the waterfall model or any other kind of (semi-) formal process definition (see *Figure F.37*).

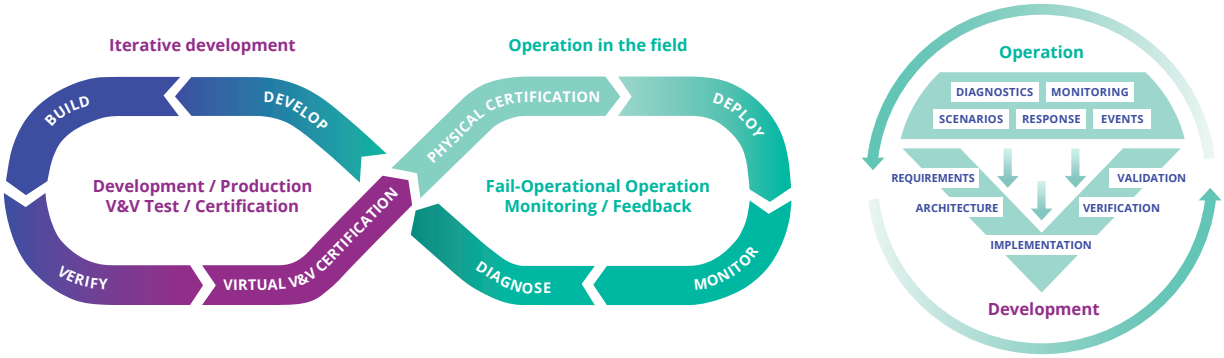


Simplified examples of applied "traditional" design processes: V-Model, Gajsky–Kuhn diagram (Y-chart) and the waterfall model. These are heavily in use, but not sufficient to handle future ECS-based systems and products.

F.37

Adding to the variety of design processes in use, the practical instantiation of these processes differs between companies, and sometimes even between different engineering teams within the same company. Nonetheless, most of these processes and their variants have common properties. They comprise several steps that divide the numerous design, implementation, analysis, and validation/verification tasks into smaller parts, which are then processed sequentially and with iterations and loops for optimisation. These steps include: activities and decisions on requirements elicitation and management; technologies used; system architecture; system decomposition into subsystems, components and modules; hardware/software partitioning and mapping; implementation and integration; and validation and testing on all levels of the design hierarchy.

CONTINOUS DEVELOPMENT AND INTEGRATION (DevOps)



F.38 *Simplified examples for continuous development processes (DevOps processes), Such processes are essential for building future ECS-based systems and products since they enable data collected during the operation phase to be used in iterative (continuous) development for updates of existing products.*

Due to the sheer size and complexity of current and future ECS-based products, the amount of functionality they perform, and the number and diversity of subsystems, modules and components they comprise, managing complexity and diversity have always been crucial in these processes. The trend of further growing complexity and diversity in future ECS-based applications increases the corresponding challenges, especially in employing model-based and model driven design approaches, and in divide-and-conquer based approaches, both on a technical level where modular, hierarchical designs need to be integrated into reference architectures and platforms –, and also on an organisational level – i.e. by employing open source solutions to increase interoperability and thus cooperation.

A further commonality in the different design processes in use today is that almost all of them end after the complete system has been fully tested and validated (and, in some domains, been homologated/certified). Although feedback from production/manufacturing has sometimes been used to increase production quality (e.g. with run-to-run control in semiconductor fabrication), data collected during the lifetime of the system (i.e. from maintenance, or even from normal operations) is rarely taken into account. If such data is collected at all, it is typically used only for developing the next versions of the system. Again, for future ECS-based applications this will no longer be sufficient. Instead, it is vitally important to extend these processes to cover the complete lifecycle of products. This includes collecting data from system's operation, and to use this data within the process to: (i) enable continuous updates and upgrades of products; (ii) enable in-the-field tests of properties that cannot be assessed at design-, development- or testing-time; and (iii) increase the effectiveness of validation and test steps by virtual validation methods based on this data (see also Major

Challenge 2 and 3 in Chapter 1.3 Embedded Software and Beyond). Apart from the technical challenges in collecting and analysing this data and/or using it for maintenance purposes, non-technical challenges include compliance to the appropriate data protection regulations and privacy concerns of system's owners (Intellectual Property) and users (privacy data). The resulting agile "continuous development processes" will ease quality properties assurance by providing design guidelines, design constraints and practical architectural patterns (e.g. for security, safety, testing), while giving engineers the flexibility and time to deliver the features that those development methodologies support ("quality-by-design solutions").

1.3

2.3.2 TECHNOLOGY-ENABLED SOCIETAL BENEFITS

The technologies described in this Chapter (methods and tools for developing and testing applications and their architectures) are the key enabler for European engineers to build future ECS with the desired quality properties (safety, security, reliability, trustworthiness, etc.) with an affordable effort and at affordable cost. As such, these technologies are necessary preconditions for all the achievements and societal benefits enabled by such applications.

ECS-based applications are becoming increasingly ubiquitous, penetrating every aspect of our lives. At the same time, they provide greater functionality, more connectivity and more autonomy. Thus, our dependency on these systems is continuously growing. It is therefore vitally important that these systems are trustworthy – i.e. that they are guaranteed to possess various quality properties. They need to be safe, so that their operation never harms humans or causes damage to human possessions or the environment; even in the case of a system malfunction, safety must be guaranteed. They also need to be secure: on the one hand, data they might collect and compute must be protected from unintended access; on the other hand, they must be able to protect the system and its functionality from access by malicious forces, which could potentially endanger safety. In addition, they must be reliable, resilient, dependable, scalable and interoperable, as well as posess many other quality properties. Most of all, these systems must be trustworthy – i.e. users, and society in general, must be enabled to trust that these systems possess all these quality properties under all possible circumstances.

2.4

Trustworthiness of ECS-based applications can only be achieved by implementing all of the following actions.

- Establishing architectures, methods and tools that enable "quality by design" approaches for future ECS-based systems (this is the objective of this Chapter). This action comprises:
  - Providing structured design processes, comprising development, integration and test methods, covering the whole system lifecycle and involving agile methods, thus easing validation and enabling engineers to sustainably build these high-quality systems.
  - Implementing these processes and methods within engineering frameworks, consisting of interoperable and seamless toolchains providing engineers the means to handle the complexity and diversity of future ECS-based systems.
  - Providing reference architectures and platforms that ensure interoperability, enable European Industries to re-use existing solutions and, most importantly, integrate solutions from different vendors into platform economies.
- Providing methodology, modelling and tool support to ensure that all relevant quality aspects (e.g. safety, security, dependability) are designed to a high level (end-to-end trustworthiness).

This also involves enabling balancing trade-offs with those quality aspects within ECS parts and for the complete ECS, and ensuring their tool-supported verification and validation (V&V) at the ECS level.

- Adding quality introspection interfaces to systems to enable engineers, authorities and end-users to inspect and understand why systems behave in a certain way in a certain situation (see "trustworthy and explainable AI" in Chapters 2.1 and 2.4), thus making AI-based and/or highly complex system behaviour accessible for quality analysis to further increase user's trust in their correctness.

2.1 2.4

The technologies described in this Chapter are thus essential to build high-quality future ECS-based systems that society trusts in. They are therefore key enablers for ECS and all the applications described in Part 3. In addition, these technologies also strengthen the competitiveness of European industry, thus sustaining and increasing jobs and wealth in Europe.

2.3.3 STRATEGIC ADVANTAGE FOR THE EU

Traditionally, Europe is strong in developing high-quality products. European engineers are highly skilled in systems engineering, including integration, validation and testing, thus ensuring system qualities such as safety, security, reliability, etc, for their products. Nevertheless, even in Europe industrial and academic roadmaps are delaying the advent of fully autonomous driving or explainable AI, for instance. After the initial hype, many highly ambitious objectives have had to be realigned towards more achievable goals and/or are predicting availability with significant delay. The main obstacle, and thus the reason for this technical slowdown, is that quality assurance methods for these kinds of systems are mostly not available at all, while available methods are not able to cover all the complexity of future systems. Worldwide, even in regions and countries that traditionally have taken a more hands-on approach to safety and other system qualities – e.g. a "learning-by-doing" type approach – a market introduction of such systems has failed, mainly due to non-acceptance by users after a series of accidents, with timing goals for market introduction being extended accordingly.

It has to be noted that currently there is a skill gap - a lack of skilled engineers who can drive the innovation process within the European electronics industry. Engineers having the correct skills and in sufficient numbers are crucial for Europe to compete with other regions and exploit the sector's true potential for the European economy. Universities have a vital role in the supply of graduate engineers, and it is essential that graduates have access to industry relevant design tools, leading edge technologies and training. Programs such EUROPRACTICE are essential in providing this access in an affordable manner and ensure that sufficient trained engineers are entering the European industry with relevant skills and experience.

The technologies described in this Chapter will substantially contribute to enabling European Industries to build systems with guaranteed quality properties, thus extending Europe's strength in dependable systems to trustworthy, high-quality system design ("made in Europe" quality), contributing to European strategic autonomy. This in turn will enable Europe to sustain existing jobs and create new ones, as well as to initiate and drive corresponding standards, thus increasing competitiveness.

Design frameworks, reference architectures and integration platforms developed with the technologies described in this Chapter will facilitate cooperation between many European companies, leading to new design ecosystems building on these artefacts. Integration platforms, in particular, will provide the opportunity to leverage a high number of small and medium-sized enterprises (SMEs) and larger businesses into a platform-based economy mirroring the existing highly successful platforms of, for example, Google, Apple, Amazon, etc.

In itself, the market for design, development, validation and test tools is already of considerable size, with good growth potential. The DECISION study[113], for example, has put the global market for materials and tools at €141 billion in 2018 (EU share: €24 billion), while Advancy considers the global market for equipment and tools for building ECS-based products at €110 billion in 2016 (EU share: 25%), with an estimated growth to €200 billion by 2025[114]. In addition to this existing and potential market, tools and frameworks are also key enabling technologies facilitating access to the application markets (cf., Part 3), since without them products cannot be built with the required qualities. Furthermore, the existence of cost-efficient processes implemented and supported by innovative development tools and frameworks that guarantee high-quality products typically reduces development time and costs by 20–50% (as shown by previous projects such as ENABLE S3, Arrowhead Tools, and many more). Thus, these technologies contribute substantially to European competitiveness and market access; cost-effectiveness also leads to lower pricing and therefore substantially contributes to making societal-beneficial technologies and applications accessible to everyone.

Last, but not least, the technologies described in this Chapter will contribute significantly to additional strategic goals such as the European Green Deal, while extending design processes to cover the whole lifecycle of products also enables recycling, re-using and a more circular economy.

2.3.4 MAJOR CHALLENGES

We identified four **Major Challenges** within the transversal topic "Architecture and Design: Methods and Tools". Together, these four challenges answer the need for Software tools and frameworks for engineering support for future ECS covering the whole lifecycle:

- **Major Challenge 1:** extending development processes and frameworks to handle connected, intelligent, autonomous and evolvable systems seamlessly vertically – from semiconductor-level to system-of-system-level – and horizontally – from initial requirement analysis via design, test, production, operation, maintenance, and evolution (updates) to end-of-lifetime. This challenge covers necessary changes in the processes needed to develop, operate, maintain and evolve future ECS- based systems, especially their extensions to cover the whole lifecycle.
- **Major Challenge 2:** managing new functionality in safe, secure and trustworthy systems. This challenge covers methods and the corresponding tool support to ensure high-quality ECS-based systems, especially with respect to the new capabilities/functions these systems will exploit.

113 *DECISION Etudes & Conseil (Eds). "Emerging Technologies in Electronic Components and Systems (ECS) – Opportunities Ahead". A study conducted for DG-CONNECT, 2019.*

114 *Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019.*

- **Major Challenge 3:** managing complexity. This challenge deals with methods to handle the ever-increasing complexity of ECS-based systems.
- **Major Challenge 4:** managing diversity. Handling diversity in all aspects of developing ECS-based systems is a key objective.

2.3.4.1 Major Challenge 1: extending development processes and frameworks (to handle connected, intelligent, autonomous, evolvable systems)

2.3.4.1.1 State of the art

There is currently a strict separation between the development and the operation of ECS-based systems. Data collected in any of these phases rarely "crosses the border" into the other phase (cf. section [2.3.1]).

Future ECS-based systems need to be connected, intelligent, highly automated, and even autonomous and evolvable (cf. section [2.3.1]). This implies a huge variety of challenges, including how to validate autonomous systems (considering that a full specification of the desired behaviour is inherently impossible), how to test them (critical situations are rare events, and the number of test cases implied by the open-world-assumption is prohibitively large), and how to ensure safety and other system quality properties (security, reliability, availability, trustworthiness, etc.) for updates and upgrades.

It is therefore necessary to overcome the "data separation barrier" and to "close the loop" by enabling systems to collect relevant data during the operation phase (Design for Monitoring) and by feeding this data back into the design phase to be used for continuous development within lifecycle-aware holistic design flows. In addition, engineering processes for future ECS-based systems should be extended to shift as much engineering effort as possible from physical to virtual engineering, and include advanced methods for systems and components design as well as new V&V methods enabling safety cases and security measures for future ECS-based systems.

2.3.4.1.2 Vision and expected outcome

The vision is to enable European engineers to extend design processes and methods to a point where they allow handling of future ECS-based systems with all their new functionalities and capabilities for the whole lifecycle. Such extended processes must retain the qualities of the existing processes: (i) efficiency, in terms of effort and costs; (ii) enable the design of trustworthy systems, meaning systems that provably possess the desired quality properties of safety, security, dependability, etc; and (iii) be transparent to engineers, who must be able to completely comprehend each process step to perform optimisations and error correction.

Such extended processes will cover the complete lifecycle of products, including production, maintenance, decommissioning, and recycling, thereby allowing continuous upgrades and updates of future ECS based systems that also address the sustainability and environmental challenges (i.e. contribute to the objectives of the Green Deal). As can be derived from the timelines at the end of this Chapter, we expect supply chain-aware digital design flows enabling design for optimised manufacturing and operation (i.e. the "from design phase to operation phase direction" of the continuous design flow) for fail-aware cyber-physical systems (CPS), where selected data from operations is analysed and used in the creation of updates, by 2027. This will be completed through seamless and continuous development processes, including automated digital data flow based on digital twins and AI-based data analysis – online in the system, edge or cloud (run-time digital twin) and offline at the system's designer – as well as data collection at run-time in fail-operational CPS (i.e. "from operation to design phase" direction), by online validation, and by safe and secure deployment, by 2030.

These extended processes also require efficient and consistent methods in each of their phases to handle the new capabilities of future ECS-based systems (cf. Major Challenge 2), as well as their complexity (cf. Major Challenge 3) and diversity (cf. Major Challenge 4).

2.3.4.1.3 Key focus areas

There are four key focus areas in this challenge.

Virtual engineering of ECS

Design processes for ECS must be expanded to enable virtual engineering on all hierarchy levels (i.e. from transistor level "deep down", up to complete systems and even System of Systems, cf. "Efficient engineering of embedded software" in Chapter 1.3 and "Systems of Embedded and Cyber-Physical Systems - SoECPS - engineering" in Chapter 1.4 for more details of this software-focused challenge, especially with respect to SoS).

1.3 1.4

Central to this approach are "digital twins", which capture all necessary behavioural, logical and physical properties of the system under design in a way that can be analysed and tested (i.e. by formal, AI-based or simulation based methods). This allows for optimisation and automatic synthesis (see also Major Challenge 1 and 2 in Chapter 2.4, and the key focus area "Modelling" in Major Challenge 2 of this Chapter) – for example, of AI- supported, data-driven methods to derive (model) digital twins.

2.1 2.4

Supporting methods include techniques to visualise V&V and test efforts (including their progress), as well as sensitivity analysis and robustness test methods for different parameters and configurations of the ECS under design. Test management within such virtual engineering processes must be extended to cover all layers of the design hierarchy, and be able to combine virtual (i.e. digital twin and simulation-based) and physical testing (for final integration tests, as well as for testing simulation accuracy).

To substantially reduce design effort and costs, a second set of supporting methods deals with the automated generation of design artefacts such as identification and synthesis of design models, automatic scenario, use-case and test vector generation, generative design techniques, design space exploration, etc. Typically, these build upon AI-supported analysis of field data.

System and component design (methods and tools)

To fully enable virtual engineering, design processes have to switch completely to model-based processes (including support for legacy components, i.e. 'black box modelling'), where those models may be constructed using data-driven methods. Models are needed for the system and all its components on every level of the design hierarchy, especially for sensors and actuators, as well as the environment of the ECS under design, including humans and their behaviour when interacting with the system. Model-based design will also enable: (i) modular and updateable designs that can be analysed, tested and validated both virtually (by formal methods, simulation, etc) and physically; and (ii) consistent integration of all components on all levels of the design hierarchy to allow application-aware HW/SW co-design.

Such processes must be implemented by seamless design and development frameworks comprising interoperable, highly automated yet comprehensible tools for design, implementation, validation and test on all levels of the design hierarchy, including support for design space exploration, variability, analysis, formal methods and simulation.

Lifecycle-aware holistic design flows

"Closing the loop" – i.e. collecting relevant data in the operation phase, analysing it (using AI-based or other methods) and feeding it back into the development phase (using digital twins, for example) – is the focus of this research topic. It is closely related to the major challenges "Continuous integration and deployment" and "Lifecycle management" in Chapter 1.3, which examines the software part of ECS, and Major Challenges 1 and 2 in Chapter 2.4.

1.3 2.4

Closing the loop includes data collected during operation of the system on all levels of the hierarchy, from new forms of misuse and cyber-attacks or previously unknown use cases and scenarios at the system level, to malfunctions or erroneous behaviour of individual components or modules. Analysing this data leads to design optimisations and development of updates, eliminating such errors or implementing extended functionality to cover "unknowns" and "incidents".

Data on physical aspects of the ECS must also be collected and analysed. This includes design for optimised manufacturing and deployment, awareness of physical effects and interferences, consideration of end-of-life (EOL) of a product and recycling options within a circular economy.

All of these aspects must be supported by new approaches for multi-level modelling, analysis, verification and formalisation of ECS's operational reliability and service life (c.f. previous challenges), including a consequent usage of open (and inner) source in HW and SW for the complete product lifecycle. As non- (or partly-) technical Challenges, all data collection activities described in this Chapter also need to comply to privacy regulations (e.g., the General Data Protection Regulations GDPR of the EU) as well as in a way that protects the Intellectual Property (IP) of the producers of the systems and their components.

Integration of new V&V methods

The required changes of current design processes identified above, as well as the need to handle the new systems capabilities, also imply an extension of current V&V and test methods. First, safety cases for autonomous systems need to rely on an operational design domain (ODD) definition – i.e. characterisation of the use cases in which the system should be operated, as well as a set of scenarios (specific situations that the system might encounter during operation) against which the system has actually been tested. It is inherently impossible for an ODD to cover everything that might happen in the real world; similarly, it is extremely difficult to show that a set of scenarios cover an ODD completely. Autonomous systems must be able to detect during operation whether they are still working within their ODDs, and within scenarios equivalent to the tested ones. V&V methods have to be expanded to show correctness of this detection. Unknown or new scenarios must be reported by the system as part of the data collection needed for continuous development. The same reasoning holds for security V&V: attacks – regardless of whether they are successful or not – need to be detected, mitigated, and reported on.

1.4 2.4

Second, the need to update and upgrade future ECS-based systems implies the need to be able to validate and test those updates for systems that are already in the field. Again, corresponding safety cases have to rely on V&V methods that will be applied partly at design-time and partly at run-time, thereby including these techniques into continuous development processes and frameworks. For both of these challenges, energy- and resource-efficient test and monitoring procedures will be required to be implemented.

2.3.4.2 Major Challenge 2: managing new functionality in safe, secure and trustworthy systems

2.3.4.2.1 State of the art

Models are abstractions that support technical processes in various forms – for instance, they help systems engineers to accelerate and improve the development process. Specific models represent different aspects of the system under development, and allow different predictions, such as on performance characteristics, temporal behaviour, costs, environmental friendliness or similar. Ideally, models should cover all of these aspects in various details, representing the best trade-off between level of detail, completeness and the limitations listed below:

- Computational complexity and execution performance: models have different levels of complexity, and therefore the computational effort for the simulation sometimes varies considerably. For system considerations, very simple models are sometimes sufficient; for detailed technical simulations, extremely complex multi-physics 3D models are often required. Assessing the needed model fidelity (abstraction resp. granularity level) for each validation task, and balancing it against the needed performance requirements, is therefore essential. To achieve the necessary performance even for high fidelity models, one solution can be the parallel processing of several simulations in the cloud on the other hand super-fast embedded computing and/or edge computing can be good solutions, too. Therefore, cloud and edge computing play an important role for this topic.
- Effort involved in creating models: very complex physically-based 3D models require considerable effort for their creation. For behavioural models, the necessary parameters are sometimes difficult to obtain or not available at all. For models based on data, including AI-based and ML-based models, extensive data collection and analysis tasks have to be carried out. Further research is urgently needed to reduce the effort for data gathering, model creation and parameterisation.
- Interfaces and integration: often, different models from different sources are needed simultaneously in a simulation. However, these models are frequently created on different platforms, and must therefore be linked or integrated. The interfaces between the models must be further standardised, e.g. FMU, FMI, extensions thereof, or similar. Interoperable models and (open source) integration platforms are needed here; they will also require further cooperation between manufacturers and suppliers. Cloud based simulation platforms require different solutions, which must be uninterrupted and with low latencies.
- Models for software testing, simulation, verification, and for sensors: another very complex field of activity concerns the model-based testing of software in a virtual environment (including virtual hardware platforms). This implies that sensors for the perception of the environment must also be modelled, resulting in further distortion of reality. The challenge here is to reproduce reality and the associated sensors as accurately as possible, including real-time simulation capacity. Standards for model creation as well as standardized metrics for quality/completeness of models with respect to validation and verification are essential.

For each model it is important to validate that they conform to real world aspects of the system under development, i.e., that they model reality with a sufficient, guaranteed fidelity.

2.3.4.2.2 Vision and expected outcome

Efforts supporting the generation of realistic models for the entire lifecycle of a complex cyber-physical product remain very high, as the requirements for simulation accuracy, the number of influencing parameters of interest and the depth of detail are constantly increasing over time. On the other hand, the

application of the highest fidelity models throughout the development process and lifecycle of products with cyber-physical components and software in turn creates numerous opportunities to save development, operating and maintenance costs. These opportunities arise in cyber-physical components or products such as vehicles, medical devices, semiconductor components, ultra-low-power ECS or any other elements in such complex technical systems. Therefore, research on advanced model-based design, development, and V&V methods and tools for the successful creation of safe, secure and trustworthy products in Europe is of utmost importance, and should be the highest priority of the research agenda. The vision is to derive efficient and consistent methods for modelling, designing, and validating future ECS-based systems, supporting the different steps in the continuous development processes derived in Major Challenge 1 by 2026 (resp. by 2029).

2.3.4.2.3 Key focus areas

This challenge comprises the following three key focus areas.

Modelling techniques for new functionalities

Model generation includes different methods (e.g. data-driven techniques, physics- or rules-based abstraction techniques) for describing (modelling) the behaviour of safety-critical, mixed, physical and logical components on different, hierarchical system levels. Model generation finally results in model libraries that are suitable for different purposes (analysis techniques, simulation, etc). There are different aspects of the modelled artefact (of the system, component, environment, etc), such as their physical properties, their (timed) behaviour, and their functional and non-functional properties, which often are modelled with different modelling approaches using different modelling tools. In addition, due to distributed architectures (edge, cloud, IoT, multi-processor architectures, etc.), future systems will become increasingly complex in their interaction and new communication and connection technologies will emerge, which must also be modelled and simulated realistically.

For the design of ECS-based systems, models are required on all levels of the design hierarchy and with different levels of fidelity (cf. Sub-section 2.3.4.2.1), ranging from physically-based 3D models of individual components via simplified models for testing component interaction (c.f. 'compact models' in Chapter 2.4) to specific models for sensors and the environment, also taking into account statistical scattering from production and system changes during the service life. Latest advances in AI and ML also enable novel data-based modelling techniques that can often, and especially, deliver excellent results in combination with known physical methods.

1.1 1.2 2.1

Furthermore, it is important to create reusable, validated and standardised models and model libraries for system behaviour, system environment, system structure with functional and non-functional properties, SoS configurations, communication and time-based behaviour, as well as for the human being (operator, user, participant).

1.4

Most importantly, model-based design methods, including advanced modelling and specification capabilities, supported by corresponding modelling and specification tools, are essential. The models must be applicable and executable in different simulation environments and platforms, including desktop applications, real-time applications, multi-processor architectures, edge computing- and hardware-in-the-loop (HiL) platforms as well as cloud (fog) based simulation with heterogeneous access management that includes uninterrupted, wireless and cellular connectivity with low latency.

Design and V&V methods for ECS evolving during lifetime (including AI-enabled systems)

The more complex the architecture of modern ECS systems becomes, the more difficult it is to model its components, their relevant properties and their interactions to enable the optimal design of systems. Classical system theory and modelling often reaches its limits because the effort is no longer economically feasible. AI-supported modelling can be used effectively when large amounts of data from the past or from corresponding experiments are available. Such data-driven modelling methods can be very successful when the exact behaviour of the artefact to be modelled is unknown and/or very irregular. However, the question of determining model accuracy resp. model fidelity is largely unsolved for these methods.

When AI-based functions are used in safety-critical components and systems, V&V methods that assure safety of the system are extremely important. Experience-based AI systems (including deep learning-based systems) easily reach their limits when the current operating range is outside the range of the training database. There can also be stochastic, empty areas within the defined data space, for which AI is not good at interpolating. Design methods for AI-enabled ECS must therefore take into account the entire operational domain of the system, compensate for the uncertainty of the AI method and provide additional safety mechanisms supervising the AI component (i.e. mechanisms to enable fail-aware and fail-operational behaviour).

A further source of uncertainty results from variabilities (production tolerances, ageing effects or physical processes that cannot be described with infinite accuracy) resulting from human interaction with the system and from other effects. For determining quality properties such as safety and reliability, these effects must be taken into account throughout the designs' V&V. The communication channels in distributed architectures (either in cloud/fog or multi-processor architectures) also fall within the scope of these uncertainties, which can, for example, exhibit certain delays or contain certain disturbances. These effects must also be simulated on the one hand and verified accordingly in the overall simulation and system test.

There are also structured (i.e. foreseeable at design-time) variabilities in technical systems in the form of configurable changes during their lifetime, whether through software updates, user interventions or other updates. For secure systems with structured variability, suitable SW and HW architectures, components and design methods, as well as tools for adaptive, extensible systems, are crucial. This includes (self-)monitoring, diagnosis, update mechanisms, strategies for maintaining functional and data security, and lifecycle management (including End-of-life management, sustainability and possible recycling), as well as adaptive security and certification concepts (c.f. Prognostic Health Management in Chapter 2.4)

2.4

The verification and validation of ECS-based systems can also be carried out with the help of AI-based test methods. This approach allows to benefit from already performed V&V activities and developed methods and to further enhance them substantially. At the same time, the development and application of completely new test methods is also possible, as long as there is sufficient training data available for this task.

The V&V of safety-critical systems does not end with the deployment of the system. Rather, for such systems, the continuous monitoring and safeguarding of adaptive and/or dynamic changes in the system or evolving threads is of utmost importance. Further release cycles might be triggered by problems occurring in operation and the DevOps cycles must be iterated again (e.g. via reinforcement learning).

1.4

Ultra-low power design methods

The potential application area for ultra-low power electronic systems is very high due to the rapidly advancing miniaturisation of electronics and semiconductors, as well as the ever-increasing connectivity enabled by it. This ranges from biological implants, home automation, the condition-monitoring of materials to location-tracking of food, goods or technical devices and machines. Digital products such as radio frequency/radio

frequency identification (RF/RFID) chips, nanowires, high-frequency (HF) architectures, SW architectures or ultra-low power computers with extremely low power consumption support these trends very well. Such systems must be functional for extended periods of time with a limited amount of energy.

The ultra-low-power design methods comprise the areas of efficiency modelling and low-power optimisation with given performance profiles, as well as the design of energy-optimised computer architectures, energy-optimised software structures or special low-temperature electronics. Helpful here are system-level automatic DSE (design space exploration) approaches able to fully consider energy/power issues (e.g., dark silicon, energy/power/performance trade-offs) and techniques. The design must consider the application-specific requirements, such as the functional requirements, power demand, necessary safety level, existing communication channels, desired fault tolerance, targeted quality level and the given energy demand and energy supply profiles, energy harvesting gains and, last but not least, the system's lifetime.

1.1 1.2 1.3

Exact modelling of the system behaviour of ultra-low power systems and components enables simulations to compare and analyse energy consumption with the application-specific requirements so that a global optimisation of the overall system is possible. Energy harvesting and the occurrence of parasitic effects, must also be taken into account.

2.3.4.3 Major Challenge 3: managing complexity

2.3.4.3.1 State of the art

The new system capabilities (intelligence, autonomy, evolvability), as well as the required system properties (safety, security, reliability, trustworthyness), each considerably increase complexity. Increasingly complex environments in which these systems are expected to operate, and the increasingly complex tasks (functionalities) that these systems need to perform in this environment, are further sources of soaring system complexity. Rising complexity leads to a dramatic upsurge in the effort of designing and testing, especially for safety-critical applications where certification is usually required. Therefore, an increased time to market and increased costs are expected, and competitiveness in engineering ECS is endangered. New and improved methods and tools are needed to handle this new complexity, to enable the development and design of complex systems to fulfil all functional and non-functional requirements, and to obtain cost-effective solutions from high productivity. Three complexity-related action areas will help to master this change:

- Methods and tools to increase design efficiency.
- Complexity reduction methods and tools for V&V and testing.
- Methods and tools for advanced architectures.

2.3.4.3.2 Vision and expected outcome

The connection of electronics systems and the fact that these systems change in functionality over their lifetime continuously drives complexity. In the design phase of new connected highly autonomous and evolvable ECS, this complexity must be handled and analysed automatically to support engineers in generating best-in-class designs with respect to design productivity, efficiency and cost reduction. New methods and tools are needed to handle this new complexity during the design, manufacturing and operations phases. These methods and tools, handling also safety related non functional requirements, should work either automatically or be recommender-based for engineers to have the complexity under control (see also the corresponding challenges in Chapter 1.3. Embedded Software and Beyond).

1.3

3.1

Complexity increases the effort required, especially in the field of V&V of connected autonomous electronics systems, which depend on each other and alter over their lifetime. The innumerable combinations and variety of ECS must be handled and validated. To that end, new tools and methods are required to help test engineers in creating test cases automatically, analysing testability and test coverage on the fly while optimising the complete test flow regarding test efficiency and cost. This should be achieved by identifying the smallest possible set of test cases sufficient to test all possible system behaviours. It is important to increase design efficiency and implement methods that speed up the design process of ECS. Methods and tools for X-in-the-loop simulation and testing must be developed, where X represents hardware, software, models, systems, or a combination of these. A key result of this major challenge will be the inclusion of complexity-reduction methods for future ECS-based systems into the design flows derived in Major Challenge 1, including seamless tool support, as well as modular architectures that support advanced computation methods (AI, advanced control), system improvements (updates), replacement and recycling by 2026. Building on these, modular and evolvable/extendable reference architectures and (hierarchical, open source-based) platforms that support continuous system improvement, self- awareness, health and environment monitoring, and safe and secure deployment of updates, will be realised by 2029.

2.3.4.3.3 Key focus areas

Methods and tools to increase design and V&V efficiency

Design efficiency is a key factor for keeping and strengthening engineering competitiveness. Design and engineering in the virtual world using simulation techniques require increasingly efficient modelling methods of complex systems and components. Virtual design methodology will be boosted by X-in-the-loop, where X (HW, SW, models, systems) are included in the simulation process, which helps to increase accuracy and speed up multi-discipline co-simulation. This starts at the architecture and design evaluation, where real tests are implemented in a closed loop such as in the exploration process.

Complexity reduction methods and tools for V&V and testing

A second way to manage complexity is the complexity-related reduction of effort during the engineering process. Complexity generates most effort in test, and V&V, ensuring compatibility and proper behaviour in networking ECS. Consistent hierarchical design and architectures, and tool-based methods to design those architectures automatically, are needed. Advanced test methods with intelligent algorithms for test termination, as well as automated metrics for testability and diagnosis (including diagnosis during run-time), must be developed and installed. Recommender-based guidance supports where no automated processes can be used. Model-based V&V and test supported by AI techniques can help to minimise the efforts driven by complexity. Models and digital twins of ECS can also be used to calculate the test coverage and extract test cases automatically.

Methods and tools for advanced architectures

Complexity, and also future complexity, is mainly influenced by the architecture. Future architectures must support complex, highly connected ECS that use advanced computational methods and AI, as well as machine learning, which lead to a change of ECS over lifetime. For this, reference architectures and platform architectures are required on all levels of the design hierarchy (for the system and SOS levels, see also the challenges “architectures for SoS”, “SoS interoperability” and related challenges in Chapter 1.4 on System of Systems).

1.4

An additional focus of architecture exploration and optimisation must be architectures that ease the necessary efforts for analysis, test, V&V and certification of applications. Hierarchical, modular architectures that support a divide-and-conquer approach for the design and integration of constituent modules with respect to subsystems have the potential to reduce the demand for analysis and V&V (“correct by design”

approach). As 'integration platforms, they have to ensure interoperability of constituent ECS. For the architecture exploration and optimisation itself, AI-based methods are needed to achieve a global optimum. Overall, holistic design approaches and tools for architectures of multi-level/multi-domain systems are the goal.

Apart from the benefits that reference architectures and platforms have at a technological level, they are also important economically. As integration platforms for solutions of different vendors, they serve as a focal point for value chain-based ecosystems. Once these ecosystems reach a certain size and market impact, the platforms can serve as the basis for corresponding "platform economies" (cf. Major Challenge "open SoCPS and SoES platforms" in Chapter 1.4).

2.3.4.4 Major Challenge 4: managing diversity

2.3.4.4.1 State of the art

In the ECS context, diversity is everywhere – between polarities such as analogue and digital, continuous and discrete, and virtual and physical. With the growing diversity of today's heterogeneous systems, the integration of analogue-mixed signals, sensors, micro-electromechanical systems (MEMS), actuators and power devices, transducers and storage devices is essential. Additionally, domains of physics such as mechanical, photonic and fluidic aspects have to be considered at the system level, and for embedded and distributed software. The resulting design diversity is enormous. It requires multi-objective optimisation of systems (and SoS), components and products based on heterogeneous modelling and simulation tools, which in turn drives the growing need for heterogeneous model management and analytics. Last, but not least, a multi-layered connection between the digital and physical world is needed (for real-time as well as scenario investigations). Thus, the ability to handle this diversity on any level of the design hierarchy, and anywhere it occurs, is paramount, and a wide range of applications has to be supported.

2.3.4.4.2 Vision and expected outcome

The management of diversity has been one of Europe's strengths for many years. This is not only due to European expertise in driving More-than-Moore issues, but also because of the diversity of Europe's industrial base. Managing diversity is therefore a key competence. Research, development and innovation (R&D&I) activities in this area aim at the development of design technologies to enable the development of complex, smart and, especially, diverse systems and services. All these have to incorporate the growing heterogeneity of devices and functions, including its V&V across mixed disciplines (electrical, mechanical, thermal, magnetic, chemical and/ or optical, etc). New methods and tools are needed to handle this growing diversity during the phases of design, manufacturing and operation in an automated way. As in complexity, it is important to increase design efficiency on diversity issues in the design process of ECS. A major consequence of this challenge will be the inclusion of methods to cope with all diversity issues in future ECS-based systems, which have been introduced into the design flows derived in Major Challenge 1, including seamless tool support for engineers.

2.3.4.4.3 Key focus areas

The main R&D&I activities for this fourth major challenge are grouped into the following four key focus areas.

Multi-objective design and optimisation of components and systems

The area of multi-objective optimisation of components, systems and software running on SoS comprises integrated development processes for application-wide product engineering along the value chain. It also concerns modelling, constraint management, multi-criteria, cross-domain optimisation and standardised

interfaces. This includes consistent and complete co-design and the integrated simulation of integrated circuits, package and board in the application context. As well it is also about methods and tools to support multi-domain designs (electronic/electric and hydraulic, etc) and multi-paradigms (different vendors, modelling languages, etc) as well as HW/SW co-design Furthermore, it deals with advanced design space exploration and iterative design techniques, the modular design of 2.5 and 3D integrated systems and flexible substrates, and the trade-offs between performance, cost, space, power and reliability.

1.1 1.2 1.3 1.4

Modelling, analysis, design and test methods for heterogeneous systems considering properties, physical effects and constraints

The area of modelling, analysis, design, integration and testing for heterogeneous systems considering properties, physical effects and constraints comprises methods and tools for the design, modelling and integration of heterogeneous systems, as well as hierarchical methods for HW/SW hybrid modeling and co-simulation, and co- development of heterogeneous systems (including multi-scale and multi-rate modelling and simulation). Furthermore, it deals with modelling methods to consider operating conditions, statistical scattering and system changes, as well as hierarchical modelling and the early assessment of critical physical effects and properties from SoC up to the system level. Finally, there is a need for analysis techniques for new circuit concepts (regarding new technologies up to the system level), and special operating conditions (voltage domain check, especially for start-ups, floating node analysis, etc).

1.1 1.2

Automation of analogue and integration of analogue and digital design methods

The area of integration of analogue and digital design methods comprises metrics for testability and diagnostic efficiency, especially for analogue/mixed signal (AMS) designs, harmonisation of methodological approaches and tooling environments for analogue, RF and digital design and automation of analogue and RF design – i.e. high-level description, synthesis acceleration and physical design, modularisation and the use of standardised components.

1.2

Connecting the virtual and physical world of mixed domains in real environments

The main task in the area of connecting the virtual and physical worlds of mixed domains in real environments is an advanced analysis that considers the bi-directional connectivity of the virtual and physical world of ECS and its environment (including environmental modelling, multimodal simulation, simulation of (digital) functional and physical effects, emulation and coupling with real, potentially heterogenous, hardware, and integration of all of these into a continuous design and validation flow for heterogeneous systems, cf. Major Challenge 1 and 2 above). Furthermore, the key focus area comprises novel more-than-Moore design methods and tools, as well as models and model libraries for chemical and biological systems.

1.1 1.2

2.3.5 TIMELINE

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

"Supply-chain-aware" design flow: from requirements to optimized system architecture considering supply chain leveraging "seamless digital twin from component to design to manufacturing to operation"

Holistic design flows taking into consideration and bridging the functional layers and architectural layers with life-cycles and value streams .

INTEGRATION OF NEW VERIFICATION AND VALIDATION METHODS

Incorporation of V&V methods and technologies into virtual engineering resp. design frameworks, incorporation into continuous development process

From offline V&V (@design-time) to online V&V (@runtime)

Usage of AI and AI-based tools for V&V and development task (exploiting AI capabilities)

Model-based and mixed real/virtual testing approaches, incl. V&V of system architecture by simulating system components on different levels of abstraction

Energy and resource efficient test procedures and equipment

V&V extended by life-time monitoring of security and reliability aspects

Major Challenge 2:
MANAGING NEW FUNCTIONALITY IN SAFE, SECURE, AND TRUSTWORTHY SYSTEMS

MODELLING TECHNIQUES FOR NEW FUNCTIONALITIES

Model creation/elicitation, modelling techniques, modelling tools, model libraries

Techniques and tools to model behaviour, timing, functional and non-functional properties of (a) components, (b) systems, (c) environment / real world, (d) test-cases / scenarios

Multi-scale modelling. Detailed and slow fine-grained models feed key parameters to design development models. The key parameters of these models are again used in real-time models as part of the system.

Executable models of sensors (incl. accuracy, confidence,...)

DESIGN AND V&V METHODS FOR ECS EVOLVING DURING LIFETIME (INCL. AI-ENABLED SYSTEMS)

Design methods for AI enabled ECS

V&V of AI enabled ECS, trustable AI (incl. quality attributes like safety, security, reliability, etc, but also un-biased decisions, explainability, etc.)

Methods and tools for online risk assessment

Methods and tools for handling cooperation (with other CPS, with humans), incl. recognizing and acting on the perceived intent of cooperation partners

Incremental V&V for all system qualities (safety, security, reliability, trustworthiness,...)

V&V for safe & secure systems with structural variability

Design methods and V&V for handling of uncertainty (in perception, in communication, in prediction, in trustworthiness of data sources, etc.

Lifetime monitoring; secure and GDPR-compliant data collection from device to multiple stakeholders (incl. system manufacturer); support for analysis & issue identification

ULTRA-LOW POWER DESIGN METHODS

Advanced design methods for ultra-low-power design, focusing on component-level as well as on system-level (most potential in system architecture and system operation)

Design methods for (autonomous) ultra-low-power systems, taking into account application-specific requirements

Method for comprehensive assessment and optimization of power management and power consumption

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

Major Challenge 3: MANAGING COMPLEXITY

METHODS AND TOOLS TO INCREASE DESIGN EFFICIENCY

XIL-testing (X-in-the-loop, with X=model, system, software, hardware,.. incl. mixed-modes

XIL simulation techniques and tools, speed up of simulation, accuracy of simulation, multi-domain co-simulation

Efficient modelling, test and analysis for reliable, complex systems on different abstraction levels

Evaluation of architecture and design of the ECS SW/HW with real tests

COMPLEXITY REDUCTION METHODS AND TOOLS FOR V&V AND TEST

Recommender-based guidance in V&V process for complex ECS systems

Automated generation of testcases from models/digital twins of ECS systems

Test coverage calculation by means of models and testcases (coverage-driven V&V)

Minimizing effort for V&V based on models, AI techniques

Advanced test methods, intelligent concepts for test termination, automated metrics/tools for testability, diagnosis, and extraction of diagnostic information

Methods and tools for consistent, hierachical design, V&V and test

Energy and resource efficient test procedures and equipment

METHODS AND TOOLS FOR ADVANCED ARCHITECTURES

Architecture exploration and optimization, including multi-aspect optimization (e.g. safety, security, comfort, functionality,...), also (incl. AI based optimization methods)

Architectures supporting advanced computation methods (AI, advanced control,...)

Architectures and tools for non von-Neumann and neuromorphic computing

Architectures supporting self-awareness, health and environment monitoring on all levels of the design hierarchy

Platform and middleware architectures, also for extremely distributed, multi-layered SoS and IoT applications

Reference architectures for continuous system improvement, i.e. across evolving system generations

Architectures for V&V and certification, including automatic evaluation of computation and deployment decisions (i.e. on chip, edge, fog, cloud)

Modular and evolvable/extendable architectures (supporting traceability of evolution, also supporting modular updates, replacement and recycling for a circular economy

(SW-HW) architecture mapping (incl. resource mapping and tracing (communication, scheduling, ...), incl. requirement matching and tracing

- ***Start research activities aiming at** Technology Readiness Level **(TRL) 2–4** (applied research – validation in laboratory environment) **or higher***
- ***Start research activities aiming at TRL 4–6** (applied research – demonstration in relevant environment) **or higher***
- ***Start research activities aiming at TRL 6–8** (applied research – prototyping in an operational environment qualified)*

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

Major Challenge 4: MANAGING DIVERSITY

MULTI-OBJECTIVE DESIGN & OPTIMISATION OF COMPONENTS AND SYSTEMS

Consistent & complete Co-Design & integrated simulation of IC, package and board in the application context

Methods and Tools to support multi-domain designs (i.e., electronic/electric and hydraulic, ...) and multi paradigm designs (different vendors, modelling languages, ...)

Advanced Design Space Exploration and iterative Design techniques, inl. Multi-aspect optimization (Performance vs. cost vs. space vs. power vs. reliability)

Modular design of 2.5 and 3D integrated systems

MODELLING, ANALYSIS, DESIGN AND TEST METHODS FOR HETEROGENEOUS SYSTEMS CONSIDERING PROPERTIES, PHYSICAL EFFECTS AND CONSTRAINTS

Methods and tools for design, modelling and integration of heterogeneous systems

Hierarchical methods for hardware/software co-simulation and co-development of heterogeneous systems (multi-scale, multi-rate modelling and simulation)

Modelling methods to take account of operating conditions, statistical scattering and system changes

Hierarchical modelling and early assessment of critical physical effects and properties from SoC up to system level

Analysis techniques for new circuit concepts and special operating conditions (voltage domain check, especially for start-up, floating node analysis ...)

AUTOMATION OF ANALOGUE AND INTEGRATION OF ANALOGUE AND DIGITAL DESIGN METHODS

Metrics for AMS testability and diagnostic efficiency (including V&V & test)

Harmonization of methods and tooling environments for analogue, RF and digital design

Automation of analogue and RF design (high-level description, synthesis acceleration and physical design, modularization, use of standardized components

CONNECTING THE VIRTUAL AND PHYSICAL WORLD OF MIXED DOMAINS IN REAL ENVIRONMENTS

Advanced analysis considering the connection of virtual and physical world and its environment

Novel More than Moore design methods and tools

Models and model libraries for chemical and biological systems

Start research activities aiming at** Technology Readiness Level **(TRL) 2–4** (applied research – validation in laboratory environment) **or higher

Start research activities aiming at TRL 4–6** (applied research – demonstration in relevant environment) **or higher

***Start research activities aiming at TRL 6–8** (applied research – prototyping in an operational environment qualified)*

2.3.6
SYNERGY WITH OTHER THEMES

The processes, methods and tools addressed in this Chapter relate to all other chapters of the ECS-SRIA. They enable the successful development, implementation, integration and testing of all applications described in of the ECS-SRIA, cover all levels of the technology stack (as indicated in Part 1) and enable the sufficient usage of all transversal technologies described in Part 2. Thus, there is a high synergy potential to carry out joint research on these topics. This holds especially true for topics in Chapter 2.4: qualities such as safety and security described there are a driver for the technologies in this Chapter, where we describe processes, methods and tools that enable engineers to design systems guaranteed to possess the required qualities in a cost- and time-efficient way. Additionally, strong ties exist to the 'engineering challenges' both in Chapter 1.3 (on embedded software) and in Chapter 1.4 (on systems of systems). Finally, especially for our challenge 4 on managing diversity, there is a overlap – and thus an opportunity to synergistically merge key topics from this challenge – with topics from Chapter 1.2 (on components and modules).

There is also a high synergy potential with additional activities outside of the pure funded projects work: reference architectures, platforms, frameworks, interoperable toolchains and corresponding standards are excellent nuclei around which innovation ecosystems can be organised. Such ecosystems comprise large industries, SMEs, research organisations and other stakeholders. They are focused on a particular strategic value chain, certain technology or any other asset for which sustainability and continuous improvement must be ascertained. The main activities of such innovation ecosystems are, first, to bring together the respective communities, implement knowledge exchange and establish pre-competitive cooperation between all members of the respective value chains. Second, they should promote the technology around which they are centred, i.e. by refining and extending the platform, providing reference implementations and making them available to the community, provide integration support, establish the standard, etc. Third, they should ensure greater education and knowledge-sharing. Fourth, they should develop those parts of the Strategic Research and Innovation Agenda and other roadmaps that are related to the respective technology, monitor the implementation of the roadmaps, and incubate new project proposals in this area.

Last, but not least, the technologies described in this Chapter are essential and necessary, but they are also to a large extent domain-agnostic, and can thus also serve as a connection point with activities in other funding programmes (for example, for example Xecs, PENTA, ITEA and other EUREKA clusters).

2.4

Cross-Sectional Technologies

QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

2.4.1 SCOPE

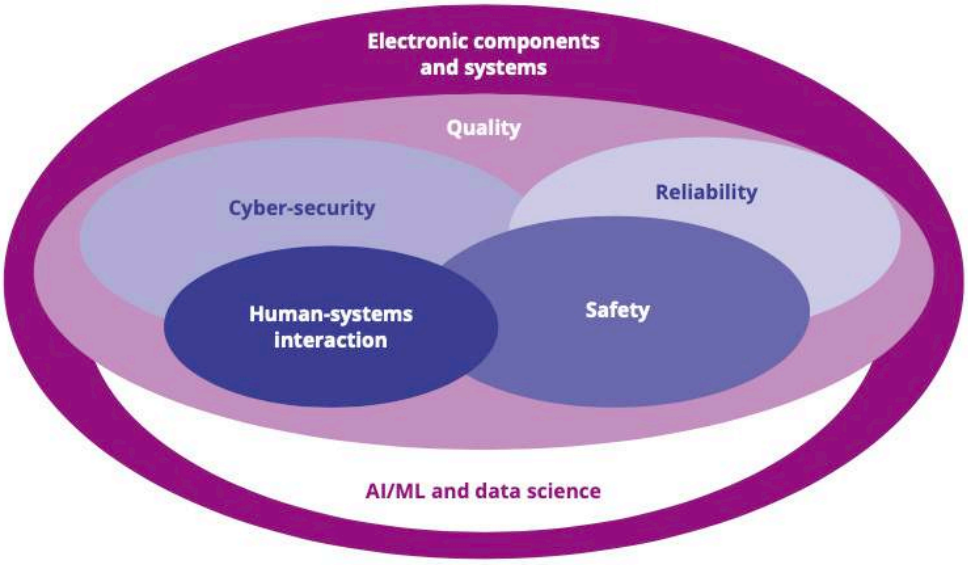
Modern technologies and new digitised services are key to ensuring the stable growth and development of the European Union and its society. These new technologies are largely based on smart electronic components and systems (ECS). Highly automated or autonomous transportation systems, improved healthcare, industrial production, information and communication networks, and energy grids all depend on the availability of electronic systems. The main societal functions[115] and critical infrastructure are governed by the efficient accessibility of smart systems and the uninterrupted availability of services.

Ensuring the reliability, safety and security of ECS is a Major Challenge since the simultaneous demand for increased functionality and continuous miniaturisation of electronic components and systems causes interactions on multiple levels. This Chapter addresses these complex interdependencies by considering input from, and necessary interaction between, major disciplines. The quality, reliability, safety and cybersecurity of electronic components and systems are, and will be, fundamental to digitised society (see *Figure F.39*). In addition, the tremendous increase of computational power and reduced communication latency of components and systems, coupled with hybrid and distributed architectures, imposes to rethink many "traditional" approaches and expected performances towards safety and security, exploiting AI and ML.

In practice, ensuring reliability, safety, and security of ECS is part of the Design, Implementation, and Validation/Testing process of the respective manufacturers and – for reasons of complexity and diversity/heterogeneity of the systems – must be supported by (analysing and testing) tools. Thus, the techniques described in Chapter 2.3 (Architecture and Design: Method and Tools) are complementary to the techniques presented here: in that Chapter, corresponding challenges are described from the design process viewpoint, whereas here we focus on a detailed description of the challenges concerning reliability, safety, and security within the levels of the design hierarchy.

2.3

115 Vital societal functions: services and functions for maintaining the functioning of a society. Societal functions in general: various services and functions, public and private, for the benefit of a population and the functioning of society.



F.39 *Role of quality, reliability, safety and cybersecurity of electronic components and systems for digitalisation.*

2.4.2 TECHNOLOGY-ENABLED SOCIETAL BENEFITS

"The role of the technology is to allow persons to express their potential". Hans Rosling, in his book *Factfulness: Ten Reasons We're Wrong About the World – and Why Things Are Better Than You Think*, plots the life quality of the world's population in groups at successive levels. He shows how such groups, even those at the bottom level, will move forward over time to the next level. Technology can help accelerate that progression. An emblematic example of that is the project launched by Facebook and the Internet Society (ISOC) to develop internet exchange points (IXPs) throughout Africa. Albeit not without difficulty, IXPs help promote e-learning to improve education in the continent, and for connected drones to deliver medicines and other products to remote populations.

The recent Covid-19 pandemic has emphasised the importance of digital technology to the western world, with the recourse to robots in several hazardous situations, from disinfecting airplanes and hospital rooms, to delivering medication to isolated patients. Digital technology that can fit these diverse needs should address holistically concerns such as quality of service, reliability, safety, trustworthy, privacy, cybersecurity and human–system integration. A degraded behaviour in any of these dimensions, or an incorrect integration among them, would affect vital properties and could cause serious damage. In addition, such shortcomings in safety, reliability and security might even outweigh the societal and individual benefits perceived by users, thus lowering trust in, and acceptance of, the technologies. All these topics and features constitute the core of this Chapter.

2.4.3
STRATEGIC ADVANTAGE FOR THE EU

Europe is internationally known for its high-quality product standards, which enjoy a strong international reputation. The European Union (EU) has a robust and reliable safety and product liability regulatory framework, and a rigorous body of safety standards, complemented by national, non-harmonised liability regulations. In the past, this has been a big success for European embedded systems in almost all industries, including automotive, telecommunications, manufacturing, railway, avionic and military defence, to name but a few of the many sectors where people rely on them.

However, in light of the two main drivers of digitalisation and connectivity, Europe is highly dependent on the supply of hardware and software from countries outside of Europe. Dominating market players in the information and communications technology (ICT) sector – such as those in the expanding sectors of social networks, logistic and e-commerce are expanding their products towards industrial domains. In addition, recent revelations regarding espionage and state-sponsored surveillance have initiated a debate on the protection of core EU values such as security, privacy, data protection and trust. Therefore, digital strategic autonomy – the ability of the EU to maintain a high level of control and security of its products, responding quickly if potential vulnerabilities are noticed – is of utmost importance. A strategic advantage can be achieved by designing reliable, safe and secure products where the dependencies to foreign products are transparently considered. A difference for EU products can also be achieved by treating privacy and necessary human interaction with its own set of independent standards, where technology will keep its limits according to European values when interacting with citizens.

2.4.4
MAJOR CHALLENGES

To introduce the topic presented in this Chapter, we first present some definitions that will be useful to clarify the concepts described in the Major Challenges:

- Production quality: often defined as “the ability of a system being suitable for its intended purpose while satisfying customer expectations”, this is a very broad definition that basically includes everything. Another widely used definition is “the degree a product meets requirements in specifications” – but without specifying the underlying specifications, the interpretation can vary a lot between different stakeholders. Therefore, in this Chapter quality will be defined “as the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (such as burn-in) but no other type of testing”. In this way, reliability, dependability and cybersecurity, which for some would be expected to be included under quality, will be treated separately.
- Reliability: this is the ability or the probability, respectively, of a system or component to function as specified under stated conditions for a specified time.
- Prognostics and health management: a method that permits the assessment of the reliability of the product (or system) under its application conditions.

- Functional safety: the ability of a system or piece of equipment to control recognized hazards to achieve an acceptable level of risk, such as to maintain the required minimum level of operation even in the case of likely operator errors, hardware failures and environmental changes to prevent physical injuries or damages to the health of people, either directly or indirectly.
- Dependability: according to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here (192-01-01) can be an individual part, component, device, functional unit, equipment, subsystem or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01-27) and maintenance support performance (192-01-29), and in some cases other characteristics such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).
- Safety: freedom from unacceptable risk of harm [CENELEC 50126].
- Security: measures can provide controls relating to physical security (control of physical access to computing assets) or logical security (capability to login to a given system and application) (IEC 62443-1-1):
  - measures taken to protect a system;
  - condition of a system that results from the establishment and maintenance of measures to protect the system;
  - condition of system resources being free from unauthorized access, and from unauthorized or accidental change, destruction or loss;
  - capability of a computer-based system to provide adequate confidence that unauthorized persons and systems can neither modify the software and its data nor gain access to the system functions, and yet ensure that this is not denied to authorized persons and systems;
  - prevention of illegal or unwanted penetration of, or interference with, the proper and intended operation of an industrial automation and control system.
- Cybersecurity: the protection of information against unauthorized disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).
- Robust root of trust systems: these are based on cryptographic functionalities that ensure the authenticity and integrity of the hardware and software components of the system, with assurance that it is resilient to logical and physical attacks.
- Emulation and Forecasting: cybersecurity evolution in parallel to increasing computation power and hybrid threats mixing geopolitical, climate change and any other external threats impose to anticipate the horizon of resilience, safety and security of systems forecasting attacks and incidents fast evolution.

Five Major Challenges have been identified:

- **Major Challenge 1:** ensuring HW quality and reliability.
- **Major Challenge 2:** ensuring dependability in connected software.
- **Major Challenge 3:** ensuring cyber-security and privacy.
- **Major Challenge 4:** ensuring of safety and resilience.
- **Major Challenge 5:** human Systems Integration.

2.4.4.1 Major Challenge 1: ensuring HW quality and reliability

2.4.4.1.1 State of the art

With the ever-increasing complexity and demand for higher functionality of electronics, while at the same time meeting the demands of cutting costs, lower levels of power consumption and miniaturization in

integration, hardware development cannot be decoupled from software development. Specifically, when assuring reliability, separate hardware development and testing according to the second-generation reliability methodology (design for reliability, DfR) is not sufficient to ensure the reliable function of the ECS. A third-generation reliability methodology must be introduced to meet these challenges. For the electronic smart systems used in future highly automated and autonomous systems, a next generation of reliability is therefore required. This new generation of reliability assessment will introduce in situ monitoring of the state of health on both a local (e.g. IC packaging) and system level. Hybrid prognostic and health management (PHM) supported by Artificial Intelligence (AI) is the key methodology here. This marks the main difference between the second and the third generation. DfR concerns the total lifetime of a full population of systems under anticipated service conditions and its statistical characterization. PHM, on the other hand, considers the degradation of the individual system in its actual service conditions and the estimation of its specific remaining useful life (RUL).

2.4.4.1.2 Vision and expected outcome

Since embedded systems control so many processes, the increased complexity by itself is a reliability challenge. Growing complexity makes it more difficult to foresee all dependencies during design. It is impossible to test all variations, and user interfaces need greater scrutiny since they have to handle such complexity without confusing the user or generating uncertainties.

The trend towards interconnected, highly automated and autonomous systems will change the way we own products. Instead of buying commodity products, we will instead purchase personalized services. The vision of Major Challenge 1 is to provide the requisite tools and methods for novel ECS solutions to meet ever- increasing product requirements and provide availability of ECS during use in the field. Therefore, availability will be the major feature of ECS. Both the continuous improvement of existing methods (e.g. DfR) and development of the new techniques (PHM) will be the cornerstone of future developments in ECS (see also Challenges 1 and 2, and especially the key focus areas on lifecycle-aware holistic design flows in Chapter 2.3 Architecture and Design: Methods and Tools). The main focus of Major Challenge 1 will circulate around the following topics:

2.3

- Digitization, by improving collaboration within the supply chain to introduce complex ECS earlier in the market.
- Continuous improvement of the DfR methodology through simultaneous miniaturization and increasing complexity.
- Model-based design is a main driver of decreasing time-to-market and reducing the cost of products.
- Availability of the ECS for highly automated and autonomous systems will be successfully introduced in the market based on PHM.
- Data science and AI will drive technology development and pave the way for PHM implementation for ECS.
- AI and PHM based risk management.

2.4.4.1.3 Key focus areas

Quality: in situ and real-time assessments

Inline inspection and highly accelerated testing methods for quality and robustness monitoring during production of ECS with ever-increasing complexity and heterogeneity for demanding applications should increase the yield and reduce the rate of early fails (failures immediately following the start of the use period):

- Controlling, beyond traditional approaches, the process parameters in the era of Industry 4.0 to minimize deviations and improve quality of key performance indicators (KPIs).

- Process and materials variabilities will have to be characterized to quantify their effects on hardware reliability, using a combination of empirical studies, fundamental RP models and AI approaches.
- Advanced/smart monitoring of process output (e.g. measuring the 3D profile of assembled goods) for the detection of abnormities (using AI for the early detection of standard outputs).
- Early detection of potential yield/reliability issues by simulation-assisted design for assembly/design for manufacturing (DfM/DfA) as a part of virtual prototyping.

Digitization: a paradigm shift in the fabrication of ECS from supplier/customer to partnership

- Involving European stakeholders to resolve the issue of data ownership:
  - Create a best practice for sharing data across the supply chain while maintaining intellectual property (IP).
  - Standardize the data exchange format, procedures and ownership, and create an international legal framework.
  - Conceive and validate business models facilitating sharing data, models derived from data and algorithms dealing with data.
- Handling and interpreting big data:
  - Create a usable and time-efficient workflow for supervised learning.
  - Consistent data collection and annotation/labelling of relevant events.
  - Standardized model training and model testing process.
  - Standardized procedures for model maintenance and upgrade.
- Make a link between data from Industry 4.0 and model-based engineering:
  - Derive working hypotheses about system health.
  - Validate hypothesis and refine physics-based models.
  - Construct data models based on new knowledge derived from model-based engineering.
- Identify significant parameters that must be saved during production to be re-used later for field-related events, and vice versa – i.e. feed important insights derived from field data (product usage monitoring) into design and production.
- Evaluate methods for the indirect characterization of ECS using end-of-line test data.
- Wafer fabrication (pre-assembly) inline and offline tests for electronics, sensors and actuators, and complex hardware (e.g. multicore, graphics processing unit, GPU) that also cover interaction effects such as heterogeneous 3D integration and packaging approaches for advanced technologies nodes (e.g. thin dice for power application – dicing and grinding).

1.1 1.2

Reliability: tests and modelling

Continuous improvement of physics of failure (PoF) based methodologies combined with new data-driven approaches, tests, analyses and degradation, and lifetime models (including their possible reconfiguration):

- Identifying and adapting methodology to the main technology drivers.
- Methods and equipment for dedicated third-level reliability assessments (first level: component; second level: board; third level: system with its housing, e.g. massive metal box), as well as accounting for the interactions between the hierarchy levels (element, device, component, sub-module, module, system, application).
- Comprehensive understanding of failure mechanisms, lifetime prediction models (including multi-loading conditions), continuously updating for new failure mechanisms related to innovative technologies (advanced complementary metal–oxide–semiconductor (CMOS), μ-fluidics, optical input/output (I/O), 3D printing, wide bandgap technologies, etc).
- Accelerated testing methods (e.g. high temperature, high power applications) based on mission profiles and failure data (from field use and tests):

  - Use field data to derive hypotheses that enable improved prioritization and design of testing.
  - Usage of field, PHM and test data to build models for ECS working at the limit of the technology as accelerating testing is limited.
- Standardize the format of mission profiles and the procedure on how mission profiles are deducted from multimodal loading.
- Design to field – better understanding of field conditions through standardized methodology over supply chain using field load simulator.
- Understanding and handling of new, unforeseen and unintended use conditions for automated and autonomous systems.
- Embedded reliability monitoring (pre-warning of deterioration) with intelligent feedback towards autonomous system(s).
- Identification of the 10 most relevant field-related failure modes based on integrated mission profile sensors.
- Methods to screen out weak components with machine learning (ML) based on a combination of many measured parameters or built-in sensor data.
- New standards/methodologies/paradigms that evaluate the "ultimate" strength of systems – i.e. no longer test whether a certain number of cycles are "pass", but go for the limit to identify the actual safety margin of systems, and additionally the behavior of damaged systems, so that AI can search for these damage patterns.
- Digital twin software development for reliability analysis of assets/machines, etc.
- Comprehensive understanding of the SW influence on HW reliability and its interaction:
  - SW Rel: start using maturity growth modelling techniques, develop models and gather model parameters.
  - SW/HW Rel modelling: find ways as to combine the modelling techniques (in other words: scrunch the different time domains).
  - SW/HW Rel testing: find ways as to test systems with software and find the interaction failure modes.

Design for reliability: virtual reliability assessment prior to the fabrication of physical HW

Approaches for exchanging digital twin models along the supply chain while protecting sensitive partner IP and adaptation of novel standard reliability procedures across the supply chain:

- Digital twin as main driver of robust ECS system:
  - Identifying main technology enablers.
  - Development of infrastructure required for safe and secure information flow.
  - Development of compact PoF models at the component and system level that can be executed in situ at the system level – metamodels as the basis of digital twins.
  - Training and validation strategies for digital twins.
  - Digital twin-based asset/machine condition prediction.
- Electronic design automation (EDA) tools to bridge the different scales and domains by integrating a virtual design flow.
- Virtual design of experiment as a best practice at the early design stage.
- Realistic material and interface characterization depending on actual dimensions, fabrication process conditions, ageing effects, etc, covering all critical structures, generating strength data of interfaces with statistical distribution.
- Mathematical reliability models that also account for the interdependencies between the hierarchy levels (device, component, system).
- Mathematical modelling of competing and/or superimposed failure modes.
- New model-based reliability assessment in the era of automated systems.

- Development of fully harmonized methods and tools for model-based engineering across the supply chain:
  - Material characterization and modelling, including effects of ageing.
  - Multi-domain physics of failure simulations.
  - Reduced modelling (compact models, metamodels, etc).
  - Failure criteria for dominant failure modes.
  - Validation techniques.
- Standardization as a tool for model-based development of ECS across the supply chain:
  - Standardization of material characterization and modeling, including effects of ageing.
  - Standardization of simulation-driven design for excellence (DfX).
  - Standardization of model exchange format within supply chain using functional mock-up unit (FMU) and functional mock-up interface (FMI) (and also components).
  - Simulation data and process management.
  - Initiate and drive standardization process for above-mentioned points.
  - Extend common design and process failure mode and effect analysis (FMEA) with reliability risk assessment features ("reliability FMEA").
  - Generic simulation flow for virtual testing under accelerated and operational conditions (virtual "pass/fail" approach).
- Automation of model build-up (databases of components, materials).
- Use of AI in model parametrization/identification, e.g. extracting material models from measurement.
- Virtual release of ECS through referencing.

Prognostics health management of ECS: increase in functional safety and system availability

- Self-monitoring, self-assessment and resilience concepts for automated and autonomous systems based on the merger of PoF, data science and ML for safe failure prevention through timely predictive maintenance.
- Self-diagnostic tools and robust control algorithms validated by physical fault-injection techniques (e.g. by using end-of-life (EOL) components).
- Hierarchical and scalable health management architectures and platforms, integrating diagnostic and prognostic capabilities, from components to complete systems.
- Standardized protocols and interfaces for PHM.
- Monitoring test structures and/or monitor procedures on the component and module levels for monitoring temperatures, operating modes, parameter drifts, interconnect degradation, etc.
- Identification of early warning failure indicators and the development of methods for predicting the remaining useful life of the practical system in its use conditions.
- Development of schemes and tools using ML techniques and AI for PHM.
- Implementation of resilient procedures for safety-critical applications.
- Big sensor data management (data fusion, find correlations, secure communication), legal framework between companies and countries).
- Distributed data collection, model construction, model update and maintenance.
- Concept of digital twin: provide quality and reliability metrics (key failure indicator, KFI).
- Development of an algorithm for data scalability and availability.
- Availability of the data for the training algorithm.
- Using PHM methodology for accelerated testing methods and techniques.
- Development of AI-supported failure diagnostic and repair processes for improve field data quality.
- AI-based asset/machine/robot life extension method development based on PHM.

- AI-based autonomous testing tool for verification and validation (V&V) of software reliability.
- Lifecycle management – modeling of the cost of the life-cycle.

2.4.4.2 Major Challenge 2: ensuring dependability in connected software

2.4.4.2.1 State of the art

Connected software applications such as those used on the Internet of Things (IoT) differ significantly in their software architecture from traditional reliable software used in industrial applications. The design of connected IoT software is based on traditional protocols originally designed for data communications for PCs accessing the internet. This includes protocols such as transmission control protocol/internet protocol (TCP/IP), the re-use of software from the IT world, including protocol stacks, web servers and the like. This also means the employed software components are not designed with dependability in mind, as there is typically no redundancy and little arrangements for availability. If something does not work, end-users are used to restarting the device. Even if it does not happen very often, this degree of availability is not sufficient for critical functionalities, and redundancy hardware and back-up plans in ICT infrastructure and network outages still continue to occur. Therefore, it is of the utmost importance that we design future connected software that is conceived either in a dependable way or can react reliably in the case of infrastructure failures to achieve higher software quality.

1.4 2.2

2.4.4.2.2 Vision and expected outcome

The vision is that networked systems will become as dependable and predictable for end-users as traditional industrial applications interconnected via dedicated signal lines. This means that the employed connected software components, architectures and technologies will have to be enriched to deal with dependability for their operation. Future dependable connected software will also be able to detect in advance if network conditions change – e.g. due to foreseeable transmission bottlenecks or planned maintenance measures. If outages do happen, the user or end application should receive clear feedback on how long the problem will last so they can take potential measures. In addition, the consideration of redundancy in the software architecture must be considered for critical applications. The availability of a European ecosystem for reliable software components will also reduce the dependence on current ICT technologies from the US and China.

2.4.4.2.3 Key focus areas

Dependable connected software architectures

1.3 1.4 2.3

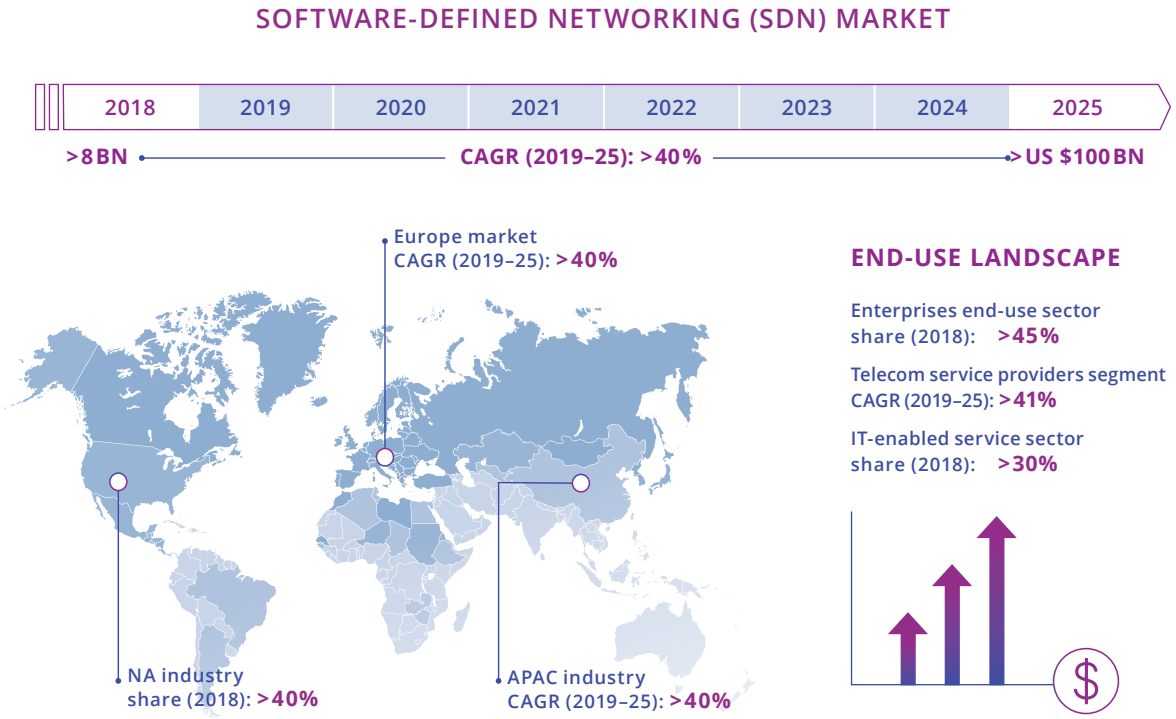
In the past, reliable and dependable software was always directly deployed on specialised, reliable hardware. However, with the increased use of IoT, edge and cloud computing, critical software functions will also be used that are completely decoupled from the location of use (e.g. in use cases where the police want to stop self-driving cars from a distance):

- Software reliability in the face of infrastructure instability.
- Dependable edge and cloud computing, including dependable and reliable AI/ML methods and algorithms.
- Dependable communication methods, protocols and infrastructure.
- Formal verification of protocols and mechanisms, including those using AI/ML.
- Monitoring, detection and mitigation of security issues on communication protocols.
- Quantum key distribution ("quantum cryptography").
- Increasing software quality by AI-assisted development and testing methods.

- Infrastructure resilience and adaptability to new threats.
- Secure and reliable over-the-air (OTA) updates.
- Using AI for autonomy, network behaviour and self-adaptivity.
- Dependable integration platforms.
- Dependable cooperation of System of Systems (SoS).

This Major Challenge is tightly interlinked with the cross-sectional technology of 2.2 Connectivity Chapter, where the focus is on innovative connectivity technologies. The dependability aspect covered within this challenge is complementary to that Chapter since dependability and reliability approaches can also be used for systems without connectivity.

2.2



F.40 *Software-defined networking (SDN) market size by 2025 (Source: Global Markets Insight, Report ID GMI2395, 2018)*

Dependable softwarisation and virtualisation technologies

Changing or updating software by retaining existing hardware is quite common in many industrial domains. However, keeping existing reliable software and changing the underlying hardware is difficult, especially for critical applications. By decoupling software functionalities from the underlying hardware, softwarisation and virtualisation are two disruptive paradigms that can bring enormous flexibility and thus promote strong growth in the market (see *Figure F.40*). However, the softwarisation of network functions raises reliability concerns, as they will be exposed to faults in commodity hardware and software components:

- Software-defined radio (SDR) technology for highly reliable wireless communications with higher immunity to cyber-attacks.
- Network functions virtualisation infrastructure (NFVI) reliability.
- Reliable containerisation technologies.
- Resilient multi-tenancy environments.

- AI-based autonomous testing for V&V of software reliability, including the software-in-the-loop (SiL) approach.
- Testing tools and frameworks for V&V of AI/ML-based software reliability, including the SiL approach.

Combined SW/HW test strategies

Unlike hardware failures, software systems do not degrade over time unless modified. The most effective approach for achieving higher software reliability is to reduce the likelihood of latent defects in the released software. Mathematical functions that describe fault detection and removal phenomenon in software have begun to emerge. These software reliability growth models (SRGM), in combination with Bayesian statistics, need further attention within the hardware-orientated reliability community over the coming years.

- HW failure modes are considered in the software requirements definition.
- Design characteristics will not cause the software to overstress the HW, or adversely change failure-severity consequences on the occurrence of failure.
- Establish techniques that can combine SW reliability metrics with HW reliability metrics.
- Develop efficient (hierarchical) test strategies for combined SW/HW performance of connected products.

Dependability in connected software is strongly connected with other Chapters in this document. In particular, additional challenges are handled in following Chapters:

- 1.3 Embedded Software and Beyond: Major Challenge 1 (MC1) efficient engineering of software; MC2 continuous integration of embedded software; MC3 lifecycle management of embedded software; and MC6 Embedding reliability and trust.
- 1.4 System of Systems: MC1 SoS architecture; MC4 Systems of embedded and cyber-physical systems engineering; and MC5 Open system of embedded and cyber-physical systems platforms.
- 2.1 Edge Computing and Embedded Artificial Intelligence: MC1: Increasing the energy efficiency of computing systems.
- 2.2 Connectivity: MC4: Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity.
- 2.3 Architecture and Design: Method and Tools: MC3: Managing complexity.

1.3 1.4 2.1 2.2 2.3

2.4.4.3 Major Challenge 3: ensuring cyber-security and privacy

2.4.4.3.1 State of the art

We have witnessed a massive increase in pervasive and potentially connected digital products in our personal, social and professional spheres, enhanced by the developments of 5G networks. Connectivity provides better flexibility and usability of these products in different sectors, with the tremendous growth of sensitive and valuable data and the complexity and the variety of deployments and configuration options, and promotes pervasive intelligence supporting our daily life but also industrial developments, efficient interaction among IoT for multiple purposes and smartness and easiness in any type of services. However, connectivity also introduces severe issues about security and privacy. At the same time, AI is becoming a key element of these digital products, especially (but not limited to) with respect to the personalisation of mass products around individual preferences and requirements.

Embedded and distributed AI functionality is growing at speed in both (connected) devices and services. AI capable chips will also enable edge applications allowing decisions to be made locally at device level.

Therefore, resilience to cyber-attacks is of the utmost importance. AI can have a direct action on the behaviour of a device, possibly impacting its physical life inducing potential safety concerns. AI systems rely on software and hardware that can be embedded in components, but also in the set of data generated and used to make decisions. Cyber-attacks, such as data poisoning or adversarial inputs, could cause physical harm and/or also violate privacy. The development of AI should therefore go hand in hand with frameworks that assess security and safety to guarantee that AI systems developed for the EU market are safe to use, trustworthy, reliable and remain under control (C.f. Chapter 1.3 "Embedded Software and beyond" for quality of AI used in embedded software when being considered as a technology interacting with other software components).

1.3 2.1

The combination of composed digital products and AI highlights the importance of trustable systems that weave together privacy and cybersecurity with safety and resilience. Automated vehicles, for example, are adopting an ever-expanding combination of sensors, devices and on-board computers (sensors, Global Positioning System (GPS), radar, lidar, cameras, on-board computers, etc.) that exchange data with other vehicles, infrastructures and environments. Autonomous vehicles represent a truly disruptive innovation for travelling and transportation, and should be able to ensure the confidentiality of the driver's and vehicle's information, as well as avoiding obstacles, identifying failures (if any) and mitigating them, and preventing cyber-attacks while safely staying operational (at reduced functionality) either through human initiated intervention, by automatic inside action or remotely by law enforcement in the case of any failure, security breach, sudden obstacle, crash, etc.

3.1

Although highly complex, interconnected and strongly data-driven, for simplicity this challenge focuses on the cyber-security and privacy trade-offs. In particular, privacy can be achieved by e.g. some novel frameworks for how new services on top of the data, edge layer can be developed; and it is becoming a discipline in its own right and not just a part of auditing, legal and compliance. This challenge is strictly related to European data strategy and data sovereignty. An additional challenge address safety and resilience, and a special focus is also devoted to investigating how safety and security influence each other.

2.4.4.3.2 Vision and expected outcome

The cornerstone of our vision is threefold. First, a robust root of trust system, with unique identification enabling security without interruption from the hardware level right up to the applications, including AI, involved in the accomplishment of the system's mission in dynamic unknown environments. This aspect has a tremendous impact on mission critical systems with lots of reliability, quality and safety & security concerns. Second, protection of the EU citizen's privacy and industrial Intellectual Protection. Third, proof-of-concept demonstrators that are capable of simultaneously guaranteeing (a given level of) security and (a given level of) privacy, as well as potentially evolving in-reference designs that illustrate how practical solutions can be implemented (i.e. thereby providing guidelines to re-use or adapt).

Besides intensive research in quantum computing the preparation for the uptake of post quantum cryptography with standard crypto primitives will need to be pushed. In expectation of the finalization of the NIST competition on post quantum cryptography with draft standards until 2024 (https://csrc.nist.gov/Projects/post-quantum-cryptography/workshops-and-timeline) not only research on secured implementations of PQC-schemes and protocols building upon PQC primitives has to be conducted, but also preparation for transition to PQC-schemes, e.g. with PQC-based remote update features and algorithm substitution mechanisms in relevant application environments, like e.g. industry4.0/5.0, connected vehicles and government infrastructures.

Putting together seamlessly security and privacy requirements is a difficult challenge that also involves some non-technical aspects. Consider, for example, the concerns raised in the public domain by person-tracking

applications that European countries are evaluating to contain the number of new Covid-19 contagions after the end of a strict lockdown period. The awareness that the number of cyber-attacks against personal data is also continuing to rise exponentially clearly adds to that anxiety. In this regard, Risk Based Security has stated that, in June 2019, "3,813 breaches were reported, exposing over 4.1 billion records". If we compare these data to those in the same period for 2018, the report[116] found that the number of breaches had grown to 52% and the exposing records to 54%. In the first quarter of 2020, however, the number of breaches and exposed data had strongly decreased, but cybercrime had increased due to the economic recession after the Covid-19 lockdown[117]. In the meantime, the cybersecurity and privacy market in 2019 was forecast to grow by 8.7% to US $124 billion[118].

In light of this scenario, this Major Challenge aims to contribute to the European strategic autonomy plan in terms of cybersecurity, digital trustworthiness and the protection of personal data.

2.4.4.3.3 Key focus areas

Trustworthiness

The goal is a robust and resilient system that operates in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be AI-enabled. In this aim, the main expected outcome is methods and concepts that build and test such systems:

- Ensuring security and privacy of systems in the Edge to cloud continuum.
- Defining different methods and techniques of trust for a system, and proving compliance to a security standard via certification schemes.
- Defining a method for multiple standards via the composition of certified parts.
- Enabling developers to have a flexible means to demonstrate security capabilities.
- Developing technologies, methods and techniques to ensure cyber-security at all levels.
- Definition and future consolidation of a framework providing guidelines, good practices and standards oriented to trust.

Security and privacy-by-design

The main expected outcome is a set of solutions that integrates privacy and confidentiality of data as built-in properties of systems:

- Ensuring performance in AI-driven algorithms (which needs considerable data) while guaranteeing general data protection regulation (GDPR) compliance.
- Establishing a secure and privacy-by-design European data strategy and data sovereignty.
- Ensuring the protection of personal data in the data-driven digital economy against potential cyber-attacks.
- Establishing Quantum-Safe Cryptography Modules everywhere in the system.

116 CyberRisk Analytics, 2019 mid year, data breach report.

117 CyberRisk Analytics, 2020 Q1 data breach report.

118 https://www.gartner.com/en/newsroom/press-releases/2018-08-15-gartner-forecasts-worldwide-information-security-spending-to-exceed-124-billion-in-2019

Ensuring both safety and security properties

The main expected outcome is to ensure compatibility, adequacy and coherence in the joint use of the promoted security solutions, and the safety levels required by the system or its components:

- Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc.).
- Ensuring safety, security and privacy of embedded intelligence (c.f. Chapter 1.3 "Embedded Software and beyond").
- Ensuring the nominal and degraded behaviour of a system when the system's security is breached or there are accidental failures.
- Guaranteeing a system's coherence among different heterogeneous requirements (i.e. secure protocols, safety levels, computational level needed by the promoted mechanisms) and different applied solutions (i.e. solutions for integrity, confidentiality, security, safety) in different phases (i.e. design phases, run-time phases, maintenance phases, repair and recovery phases).
- Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of transparency without compromising information and trustworthiness.
- Evaluating the impact of the contextualization environment on the system's required levels of safety and security.

1.3

2.4.4.4 Major Challenge 4: ensuring of safety and resilience

2.4.4.4.1 State of the art

Safety has always been a key concept at the core of human civilisation. Throughout history, its definition, as well as techniques to provide it, has evolved significantly. In the medical application domain, for example, we have witnessed a transformation from safe protocols to automatic medication machines, such as insulin pumps and respiratory automation, which have integrated safety provisions. Today, we can build a range of different high-integrity systems, such as nuclear power plants, aircraft and autonomous metro lines. The safety of such systems is essentially based on a combination of key factors, including: (i) determinism (the system's nominal behaviour is always the same under the same conditions); (ii) expertise and continuous training of involved personnel; (iii) deep understanding of nominal and degraded behaviours of the system; (iv) certification/qualification; and (v) clear liability and responsibility chains in the case of accidents.

Nowadays, the digitalisation of ubiquitous systems, and the embedding of AI components (hardware or software) in them, highlights the limits of traditional safety techniques, which need to be extended and/or embedded in new overall safety-case arguments (c.f. Chapter 2.3. for some of the extensions needed). These techniques for building safe systems include fault-tree analysis, failure modes and effect analysis, evidence-based development standards (such as ISO26262 and ISO 21448), redundancy, diversification and defence-in-depth (c.f. Chapter 1.3 "Embedded Software and beyond" for Major Challenge 1: efficient engineering of embedded software to enable transition from embedded software engineering to embedded systems engineering.). As a result of the realities in modern systems and their usage, one promising approach is to move the safety paradigm has moved from safety as traditionally studied in embedded systems, to resilience. Most of the methodical factors mentioned above are currently insufficient to cope with resilience in its full meaning. New innovations are required to increase the resilience of systems by tackling challenges involving cross-cutting considerations such as legal concerns and user abilities. For example, the inherent inscrutability of AI algorithms combined with the increasing autonomy of the system threatens liability and responsibility chains in the case of an accident. Understanding the nominal and degraded behaviours of AI-driven system is also extremely complex, and operators of several AI-driven systems are the main users

2.3

1.3

of the system (for example, a child that uses an autonomous vehicle) – i.e. users not necessarily expert in the system itself, unlike the operators in the traditional high-integrity systems, such as operators of nuclear power plants.

2.4.4.4.2 Vision and expected outcome

The vision points to the development of safe and resilient autonomous cyber-physical systems in dynamic environments, with a continuous chain-of-trust from the hardware level up to the applications that is involved in the accomplishment of the system's mission, including AI. Our vision takes into account physical limitations (battery capacity, quality of sensors used in the system, hardware processing power needed for autonomous navigation features, etc.) and also considers optimizing the energy usage and system resources of safety-related features to support sustainability of future cyber-physical systems. Civilian applications of (semi-) autonomous cyber-physical systems are increasing significantly. For example, drones can be deployed for monitoring social distancing and providing safety to the population (and also to deliver medicine in the UK). However, the use of drones is not accident-free. In 2015, at the Pride Parade in Seattle, a drone crashed and caused an accident that resulted in a woman being knocked out. Civilian applications thus inherently entail safety, and in the case of an accident or damage (for example, in uploading a piece of software in an AI system) liability should be clearly traceable, as well as the certification/qualification of AI systems.

2.1

The increasing trend towards the adoption of AI in civilian applications represents a great opportunity for European economic growth. However, unlike traditional high-integrity systems, the hypothesis that only expert operators can manipulate the final product undermines the large-scale adoption of the new generation of autonomous cyber-physical systems.

In addition to the key focus areas below, the challenges cited in Chapter 2.3 on Architecture and Design: Methods and Tools are also highly relevant for this topic, and on Chapter 1.3 on Embedded Software and beyond.

1.3 2.3

2.4.4.4.3 Key focus areas

Safety and resilience of (autonomous AI) systems in dynamic environments

The expected outcome is systems that are resilient under physical constraints:

- Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimization.
- Resources' management of all system's components to accomplish the mission system in a safe and resilient way by considering to minimize the energy usage and system resources of safety-related features to support sustainability of future cyber-physical systems.
- Identify and address transparency and safety-related issues introduced by AI applications.
- Concepts and principles for trustable integration and the V&V of intelligent functions in systems/products under uncertain and/or dynamic environments.

Modular certification of trustable systems and liability

The expected outcome is a clear traceability of liability in the case of damage or accident:

- Having explicit workflows for automated and continuous layered certification/qualification, both when designing the system and for checking certification/qualification during run-time or dynamic safety contracts, to ensure continuing trust in dynamic adaptive systems in changing environments.
- Contract-based co-design methodologies, consistency management techniques in multi-domain collaborations.
- Certificates of extensive testing, new code coverage metrics (e.g. derived from mutation testing), formal methods providing guaranteed trustworthiness.

Dynamic adaptation and configuration, self-repair capabilities, (decentralised instrumentation and control for) resilience of complex and heterogeneous systems

The expected outcome is resilient systems that are able to dynamically adapt their behaviour in dynamic environments:

- Responding to uncertain information based on digital twin technology, run-time adaptation and redeployment based on simulations and sensor fusion.
- Automatic prompt self-adaptability at low latency to dynamic and heterogeneous environments.
- Architectures that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification.
- Develop explainable AI models for human interaction, system interaction and certification.
- Support for dependable dynamic configuration and adaptation/maintenance to help cope with components that appear and disappear, as ECS devices to connect/disconnect, and communication links that are established/released depending on the actual availability of network connectivity (including, for example, patching) to adapt to security countermeasures.
- Concepts for SoS integration, including legacy system integration.

Safety aspects related to the human/system interaction

The expected outcome is to ensure safety for the human, system and environment during the nominal and degraded operations in the working environment (cf. Major Challenge 5 below):

- Understanding the nominal and degraded behaviour of a system that could potentially have AI.
- Minimising the risk of human or machine failures during the operating phases.
- Ensuring that the human can safely interface with machine, and also that the machine can prevent unsafe operations.
- New self-learning safety methods to ensure safety system operations in complex systems.
- Ensuring safety in machine-to-machine interaction.
- Safely manage human interaction in complex systems, SoS and application scenarios.

2.4.4.5 Major Challenge 5: human systems integration

2.4.4.5.1 State of the art

This ECS SRIA roadmap aligns societal needs and challenges to the R & D & I for electronic components. The societal benefits thereby motivate the foundational and cross-sectional technologies as well as the concrete applications in the research agenda. Thereby, many technological innovations occur on a subsystem level that are not directly linked to societal benefits themselves until assembled and arranged into larger systems. Such larger systems then most of the time require human users and beneficiary to utilize them and thereby achieve the intended societal benefits. Thereby, it is common that during the subsystem development

human users and beneficiaries stay mostly invisible. Only once subsystems are assembled and put to an operational system, the interactions with a human user become apparent. At this point however, it is often too late to make substantial changes to the technological subsystems and partial or complete failure to reach market acceptance and intended societal benefits can result. To avoid such expensive and resource intensive failures, Human Systems Integration (HSI) efforts attempt to accompany technological maturation that is often measured as Technological Readiness Levels (TRL) with the maturation of Human Readiness Levels (HRL). Failures to achieve high HRL beside high TRLs have been demonstrated in various domains such as military, space travel, and aviation. Therefore, HSI efforts to achieve high HRLs need to be appropriately planned, prepared, and coordinated as part of technological innovation cycles. As this is currently only rarely done in most industrial R&D activities, this Chapter describes the HSI challenges and outlines a vision to address them.

There are three high-level HSI challenges along ECS SRIA products:

- The first challenge consists of conceiving technologies that are acceptable, trustworthy, and therefore sustainably used and thereby have a chance to achieve the overall targeted individual, societal, and organizational benefits. Thereby, the overall vision for the practical use of a product by real users within their context must often precede the technological specification of the subsystems. In many current innovation environments, this works in the opposite way such that the available technological capabilities are assembled toward use cases that are only meant to demonstrate the technological capabilities. Thereby, sufficiently detailed operational knowledge of the environmental, organizational, and user characteristics is often either not available or cannot be integrated into established technology development cycles. Therefore, the conception of accepted and trusted, and sustainably used technologies is often more the result of trial-and-error than strategically planned development efforts.
- The second challenge consists of designing envisioned products to achieve the appropriate characteristics that lead to accepted, trusted, sustained usage. Increasingly complex and smart products require often intricate user interaction and understanding than the often much simpler products of the past. Even for a potentially highly promising product, the developing engineers often do not know the concrete usage conditions or constraints of their users and make architecture decisions that can only be costly undone later on. For example, drivers and workers generally do not like to purely monitor or supervise automated functions, while losing their place as active process participants. This is especially critical when humans have to suddenly jump back into action and take control when unexpected conditions require to do so. Therefore, aligning the automation capabilities with the acceptable tasks, available knowledge, and expectable responsibilities of the human users are becoming paramount to bring a product to actual fruition. Thereby, required and desirable human competences and skills need to be formulated so that educational curricula can start working toward achieving them.
- Thirdly, continuous product updates and maintenance are creating dynamically changing products that can be challenging for user acceptance, trust, and sustained usage. Frequent and increasingly automated software updates have become common place to achieve acceptable security and to enable the latest feature sets as well as allow self-learning algorithms to adapt to user preferences and usage history, and improved performance. However, such changes can be confusing to users if they come unprepared or are difficult to understand. Also, the incorrect usage that may results from this may lead to additional security and acceptance risks. Therefore, the product maintenance and update cycles need to be designed appropriately within the whole product lifecycle to ensure maximum user acceptance and include sufficient information on the side of the users. Here HSI extends beyond initial design and fielding of products.

2.4.4.5.2 Vision and expected outcome

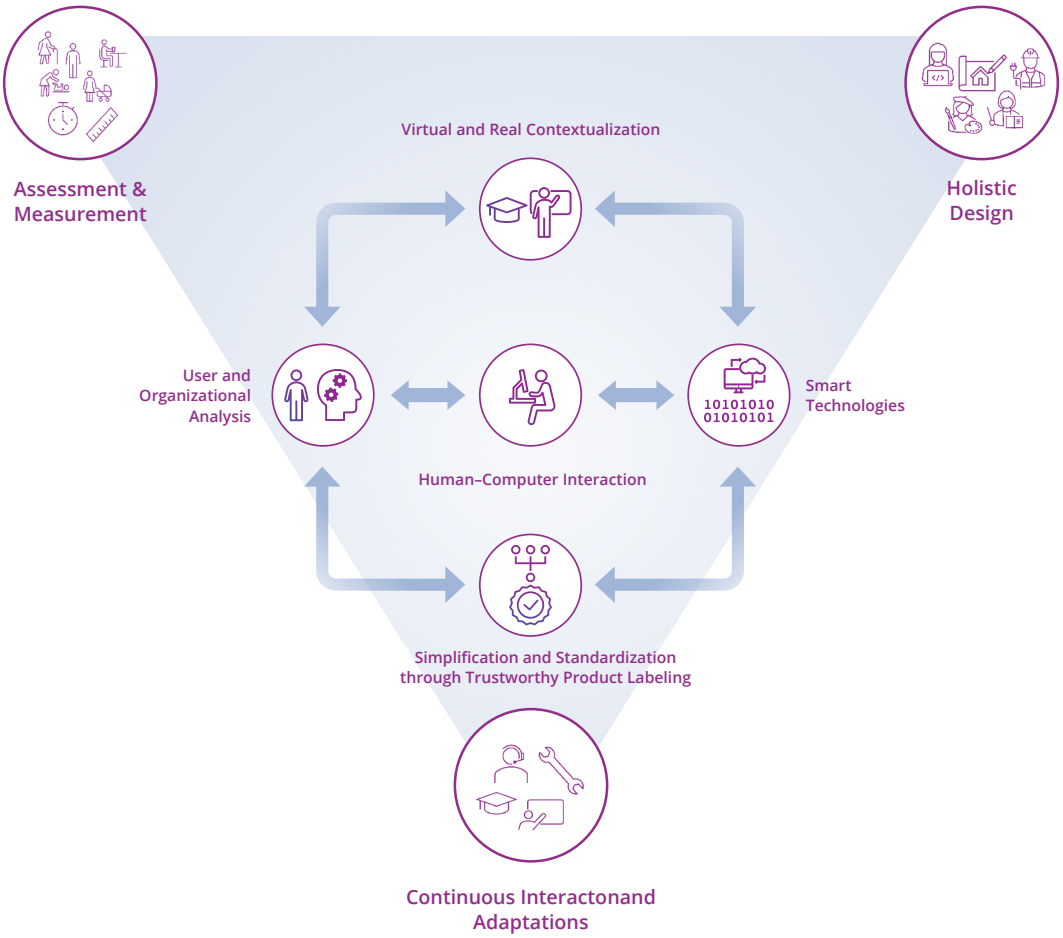
The vision and expected outcome is that these three HSI challenges in the ECS SRIA can be addressed by appropriately orchestrating the assessments of needs, constraints, and abilities of the human users with the usage conditions in terms of environmental and organizational context, during conception, design, and lifetime support phases of product. Specifically, the vision can be formulated around three cornerstones:

- Vision cornerstone 1: conceiving systems and their missions that lead to their sustained acceptance and usage start in the early assessment of the usage con-text, as well as user needs and constraints and to translate this information into a useful form to inform system design and development. Such information is currently not readily available to the conceivers of new systems and such knowledge is currently either hidden or not assessed at the time when it is needed to make an impact during system conception. Needed assessments include the user population and the usage situation including criticality, responsibilities, environment, required tasks and concurrent tasks. Also, the organizational conditions and processes within which the users use the system play an important role that should be allowed to impact design decisions, for example to decide on appropriate explainability methods. The recording and sharing of such information in a format that is understandable to system conceivers, architects, and engineering teams requires special activities and tools.
- Vision cornerstone 2: to translate a well-conceived system into orchestrated system development requires holistic design processes where multifaceted developer communities jointly work together to achieve acceptable, safe, and trustworthy products. Thereby, the product is not designed and developed in isolation but within actively explored contextual infrastructures that allow to surround the development and design communities within the use environment and conditions of the product. Considering this larger contextual field in the design of products requires advanced R&D approaches and methodologies, to pull together the various fields of expertise and allow mutual fertilization. This requires sufficiently large, multi-disciplinary research environments for active collaboration and enablement of a sufficient intermixture between experts and innovation approaches. This also requires virtual tool sets for collaboration, data sharing, and solution generation.
- Vision cornerstone 3: detailed knowledge about the user and use conditions are also pertinent to appropriately plan and design the continuous adaptations and updates of products during the lifecycle. Converging of user knowledge and expectations will allow more standardized update policies. This will be addressed by bringing the European end-users, workers, and operators toward achieving the digital literacy with a chance to enable the intended societal benefits. The formation of appropriate national and international training and educational curricula will work toward shaping users with sufficiently converging understanding of new technology principles and expectations as well as knowledge about responsibilities and common failure modes to facilitate sustained and positively perceived interactions.

2.3

2.3

Within these cornerstones, the vision is to intermingle the multi-disciplinary areas of knowledge, expertise, and capabilities within sufficiently inter-disciplinary research and development environments where experts can interact with stakeholders to jointly design, implement, and test novel products. Sufficiently integrated simulation and modeling that includes human behavioral representations are established and link the various tasks. The intermingling starts with user needs and contextual assessments that are documented and formalized sufficiently to stay available during the development process. Specifically, the skills and competences are formally recorded and made available for requirements generation.



The fourfold vision and expected outcome of human–systems integration F.41

2.4.4.5.3 Key focus areas

- Systematize methods for user, context, and environment assessments and sharing of information for user-requirement generation. Such methods are necessary to allow user centered methods to achieve an impact on overall product design.
- Develop simulation and modeling methods for the early integration of Humans and Technologies. The virtual methods link early assessments, holistic design activities, and lifelong product updates and bring facilitate convergence among researchers, developers, and stakeholders.
- Establish multi-disciplinary research and development centers and sandboxes. Interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support.

2.4.5 TIMELINE

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: ensuring HW quality and reliability	**Topic 1.1:** quality: *in situ* and real-time assessments	• Create an environment to fully exploit the potential of data science to improve efficiency of production through smart monitoring to facilitate the quality of ECS and reduce early failure rates
	Topic 1.2: reliability: tests and modelling	• Development of methods and tools to enable third generation of reliability – from device to SoS
	Topic 1.3: design for (EoL) reliability: virtual reliability assessment prior to the fabrication of physical HW	• Continuous improvement of EDA tools, standardisation of data exchange formats and simulation procedures to enable transfer models and results along full supply chain
	Topic 1.4: PHM of ECS: increase in functional safety and system availability	• Condition monitoring will allow for identification of failure indicators for main failure modes
Major Challenge 2: ensuring dependability in connected software	**Topic 2.1:** dependable connected software architectures	• Development of necessary foundations for the implementation of dependable connected software to be extendable for common SW systems (open source, middleware, protocols)
	Topic 2.2: dependable softwarisation and virtualisation technologies	• Create the basis for the increased use of commodity hardware in critical applications
	Topic 2.3: combined SW/HW test strategies	• Establish SW design characteristics that consider HW failure modes
Major Challenge 3: ensuring privacy and cybersecurity	**Topic 3.1:** trustworthiness	• Root of trust system, and unique identification enabling security without interruption from the hardware level up to applications, including AI • Definition of a framework providing guidelines, good practices and standards oriented to trust
	Topic 3.2: security and privacy- by-design	• Establishing a secure and privacy-by-design European data strategy and data sovereignty
	Topic 3.3: ensuring both safety and security properties	• Guaranteeing information properties under cyber-attacks (quality, coherence, integrity, reliability, etc.) independence, geographic distribution, emergent behaviour and evolutionary development

MEDIUM TERM (2027–2031)	LONG TERM (2032–2037)
• Establish a procedure to improve future generation of ECS based on products that are currently in the production and field → feedback loop from the field to design and development	• Provide a platform that allows for data exchange within the supply chain while maintaining IP rights
• Implementation of a novel monitoring concept that will empower reliability monitoring of ECS	• Identification of the 80% of all field-relevant failure modes and mechanisms for the ECS used in autonomous systems
• Digital twin as a major enabler for monitoring of degradation of ECS	• AI/ML techniques will be a major driver of model-based engineering and the main contributor to shortening the development cycle of robust ECS
• Hybrid PHM approach, including data science as a new potential tool in reliability engineering, based on which we will know the state of ECS under field loading conditions	• Standardisation of PHM approach along all supply chains for distributed data collection and decision-making based on individual ECS

• Set of defined and standardised protocols, mechanisms and user-feedback methods for dependable operation	• Availability of European ecosystem for dependable software, including certification methods
• Definition of softwarisation and virtualisation standards, not only in networking but in other applications such as automation and transport	• Widely applied in European industry
• Establish techniques that combine SW reliability metrics with HW reliability metrics	• Efficient test strategies for combined SW/HW performance of connected products

• Definition of a strategy for (modular) certification under uncertain and dynamically changing environments • Consolidation of a framework providing guidelines, good practices and standards oriented to trust	• Liability
• Ensuring the protection of personal data against potential cyber-attacks in the data-driven digital economy • Ensuring performance and AI development (which needs considerable data) by guaranteeing GDPR compliance	
• Ensuring the nominal and degraded behaviour of a system when the underlying system security is breached or there are accidental failures • Guaranteeing a system's coherence while considering different requirements, different applied solutions, in different phases • Evaluating the impact of the contextualisation environment on the system's required levels of safety and security	• Developing rigorous methodology supported by evidence to prove that a system is secure and safe, thus achieving a greater level of trustworthiness

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 4: ensuring safety and resilience	**Topic 4.1:** safety and resilience of (autonomous AI) systems in dynamic environments	• Resources' management of all system's components to accomplish the mission system in a safe and resilient way • Use of AI in the design process – e.g. using ML to learn fault injection parameters and test priorities for test execution optimisation
	Topic 4.2: modular certification of trustable systems and liability	• Contract-based co-design methodologies, consistency management techniques in multi-domain collaborations
	Topic 4.3: dynamic adaptation and configuration, self-repair capabilities (decentralised instrumentation and control for), resilience of complex systems	• Support for dependable dynamic configuration and adaptation/maintenance • Concepts for SoS integration, including the issue of legacy system integration • Using fault injection methods, models-of-the-physics and self-diagnostic architecture principles to understand the true nature of the world, and respond to uncertain information (included sensor's false positives) or attacks in a digital twin, • Run-time adaptation and redeployment based on simulations and sensor fusion • Architectures that support distribution, modularity and fault containment units to isolate faults, possibly with run-time component verification
	Topic 4.4: safety aspects related to HCI	• Minimising the risk of human or machine failures during the operating phases • Ensuring that the human can safely interface with the machine, and also that the machine prevents unsafe operations • Ensuring safety in machine-to-machine interaction
Major Challenge 5: human–systems integration	**Topic 5.1:** systematize methods for user, context, and environment assessments and sharing of information for user-requirement requirements generation	• Provide means for user centered methods to achieve an impact on overall product design. • Establish stakeholder knowledge, skills, and competence capturing techniques to inform requirements generation
	Topic 5.2: develop simulation and modeling methods for the early integration of Humans and Technologies	• Link early assessments, holistic design activities, and lifelong product updates and bring facilitate convergence among researchers, developers, and stakeholders • Establish tools to bring stakeholder knowledge, skills, and competence capturing techniques to inform design and development activities
	Topic 5.3: establish multi-disciplinary research and development centers and sandboxes	• Interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support. • Establish tools and processes to update stakeholder knowledge, skills, and competence capturing techniques to inform design and development activities

MEDIUM TERM (2027–2030)	LONG TERM (2031–2036)
• Automated operation • Concepts and principles for trustable integration and V&V of intelligent functions in systems/products under uncertain and/ or dynamic environments • Identify and address transparency and safety-related issues introduced by AI applications • Having explicit workflows for automated and continuous layered certification/qualification, to ensure continuing trust in dynamic adaptive systems in changing environments	
• Having explicit workflows for automated and continuous layered certification/qualification, to ensure continuing trust in dynamic adaptive systems in changing environments	• Certificates of extensive testing, new code coverage metrics (mutation testing), formal methods providing guarantee of trustworthiness
• Automatic prompt self-adaptability at low latency in dynamic and heterogeneous environments	• Develop explainable AI models for human interaction, system interaction and certification
• Understanding the nominal and degraded behaviour of a system, potentially with AI • New self-learning safety methods to ensure safety system operations in complex systems • Ensuring safety in machine-to-machine interaction	• Safely manage human interactions in complex systems, SoS and application scenarios

• Apply methods for user context and environment assessments and sharing of information for stakeholder-requirement generation to prototypical use cases, establish practices of use and generally applicable tools	• Develop standard processes for stakeholder context and environment assessments and sharing of information • Develop standard processes for stakeholder knowledge, skills, and competence capturing techniques to inform requirements generation • Develop educational programs to increase the levels of common stakeholder knowledge, skills and competences for sustainable product uptake across Europe
• Develop centers of excellence for early assessments, holistic design activities, and lifelong product updates and bring facilitate convergence among researchers, developers, and stakeholders can be realized, practiced, and established as lighthouses of holistic Design and Development of embedded components	
• Develop prototypical use cases where interdisciplinary research and development centers allow for the intermingling of experts and stakeholders for cross-domain coordinated products and life-long product support. This should allow sufficient demonstrate	

2.4.6
SYNERGY WITH OTHER THEMES

The **Major Challenge** "Ensuring HW quality and reliability" is a key element for any ECS, which is why it can be linked to any application area. It is directly linked to the technology Chapter: **Components, Modules and Systems Integration**. For quality, the novel design of reliability methodologies such as PHM requires direct connection to all cross-sectional technologies (**Edge Computing and Embedded Artificial Intelligence; and Architecture and Design: Methods and Tools**).

The **Major Challenge** "Ensuring dependability in connected software" is strongly linked to the Chapter **Embedded Software and Beyond** as implementations will cover embedded devices to a high degree. It is also linked to the **Connectivity** Chapter and the **Edge Computing and Embedded Artificial Intelligence** Chapter since software must reliably interact remotely, from a system to the edge and to the cloud. From a different perspective, it is also linked to the Chapter on **System of Systems** considering that software-based systems will be integrated over distances.

The **Major Challenges** "Cybersecurity and privacy" and "Safety and resilience" address robust and resilient systems in a complex ecosystem without interruption, from the hardware level up to applications, including systems that may be enabled by AI. The outcome of these challenges supports all application Chapters, in particular **Health and Wellbeing, Mobility, Digital Industry, Digital Society** and **Agrifood and Natural Resources**. Moreover, they are also linked to the Chapters **Edge Computing and Embedded Artificial Intelligence, Architecture and Design: Methods and Tools, Embedded Software and Beyond and System of Systems**.

3.1
MOBILITY

3.2
ENERGY

3.3
DIGITAL INDUSTRY

3.4
HEALTH AND WELLBEING

3.5
AGRIFOOD AND NATURAL RESOURCES

3.6
DIGITAL SOCIETY

3

Strategic Research and Innovation Agenda 2022

ECS KEY APPLICATION AREAS

3.1

ECS Key Application Areas

MOBILITY

3.1.1 SCOPE

Mobility is a basic human need and Europe's mobility industry is a key contributor to it. The automotive sector alone provides employment, both direct and indirect, to 13.8 million Europeans, representing 6.1% of total EU employment. 2.6 million people work in the direct manufacturing of motor vehicles, representing 8.5% of EU employment in manufacturing. The automotive sector is also the driver for innovation in many other mobility sectors in Europe, including aerospace, maritime and rail.

During the COVID crisis individual transport was largely favoured due to a basic user need, a clean and safe personal environment. Only cars can offer such an environment today. A major challenge will be to offer individual space in a public or shared mobility.

Two major societal challenges are significantly pushing the mobility domain: the reduction of CO_2 and other emissions, and the inclusive safe and secure mobility for an ageing global society across different mobility sectors.

The first societal challenge, known as the European Green Deal, is at the forefront of the EU's priority list. As automotive traffic is currently contributing approximately 14% of global CO_2 emissions, CO_2-neutral mobility requires alternative powertrain systems for automotive vehicles, ships and flying equipment, and smart energy-producing and charging infrastructure and systems for optimised and wherever possible the use of existing mobility infrastructure. The key enabling technologies are essential building blocks for these new CO_2 neutral and energy efficient mobility. More and more energy- and cost-efficient electronic and optoelectronic components, interconnected intelligent systems and (AI-based) embedded software are required in modern cars, trains, airplanes or off-road vehicles, because microelectronics based computers, sensors actors and communication equipment are meanwhile ubiquitous and their energy consumption contribute to the increasingly more to the global warming.

In addition to the strong research focus on battery electrical vehicles (vehicles here are identified as automobiles, trains, airplanes, ships, off-road vehicles, trucks, etc), research on H2-based electrical vehicles (especially long-haul trucks) , trains, ships and even airplanes is gaining in importance due to their very good environmental performance and "cradle to grave" impact. This ECS SRIA Chapter on mobility is aligned with the proposal for the partnership "Towards zero emission road transport" (2Zero) programme proposal by Horizon Europe to achieve carbon-neutrality in road transport by 2050. There are plans to continue and strengthen this cooperation between 2Zero and KDT.

The second societal challenge focuses on the usage of smart perception, safety and automated mobility solutions and services to provide safe and comfortable inclusive mobility that is also suitable for the elderly as well as people with special needs. Research, development and innovation (R&D&I) of embedded AI-based software, sensors and electronic components and systems provide the core of automated on- and off-road vehicles, ships, trains and airplanes. A special focus requires validation of the safety and reliability of the automated mobility systems in all traffic and environmental situations as there are currently no adequate methods and tools available. This ECS SRIA Chapter on essential technologies for the digitalization in mobility is also closely aligned with the proposal for the partnership "Connected, Cooperative and Automated Mobility" (CCAM) under Horizon Europe.

Additional key aspects of the contribution by KDT to the future of mobility are increasing user value, security, privacy protection features, affordability and human interaction. Particularly in urban areas, intermodality and technologies supporting the shared principles will be crucial.

3.1.2 MAJOR CHALLENGES – OVERVIEW

The Green Deal and digitalisation are significantly influencing the ECS SRIA in the mobility domain: the reduction of CO_2 and other emissions, and ensuring an inclusive safe and secure mobility for an ageing global society. This leads to five challenges in R&D&I for mobility.

There are two Major Challenges in mobility derived from the Green Deal:

- **Major Challenge 1** (climate and energy): enable electrification and sustainable alternative fuels for CO_2-neutral mobility.
- **Major Challenge 2** (safety): enable affordable, safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, small drones, etc) and mobile machinery (for smart farming).

The results of R&D&I from Major Challenge 1 will be used in green CO_2-neutral vehicles integrated into the 2Zero EU partnership, and therefore roadmaps and research programmes are (and will be) aligned.

The Strategic Research, Innovation and Deployment Agenda of the AI, Data and Robotics Partnership (BDVA) stated in its third version: *"The sudden stop of economic activities caused by the Covid-19 pandemic has only slowed down investments in digital technologies, which are already picking up at the end of 2020 and are expected to go back to high growing rates from 2021. Based on ongoing surveys, IDC forecasts worldwide spending on AI11 to jump from 40 B€ in 2019 to 119 B€ in 2025, while spending in Robotics12 will increase from 86 B€ to 254 B€ in 2025, driven by massive automation investments. The already large Big Data and Analytics (BDA) 13 market will grow from 165 B€ to 294 B€ in 2025. (BDVA, 2021)".* A significant portion of this market is increasing integration of automation functions in the mobility sector.

Additionally, the SRIA of the private public partnership CCAM working on "Connected, Cooperative & Automated Mobility" is well aligned with this SRIA as key digital components, tools and systems described in this SRIA are essential building blocks in the challenges in CCAM. The outcome of the research on the challenges described here will used in partial or fully automated vehicles for the CCAM EU programme. Therefore, roadmaps and research programmes of CCAM, KDT and BDVA are (and will be) aligned.

The challenges for key digital technologies focused on the adoption of ECS in the mobility application sector are the following:

- **Major Challenge 3** (automation): enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water.
- **Major Challenge 4** (validation): provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility.
- **Major Challenge 5** (real-time data handling): achieve real-time data handling for multimodal mobility and related services.

The key digital components resulting from the work on these challenges will be used in partial or fully automated and/or connected electrified vehicles.

3.1.3 AUTOMOTIVE TRENDS AND SOCIETAL BENEFITS

Mobility is at the heart of European lifestyle and its economy. Efficient transportation systems are more important than ever, and also contribute to the consolidate the European Union. However, the promise of freedom offered by road transport is viewed in sharp contrast to a range of concerns about its effect on safety, health and the environment. Therefore, transport and mobility systems are in the process of a fundamental transformation towards a vision of sustainable, CO_2 emission neutrality that involves efficient, inclusive and seamless solutions.

For decades, disabled people have promoted a universal approach to the design of transport systems to make them more accessible and useful for everybody. In view of the Covid-19 pandemic, this focus on human factors of transport innovation is expected to increase; it will particularly call for smart and intelligent mobility systems enabled by ECS.

Mobility is not only a visible expression of Europe's economic and societal prosperity, it is also an important source of that prosperity. According to Europe's car manufacturers and transporters, the automotive sector employs around 12 million people (approximately 2.6 million directly and close to 10 million indirectly), contributing 16% of the EU's GDP. Currently, the transportation sector is undergoing a fundamental and complex transformation across all modes.

Europe is ranked number one in automotive semiconductors. In the automotive value chain, Tier 1's and original equipment manufacturers (OEMs) are also top global players and intend to gain further market share through close collaboration with semiconductor and embedded software leaders in Europe.

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

The current leading position of the European aerospace and rail industry will require a further shift to the greater autonomy of planes, trains and infrastructure, and increased trustworthiness of radio and other communication technologies. Therefore, it is also strongly dependent on progress in key digital components and AI-based real-time software.

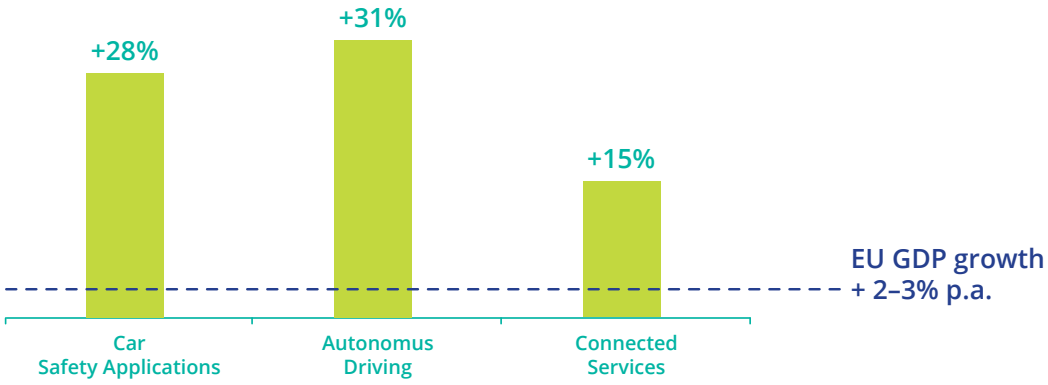
An important priority of the European Commission in its Communication on the European Green Deal is "accelerating the shift to sustainable and smart mobility". This will require a strong boost to multimodal transport, automated and connected multimodal mobility, a ramp-up of the deployment of sustainable alternative transport fuels and less polluting transportation, especially in cities.

The electronics components and systems (ECS) community will contribute substantially to these tasks by using new technologies, components and systems to target the following topics:

- Autonomous vehicles and coordinated mobility to make traffic more efficient and thus reduce pollution by new electronics architectures, smart and connected sensor systems, AI-based real-time software, higher-performance in-vehicle controllers and networks, as well as connectivity devices and advanced embedded software solutions. There will be a need to more intensively monitor, interact with, and update the car remotely. Software upgrades need to be done over-the-air (OTA). Semiconductors have a shorter lifetime than cars and hence it is needed to predict their end-of-life and to replace them on-time before the car breaks down.
- Electrification of vehicles and development of powertrains for carbon-free energy carriers. Enabling technologies come from the European ECS industry – for instance, energy-efficient devices, power electronic components and systems, energy (e.g. battery) management systems, and embedded software solutions for power management. Batteries will need to read a mileage of at least 600 km without recharging.
- New means of transport systems and interaction among different providers (public/private), including other transport modes (multimodal transport for passengers and goods), will be enabled through further development of new and harmonised vehicle-to-everything (V2X), logistics operation software, traffic management devices and guidance systems to enable mobility-as-a-service (MaaS). Easy access to these systems for users will guarantee the highest standards of privacy to avoid potential impacts caused by the general data protection regulation (GDPR) since information (about origin, destination, financial information, etc) needs to be shared.
- Rapid advances in AI and edge computing will ensure Europe can produce a step change in these areas. Autonomous driving, mobility and logistics are high-profile applications where the use of AI technologies is growing very rapidly, affecting both society and industry directly. The European transport industry is being revolutionised by the introduction of AI (combined with electric vehicles). However, AI applications in transport are very challenging, as they typically involve highly complex environments, a large number of possible situations and real-time, safety- relevant decision-making. Leading IT companies in the US and China in particular are providing a challenge to European industry in these areas, and significant effort will be required to safeguard the leading position of the European automotive industry.
- Revenues related to autonomous driving and connected cars are expected to boom (see *Figure F.42*), with safety applications (e.g. automatic collision detection/prevention) expected to reach USD58 billion (up from USD18 billion in 2017), autonomous driving (e.g. distance/park/ motorway assistant, pilot, traffic sign detection/ recognition) set to reach USD55 billion (up from USD14 billion in 2017) and connected services expected to reach USD43 billion in 2022 (up from USD21 billion in 2017).

FORECAST GROWTH BY MARKET VS. EU GDP GROWTH

5 years compound annual growth rate



Forecast growth by market vs. EU GDP growth (Source: Goldstein Research)

F.42

3.1.4
MAJOR CHALLENGES

The expected achievements of the research and innovation activities for Horizon Europe on KDT for mobility (i.e. the fields of embedded AI-based software, sensor, electronics and photonics components, and systems) will be reached in cooperation with the 2Zero and CCAM programmes. The latter two will incorporate the KDT results into new CO_2-neutral vehicles, trains and airplanes to enable safe, reliable and inclusive mobility. The joint goals of these three programmes are as follows:

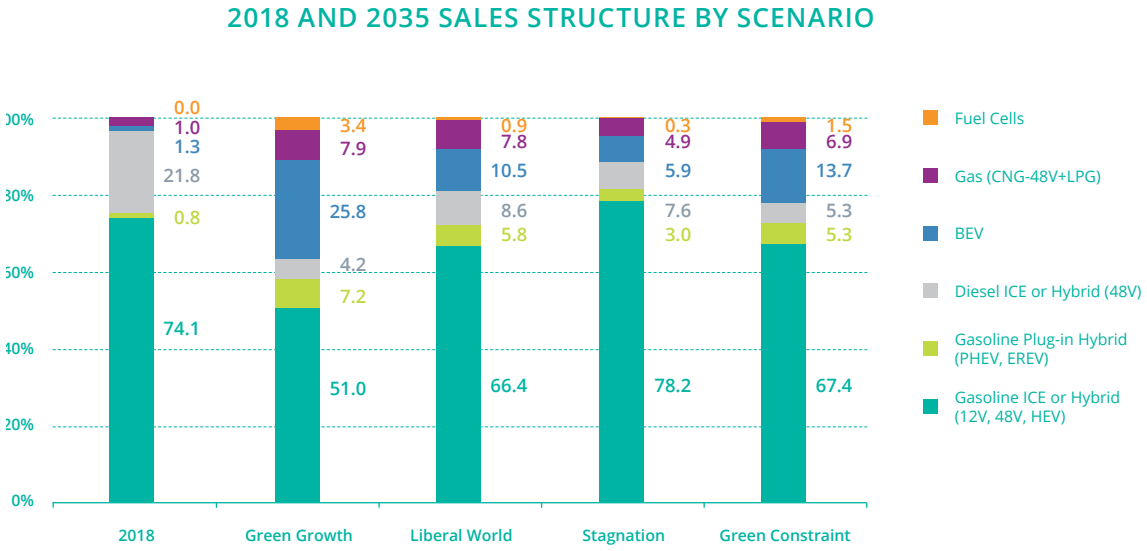
- Digital innovation to achieve the Green Deal for mobility with the 2Zero goals of –37.5% CO_2 by 2030 versus 2021 (according to the Worldwide Harmonised Light Vehicle Test Procedure, WLTP) and zero emissions in cities by 2040, and zero net emission by 2050 by providing the KDTs in, for example, the reduction of power electronics costs by 40% while increase power density per litre by 500% until 2035.
- Digital innovation to increase road safety (by providing the KDTs to the CCAM programme) in reducing the number of road fatalities and accidents caused by human errors to zero by 2050, as well in ensuring that no additional road fatalities are introduced by automated transport while bringing validation costs down by 50% of development costs from the current 70–80%.
- Digital innovation for the inclusiveness of mobility in ensuring inclusive mobility for persons and goods by providing mobility access to everyone, with a focus on special needs reaching 90% of the EU population (as opposed to the current 60%) from assisted vehicles by 2050 as targeted by CCAM.

- Strengthen competitiveness of the European industrial mobility digitalisation value chain by protecting global technological leadership and supply chain consistency in the automotive sector, ensuring long-term growth and jobs.

3.1.4.1 Major Challenge 1: enable electrification and sustainable alternative fuels for CO_2-neutral mobility

3.1.4.1.1 Status, vision and expected outcome

Worldwide efforts on the regulation of pollution and CO_2 emissions are leading to a strong increase in the electrification of vehicles, either with batteries ("battery electric vehicles", BEVs), "hybrid electric vehicles" (HEVs) with petrol or diesel engines, or using fuel cells. Possible scenarios developed by BIPE in France are shown in Figure 44. Depending on the evolution of regulations in particular, the split could be significantly different between the various technologies. However, the most probable scenario is that of the "Green Constraint". But currently there are discussion about bans of fossile fuel engines even as soon as 2035, therefore the data are expected to change.



F.43 *Sales structure of cars 2018 and 2035 (4 scenarios) (Source: PFA France 2018)*

Looking in more detail at the difference between low voltage systems (particularly 48V) and high voltage systems, there are six important observations that can be made:

- All new cars in Europe will be electrified by 2035.
- The proportion of electrified cars in the world will reach about 70%.
- Low voltage systems will take about 60% of the market, with high voltage the rest.
- Around one-third of the market will require on-board chargers for high voltage in the range 400–800V.
- Fuel cell electric vehicles will still play a minor role by 2035, although their overall share in terms of absolute numbers might reach about 1.5 million cars per year worldwide.

- The major application of fuel cells will most likely start in truck and train applications, as well as in airplanes, ships and drones.

The expectation is that the overall electrification scenario will lead to massive changes in the supply chains and the distribution of competences. In the field of power electronics, Europe is now in an excellent position and its industry needs to organise itself to ensure it benefits from the opportunity.

3.1.4.1.2 Key focus areas

- Low environment impact of new technologies in terms of energy consumption at production, deployment, use and end of life treatment.
- Reduction of sensible materials such as rare earth materials.
- Recyclability.
- New control software is required to take full advantage of new solid-state batteries so that they have an extended lifetime, as well as their driving range in vehicles. As lifetime is key for batteries used in mobility systems, tools for accelerated lifetime testing, diagnostic systems as well as control systems that can extend the lifetime and limit degradation are essential for the success of electrified green mobility. New power electronics based on silicon carbide (SiC) and gallium nitride (GaN) devices are needed to ensure energy-efficient operation. AI and model-predictive control algorithms, supported by high-performance, multi-core, real-time operating systems, has to offer the necessary intelligence based on ultra-low power/high-performance control units. 1.4 2.1
- Similarly, advanced control methods for fuel cell-based vehicles (mainly in trucks and buses) that both minimise degradation and maximise efficiency are crucial. For example, predictive control schemes that take into account forecasts on e.g. route, traffic, weather, etc. are necessary. State-of-health monitoring systems (virtual sensors) as well as adequate new sensors to measure the operating conditions within fuel cells without negatively influencing their operation are required. Of equal importance are dynamic test systems that allow to predict fuel cell / battery degradation and optimise their lifetime and efficiency. Such systems will be new essential base components from KDTs. Over-the-air update strategies to improve degradation models (based on real driving data) and also optimize the vehicle operating strategy allow to implement e.g. adaptive energy and thermal management strategies which will extend component lifetime. 1.4 2.1
- For both electric battery and fuel cell-based mobility, new safety concepts using (AI-based) IoT diagnostics must ensure the safety of these systems, especially in accident situations.
- Efficient and fast charging and filling of alternative energy into green vehicles is another critical research topic.
- The conversion of renewable energy into green energy as electricity stored in vehicles or H_2, or alternative fuels, also need efficient electronics with real-time embedded software communication with the power grid to minimise the need of new charging/filling infrastructure, which is one of the cost drivers limiting the speedy success of green mobility. 3.2
- Smart Battery: with the batteries in electric vehicles being the most expensive and life-time critical parts, future battery systems will be equipped with sensing technology, intelligence and communication systems to monitor their own health and record their lifetime dataset. This enables better usage of the batteries as well as optimized second life concepts.

3.1.4.2 Major Challenge 2: enable affordable safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, drones, etc) and mobile machinery (as smart farming)

3.1.4.2.1 Status, vision and expected outcome

Digital innovation is key to ensuring inclusive mobility for persons and goods by providing mobility access to all, with a focus on special needs, by reaching 90% of the EU population compared to the current 60%. As targeted by CCAM, this can be achieved through assisted vehicles by 2050.

By 2050, 67% of the population is expected to live in urban areas. As cities become bigger and smarter, this trend will lead to new opportunities for tailored and specialised vehicle design specific to urban users, including the needs and operations of commuters, as well as ride-hailing and last-mile delivery.

New vehicle concepts and ECS-enabled architectures should lead to flexibility, scalability, and modularity - while featuring safety, security and reliability - to ensure urban-readiness (appropriate range, compatibility with charging infrastructures, ease of parking and operations, etc) in all kinds of urban and suburban areas, most likely with different implementation levels of infrastructure and smart technologies. Additionally, it is assumed that these vehicles will not have to be designed for high-speed operation and long range and can easily be charged sufficiently fast and comfortably to meet the daily needs of urban and suburban mobility usage scenarios. This aspect may also include sharing concepts, and consideration should also be given to use by the elderly and disabled.

Targeted vehicles will cover small and light land vehicles (road/off-road), but also air and water vehicles. These will all follow the design principles of tailored ECS solutions and right-sizing for their objectives. In addition, they should satisfy performance key targets such as improved efficiency during usage (e.g., using low power electronic components, smart materials or appropriate control strategies based on data from traffic flow monitoring or prediction systems) towards zero emissions, as well as integration into the mobility plans (mobility and transport as a service) of the respective areas of operation. This will be facilitated by more effective use of parking spaces, scheduling and possibly decreased congestion, including demands arising for mobility and logistics across functional urban boundaries (e.g., urban to suburban). The implementation of sensors, electronic control units and control strategies for advanced driver assistance will enable the improvement of safety, comfort and quality of life during transportation.

Another important aspect is the need for reliable and efficient wireless communication technology to achieve efficient traffic and increase safety as well as reduce fatalities. This further set requirements on components and systems for wireless communication to achieve ultra-high reliability and resilience as well as to meet challenging performance and latency demands.

2.2

The challenge particularly targets the following vehicle categories:

- Motor vehicles with less than four wheels (L category).
- Vehicles having at least four wheels and used for the carriage of passengers (including light four-wheelers, M1/M2 category).
- Power-driven vehicles having at least four wheels used for the carriage of goods (N1), agricultural and forestry tractors, and non-road mobile machinery (T).
- Off-road vehicles (G).
- All kind of unmanned air vehicles (such as drones).
- All kind of manned light air vehicles.
- Special-purpose light vehicles (air, land, water).
- Self-cleaning cars (e.g. electrical ozon generation for cleaning purposes, bacteria sensors...).

This will have the following impact on European society:

- Urban light personal and freight mobility: the success of vehicles such as monowheels, electric scooters and drones suggests it would be useful to explore innovative micro-vehicle designs suitable for urban/suburban commuters' needs, with the option for usage within shared mobility schemes. Such micro-vehicles would also be capable of interfacing with urban collective transport systems (i.e. easy access to buses, trams and trains for last-mile transfers to achieve full intramodality).
- Light and flexible multi-passenger vehicles (e.g., collective or individual, owned or shared up to M1 category) with robust safety measures for passengers and vulnerable road users, and including specific features to facilitate shared use such as autonomous-capable vehicles with automated relocation to charging points or areas with insufficient vehicle density.
- Right-sized vehicles and tailored ECS for commercial uses, such as for last-/first-mile delivery, construction and maintenance support, which are suitable for urban scenarios. These types of vehicle will benefit local air quality and offer rapid implementation due to their holistic and design-for-purpose approach.
- Increased acceptance of single-purpose design ECS-enabled vehicles is expected due to the physical demonstration of their feasibility (both technical and economical) with equivalent or superior performance, upgradeability and operational safety in relevant environments, particularly for light and flexible transport.
- Connected and automated mobile machinery to optimise harvesting and reduce accidents.
- Real driving testing to demonstrate the ambitious targets of up to 10% energy-efficiency improvement compared to the existing solutions for the same vehicle classes.
- Interoperability between land, air and water vehicles in terms of ECS solutions and ECS trustworthiness (safety, security, availability, connectability, resilience).

3.1.4.2.2 Key focus areas

The key focus areas are:

- Modular, flexible and scalable platforms and electrical/electronic (E/E) architectures.
- Reconfigurable and adaptable software architectures.
- Hardware upgradability.
- Software updateability (including over-the-air, OTA).
- Embedded intelligence:
  - Control software, real-time capable algorithms.
  - Fault-tolerance, fail-operational concepts.
  - Cognitive vision
- On-board technologies (devices, actuators and sensors, virtual sensors).
- Power electronics (fast-switching elements, wide bandgap materials, low power, etc).
- Predictive diagnosis and maintenance (including recovery strategies, fault detection and localisation, surveillance sensors, etc).
- Cloud/edge/fog processing approaches.
- AI-powered and AI-enabled intelligence.
- Distributed logistics systems for smart farming, movers and shuttles.
- Standards, including communication and interoperability standards, electromagnetic spectrum and bandwidth management, charging units, car access systems, etc.
- Reliable and human-like perception systems.
- Tailored ECS-enabled solutions for disabled people (supporting robots, smart wheelchairs, etc).
- Proof of robustness and trustworthiness of architectures and quantification of the operational risks.

1.2 1.3
2.1
2.2

- Collaborative and self-organised multi-agent systems, e.g., in logistics applications also covering cooperation between land and air vehicles.
- Bio-inspired transport solutions and systems

1.4

3.1.4.3 Major Challenge 3: enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water

3.1.4.3.1 Status, vision and expected outcome

The European transportation industries have to strengthen their leading position to provide sustainable solutions for safe and green mobility across all transportation domains – automotive, avionics, aerospace, maritime (over water as well as under water transport) and rail. Their competitive asset is well-established expertise based on developing complex electronic components, cyber-physical systems and embedded intelligence. Nevertheless, a number of challenges in terms of autonomy, complexity, safety, availability, controllability, economy and comfort have to be addressed to harvest the opportunities coming from increasingly levels of automation and related capabilities.

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

1.4 2.4

One of the key motivators is to reduce the number of road fatalities and accidents caused by human error to zero by 2050, as well as in ensuring that no additional road fatalities are introduced through automated transport while bringing validation costs down to 50% of development costs from the current 70–80%. Key Digital Technologies will be developed to support the CCAM public/private partnerships (PPPs) in these ambitious goals. No single organisation will be able to capture these tremendous efforts in research and development. For Europe to maintain a leading position, it is therefore necessary to establish collaborations in and across industrial domains, learn from operational field data, and jointly drive the required strategic actions.

Also, in the waterborne transport sector ships will become fully connected across the globe. Remote monitoring of vessels is already possible, allowing for condition-based maintenance. Building on increasing onboard automation, the remote operation of vessels will become possible, eventually moving towards full autonomy for vessels. The wider use of unmanned autonomous vessels (UAVs) – either aerial, underwater or on the surface – will increase the flexibility and energy efficiency of operations.

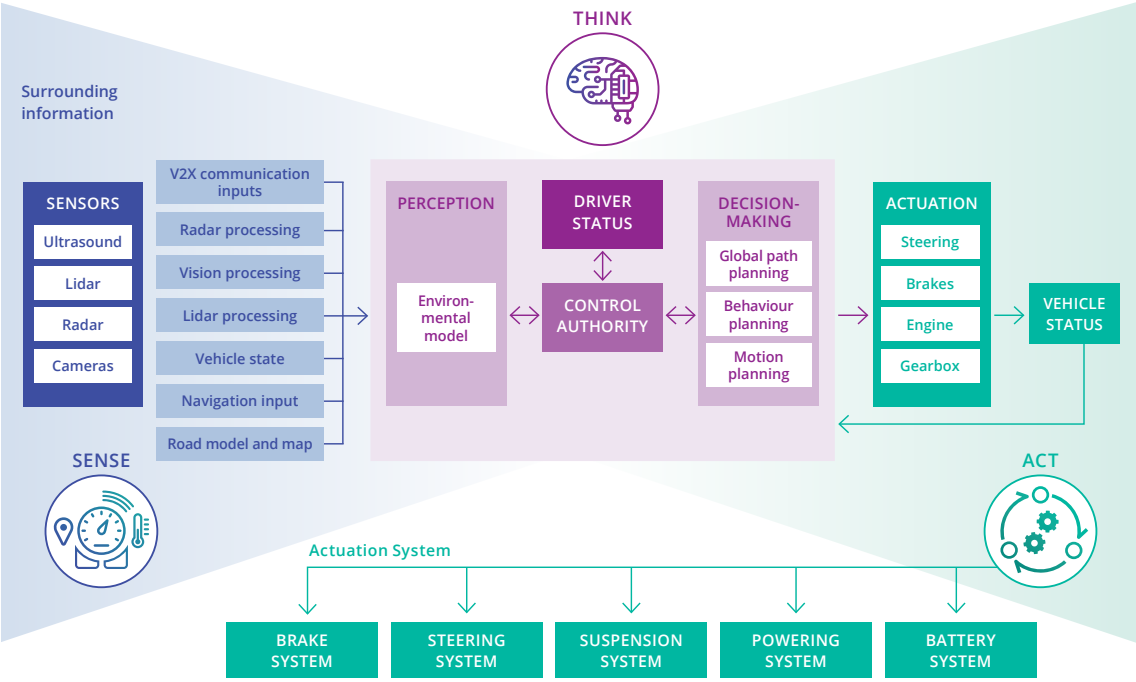
1.4 2.2

Connected, cooperative and ultimately automated mobility and transportation is seen as one of the key technologies and major technological advancements influencing our future quality of life. KDTs will enable different levels of partial, conditional, highly and fully automated transportation, posing new challenges for traffic safety and security in mixed scenarios where vehicles with different automation levels coexist with non-automated vehicles. Both development approaches – evolutionary (the stepwise increase of automation level: “conversion design”) and revolutionary (Society of Automotive Engineers, SAE, level 5: “purpose design”, e.g. a people mover in a structured environment) – should be covered, as well as cross-fertilisation with other industrial domains such as Industry 4.0. X-fertilization between automotive and 5G evolution and 6G is important to ensure a reliable and resilient communication needed in next generation mobility as described before.

As the proportion of electronics and software as a percentage of the total construction cost of a vehicle increases, so does the demand for the safe, secure, reliable and unhackable operation of these systems. In addition, privacy protection is a key element for car owners and drivers/operators. These requirements demand fail-operational technologies that deliver intrinsically safe operation and dependable fall-back position from component to subsystem, and provides a solution for problems in interaction with the cloud. This requires new developments in terms of multi-core-based platforms and sensing devices, combining advanced sensing in harsh conditions, novel micro- and nano-electronics sensors, advanced sensor fusion and innovative in-vehicle network technologies.

1.2 1.3 2.4

Key elements of KDTs for cars that need to be developed are shown in *Figure F.44*.



KDT components of automated vehicle **F.44**

3.1.4.3.2 Key focus areas

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

- Dependable and affordable environment perception and localisation sensors, and V2X communication. Attention should be paid to sensor interference, more in particular the robustness of sensors to environmental conditions, to interference by other sensors and to malicious interference.
- Centralised service/function-oriented hardware/software architectures, including open APIs, for vehicles, ships, trains that are supported by the cloud and edge computing via 5/6G.
- Dependable and reconfigurable hardware and software, including remote access and Over-The-Air (OTA) software upgrades.

1.4 2.2 2.4

- Hardware and software platforms for control and higher performance in-vehicle networking (up to 25Gbit/s) units for automated mobility and transportation (including support for AI) – e.g. IoT integration platforms for automated and connected environmentally friendly vehicles. 1.4 2.3
- New developments towards higher performance and efficiency. These are also required to ensure the reliability and safety of the power electronic components and systems for the drivetrain and charging systems, as well as for steering, break/suspension/air condition control in automobiles, trains, ships and flying equipment.
- Trustworthiness of vehicles' data. 2.4
- Interaction between humans and vehicles.
- Active safety systems.
- Vehicle hardware/software to improve comfort in parallel with safety.
- (Predictive) health monitoring and lifetime analysis for the perception and control systems (including all required sensors, V2X systems and localisation systems) and AI components of (highly) automated vehicles used in the operational phase.
- Connected maritime systems and automated transport.
- Smart and autonomous ships.

3.1.4.4 Major Challenge 4: provide tools and methods for validation and certification of safety, security and comfort of embedded intelligence in mobility

3.1.4.4.1 Status, vision and expected outcome

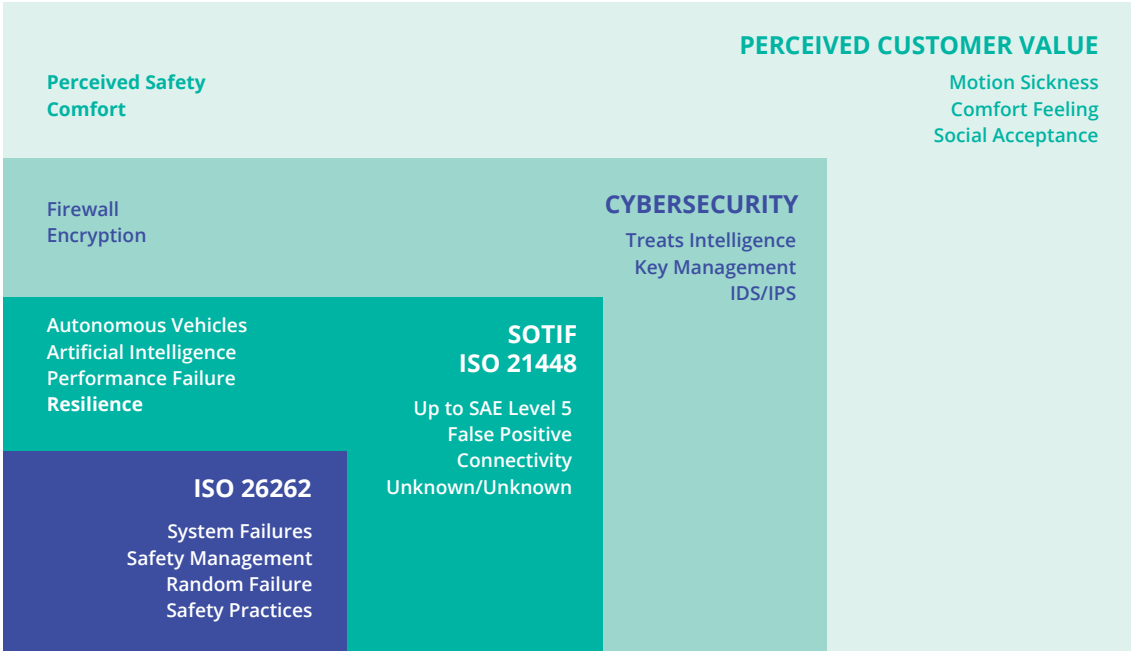
To achieve the EU-wide goal of zero fatalities by 2050, active safety systems and automated vehicles are necessary (the term "vehicle" here covers mobility systems on land, water and in the air: cars, trains, ships and airplanes). Although several technology demonstrators for highly automated vehicles already exist, there is a severe lack of cost-effective, commonly accepted verification & validation (V&V) methods and tools. Winner et al predict that more than 400 million km of road driving would be required to statistically prove that an automated vehicle is as safe as a manually driven one, implying that a proven- in-use certification by performing physical tests on the road is no longer feasible. This lack of effectively applicable V&V methods has created a major barrier for the market introduction of these systems. Meanwhile many experts in Europe as well as in many other countries of the world work together under the guidance of UN/ECE to create standards for the approval of ADAS and AD functions in mobility. The draft of the Regulation (EU) 2019/2144 for ADAS function is about to be approved and contains definitions for the expected functionality of many ADAS functions as well as first indications how to prove them. The associated ADAS and AD functions are Lane Departure Warning System, Advanced Emergency Braking on Heavy Duty Vehicles, Speed Limitation Devices, Reversing Detection, Pedestrian and Cyclist Collision Warning, Blind Spot Information System, Emergency Lane Keeping System, Advanced Emergency Braking on Light Duty Vehicles, Protection of Vehicles against Cyber Attack, Intelligent Speed Assistance, Emergency Stop Signal, Alcohol Interlock Installation Facilitation, Driver Drowsiness and Attention Warning, Driver Availability Monitoring System, Event Data Recorder, Systems to replace driver's control; Systems to provide the vehicle with information on state of vehicle surrounding area and Platooning.

The main challenge is the tight interaction of these safety-critical automated systems with their environment. These interactions get more complex the higher the automation level gets. This means that not only does the correct functioning of the automated cyber-physical mobility system itself need be tested, but also its correct reaction to the behaviour and specifics of its surroundings. This leads to a huge number of potential 1.4 2.3

scenarios that every automated mobility solution will have to handle in a safe way. It is important to take into account not only the commonly occurring scenarios encountered by the mobility systems as vehicles, trucks, airplanes, ships et al, but also the occurrence of safety critical events during these scenarios. Many of these safety critical events fortunately do occur only seldom, but that makes it even more difficult to test the correct reactions of the automation systems in these situations.

Many highly automated cyber-physical systems have adopted machine learning (ML) and AI to enable autonomous decision-making and render applications smart. While the use of ML and AI components offers great promise for improving our everyday lives in many, sometimes unimaginable, ways, it also brings a host of very difficult verification, validation and certification challenges in the context of safety- critical applications. The opacity of ML/AI components requires the development of completely new V&V techniques, and to accordingly extend existing V&V methodologies. It is important to not only secure stable solutions based on ML, but also how to exploit increased learning based on new data, and to update existing vehicles with updated algorithms using the additional learning from new data, while guaranteeing no side-effects.

2.1 2.3 2.4



Validation framework for automated vehicles (Source: AVL List GmbH)

F.45

Modern highly automated cyber-physical systems increasingly dynamically evolve after their deployment, and OTA updates and upgrades are becoming necessary in such systems. New methods and tools for these updates and upgrades, together with the respective re-verification and re-certification approaches, are necessary to avoid negative impacts on both safety and security.

Automation functions of vehicles rely on environment sensors, such as cameras, lidar, radar and ultrasonic sensors, as well as communication to other vehicles or infrastructures. As these safety relevant components may degrade over time or be exposed to cyber-threats, accelerated reliability and cybersecurity test methods are required. This will need further diagnostic devices to check the reliability of hardware, sensors and their software.

The role of the driver and any additional passengers in an automated vehicle is completely changing, and therefore new test methods and tools are necessary to ensure comfort and perceived safety (societal acceptance). These are already in the early development phases in terms of new functionality and their safety.

Many of the above issues are mentioned in existing or upcoming automotive standards for cyber-physical systems – for example, Safety of Intended Functionality (SOTIF), ISO 26262 and UL4600 (see *Figure F.45*). As none of these standards are mature enough to certify fully automated vehicles with reasonable effort, close cooperation between the standardisation committees and the research consortia will be necessary.

The expected outcome is twofold:

- Digital innovation to increase road safety as specified in the CCAM programme: reduce the number of road fatalities and accidents caused by human errors to zero by 2050, as well as ensuring that no additional road fatalities are introduced by automated transport.
- Reduce validation costs down from the current two-to-five times of the implementation of automation functions in mobility by 60–80%.

3.1.4.4.2 Key focus areas

To ensure the safety, security and comfort of automated mobility systems consisting of embedded AI-based software, sensors and actuators, as well as processing platforms in vehicles, ships, trains, airplanes and off-road vehicles, several verification, validation and certification toolchains are necessary. These should ensure the safety, reliability, security and comfort for passengers and the surrounding traffic participants based on costs that do not exceed those of the design and implementation of the following functions:

- Verification of components of automated mobility systems as environment sensors/communication systems, perception systems, environment awareness, route planning and actuator systems, diagnostics devices and black-box monitoring systems. A special case here is the use of consumer-grade components in vehicle automation. Test concepts and tools have to be developed on several levels:
  - Perception system tests focusing on an adequate functionality of sensors and the fusion of several sensor inputs.
  - Manouver planning route decision and track control systems testing.
  - Complete automated vehicle, airplane, ship etc. all in the defined operating environments (ODDs).
  - Correct and secure communication with other traffic participants and/or traffic operators.
- Validation of complete automated vehicles to perform safely and securely, and to provide comfort for passengers as well as other traffic participants in the specified operation design domain (geolocation area, weather conditions, road/sea/air conditions, etc).
- Validation of the reliability of all components as well as their interaction as a complete automated cyber-physical system in the specified operation period.
- Validation of the safety, security, reliability and comfort for the deployment of OTA update packages for automated on-road or off-road vehicles, trains, ships and airplanes.
- Verification of the completeness and reliability of training datasets for machine-learning and AI algorithms used in automated cyber-physical systems.
- Validation of the accuracy of simulation models in the specified operational design domain (ODD) used in virtual validation toolchains.

Validation toolchains, their components and underlying methods should lead to safe, reliable and secure argumentation describing why the performed tests resulted in the estimated residual risk for automated

cyber-physical systems for on-road or off-road vehicles, ships, trains and airplanes. Optimisation methods can be used to balance multiple design objectives – e.g. that the residual risk remains below a certain limit (such as that stipulated by regulatory bodies) while meeting financial design targets. The verification, validation and certification tools and methods may be used for cyber-physical systems with different levels of automation.

A special focus is on the verification, validation and certification of embedded AI-based systems, and the required training data for the respective machine-learning algorithms. Ecosystems for the creation and maintenance of reliable labelled data are envisioned. To integrate with different legacy systems, eco-systems supporting open platforms are required.

2.1 2.3

Virtual validation, or more concretely scenario-based virtual validation, is considered a cornerstone for the verification, validation and certification of vehicles. Two aspects are essential here: (i) scenarios representing the most relevant situations; and (ii) reliable simulation models.

Scenarios may be derived from requirements of safety analyses, extracted from naturalistic driving or synthetically created using gaming theory-based methods with a defined relevance. Statistical safety evidence from scenario-based verification and validation derived from naturalistic driving is needed. Also, here the establishment for open platforms and ecosystems for the creation and maintenance of reliable scenarios is encouraged. The definition of performance (safety, security, reliability and comfort) indicators for different automation functions and SAE levels (in the case of road vehicles) is necessary. Again, eco systems to share these data are useful.

Reliable simulation models for environmental sensors, vehicles, drivers and traffic participants, as well as traffic, are vital. The development of these models, and the corresponding test systems, are essential. To test safety-critical scenarios using real vehicles in a safe environment requires the creation of stimulators for the different environmental sensors under different weather, traffic and road conditions. The verification, validation and certification of vehicles will be carried out with a combination of virtual test environments using model-in-the-loop (MIL) and software-in-the-loop (SIL) in the cloud with massive parallel processing in order to allow for testing of very high numbers of scenarios in combination with different critical events and varying ODD conditions as sun, rain, fog, snow etc., mixed virtual/real environments (vehicle-in-the-loop, VIL, and hardware-in-the-loop, HIL), as well as a proving ground for real-world public road testing. Road testing will result in amounts of data larger than 20TB per hour per vehicle, and therefore adequate data acquisition, management and (cloud or on-premise) evaluation systems capable of handling the specific data types of the sensors are critical (although these do not exist yet). Additionally, OTA data collection from in-use operations is required to continuously collect unknown scenarios that can be fed back into development to improve the quality of the systems.

2.3 2.4

Additional challenges covering this topic can also be found in Chapter 2.3 (Architecture and Design: Methods and Tools) and Chapter 2.4 (Quality, Reliability, Safety and Cybersecurity) of this SRIA.

3.1.4.5 Major Challenge 5: achieve real-time data handling for multimodal mobility and related services

3.1.4.5.1 Status, vision and expected outcome

To help provide better health and quality of life for their citizens, European municipalities will continue to ban cars with conventional powertrains from city centres, and promote more equal urban land use. At the same

time, the demand for individual accessibility, flexible transit and fast delivery is on the increase. Therefore, multimodality is a cornerstone of the EU's strategy on transport. This combines collective and individual solutions, ranging from micro-mobility such as e-scooters via car-sharing and ride-pooling fight up to long-haul transport systems through common hubs, platforms and systems for booking, customer services and payment. In the future, Europe will also aim to offer more sustainable and systemic transport solutions besides road transport, such as high-speed rail or electric aircraft. Concurrently, limited peak capacities, missing last-mile connections and self-contained mobility-as-a service systems will remain somewhat of a bottleneck when it comes to shortening travelling times, keeping supply chains clocked, and reducing single occupancy trips, with the accompanying reductions in congestion, environmental concerns and cost of travel. Therefore, sharing services are the key element to maximising the flexibility of public transport systems, and new technologies such as taxi and delivery drones or guided transport (hyperloop) solutions can be expected to fill the gaps in the time, cost and green environment map.

Recent events such as the Covid-19 pandemic but also natural disasters have put some elements of this quite systemic future vision in question. Public transport, as the cornerstone of a multimodal mobility system, is particularly affected as the desire for readily available, trustworthily hygienic and health-protecting ways of getting from A to B became paramount. And, highly connected and infrastructure-based mobility solutions show limited resilience against flooding and wildfires. It will remain a challenge for mobility service providers to develop and deploy novel solutions, such as self-sanitising and protective mobility shells (physical or virtual), for a vulnerable society that combine the flexibility of a multimodal system with the required infection safety and provide a CO_2 and emission neutral mobility at the same time. The same applies to make autarkic heavy vehicles and machinery for rescue and clean-up operations zero-emission. In another sense, multimodal mobility could also mean putting services and deliveries on wheels, which so far would have required people to travel to places where they risk being exposed to the virus. And, having robotic functionality, ad-hoc networking capabilities and a battery as mobile electricity source on a tractor might provide just the right level of resilience that will be needed future emergencies, and make full use of the opportunities of automation, connectivity and electrification in a new way.

As pointed out by the EU-funded Coordination and Support Action "Action Plan for the Future of Mobility in Europe"[119], the vision of a truly integrated and seamless transport system for people and freight must be developed and implemented, and the full potential of transformative technologies has to be exploited. This can only be achieved if user-centredness, cross-modality and technology transfer become the focus of efforts for all stakeholders in transport.

3.1.4.5.2 Key focus areas

- Design a low/zero emission, safe and accessible transport system tailored to user needs by exploring user needs and expectations, defining user profiles and mobility patterns, and identifying technology options.
- Enable mobility everywhere for everyone through the technological development of, for example, sensors, AI, machine learning, predictive maintenance, safe and secure vehicle software and electronics.
- Enhance efficiency and capacity in rail projects for automated maintenance and transfer of goods between modes.
- Create intelligent decision-support systems for passengers and transport operators that enable smart travel demand management.

119 Mobility4EU, www.mobility4eu.eu

- Achieve real-time data handling for multimodal mobility and related services.
- Develop convenient sharing concepts through automated maintenance of vehicles, and define approaches for implementation.
- Develop a framework for cybersecurity in passenger and goods transport across all modes, and provide IT connectivity that allows plug and play data sharing.
- Increase data security and privacy in authentication and payment processes for mobility services (through the concepts of trustee roles, blockchain, etc), and support the respective initiatives. 1.4 2.4
- Employ robots, drones and shared public transport services for logistics.
- Infection-risk detection, self-sanitising and protective functions for public transport use.
- Multimodal navigation systems providing travellers with efficient, safe and healthy transfer options.
- Development of modular mobility platforms for the on-site provision of services and goods delivery.
- Integrate cross-modal hubs and interfaces into the urban structure, and connect them by harmonised infrastructure to smart sustainable corridors. 1.4 2.3
- Provide open application programming interfaces (APIs) and user data and statistics for all modes and providers, enabling demand-oriented and demand-responsive cross-modal transport offers.
- Ensure accessibility of shared services, and incentivise shared fleets of personal mobility devices at hubs to facilitate mode change for those with disabilities and reduced mobility.
- Hygienic and individualized mobility shells for demand-responsive transportation means.
- Make vehicles and transportation systems more resilient by smart application of automation, connectivity and electrification .

3.1.5 REQUIREMENT OVERVIEW

In addition to the availability of technology, components and systems as described in other parts of this document, it is important that a number of societal needs are met, particularly the following:

- Legislation for automated vehicles throughout Europe: some initial pilot sites have been identified, but an overall legislative framework is required to achieve full deployment of highly automated driving (HAD). To date, there has been no regulatory approach to define a security/privacy framework for the IoT that involves billions of identities and devices being connected with each other. Technological stakeholders and the political arena have to share findings and derive recommendations to EU's and national regulatory bodies concerning the minimal regulatory framework needed to assure the security and privacy of citizens and companies.
- Social acceptance of the technology by citizens and users: society (governments, media, press, citizens, educational institutes, etc) has to be prepared for the introduction of some of this technology (such as by human factor-based questionnaires) and their thinking monitored to help define what actions can be taken on how new technologies and related services can be more easily accepted.
- It is crucial that future systems meet the expectations of end users, and that their underlying technology and platforms can be operated by service providers with appropriate business models; end users will expect flexible, reliable and cost-efficient services that can be personalised

for them. For both end users and service providers, GDPR compliance is essential to ensure maximum transparency and user acceptance.

Some examples of attention areas are:

- Evolving from regional/national policies to a European-wide supported common policy with respect to HAD.
- Evolving from regional/national pilot test sites to European-wide deployment.
- Ensuring privacy protection in connected cars, and how this should be communicated to citizens.
- Ensuring business perspectives for MaaS operators, seamless mobility to end users and the reduction of emissions and urban congestion.

3.1.6 TIMELINE

The roadmap for the key digital technologies in mobility are aligned with European roadmaps for terrestrial, water and aerospace transport:

- A new European Road Transport Research Advisory Council (ERTRAC) roadmap entitled sustainable Energies and Powertrains for Road Transport – Towards Electrification and other Renewable Energy Carriers".
- Urban mobility roadmap.
- Long-distance freight transport roadmap.
- Towards zero logistics emissions by 2050.
- The joint European Technology Platform (ETP) common paper published in 2019.
- The European roadmap on connected and automated driving published in 2019.
- The Joint Strategic Research Innovation and Deployment Agenda (SRIDA) for the AI, Data and Robotics Partnership (euROBOTICS), September 2020.

The roadmap combines the objectives in the application research programmes 2Zero and CCAM with the derived KDT mobility challenges. The following roadmap indicates when R&D&I activities are required to ensure the key digital technologies are available for use in the different mobility domains. In areas that already have ongoing electric mobility, the focus is more on improvements to existing concepts (for example, optimisation of costs), while for others (such as electric aircrafts) it is more about focusing on lower technology readiness levels (TRLs). These are both going on in parallel, and are also influencing each other.

This roadmap is a preliminary estimate in regard to when the KDTs will need to be ready for the various technology fields. It will be continuously updated as new domain roadmaps become available.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031

R&D&I TOPIC IN KEY DIGITAL TECHNOLOGIES FOR MOBILITY

1 – ELECTRIFICATION & SUSTAINABLE ALTERNATIVE FUELS FOR CO_2 NEUTRAL MOBILITY

1.a KDT for electr. passenger cars, electrified (short range) and fuel cell trucks

1.b KDT for H2 fuel cell passenger cars synthetic fuelled mobility

1.c KDT for CO_2-neutral energy optimised mobility (from cradle to grave)

2 – LIGHT MOBILITY (BIKES, TRICYCLES, WHEELCHAIRS, DRONES, ETC)

2.a KDT for electrified light mobility

2.b KDT for H2 fuel cell based light mobility

3 – ENABLE AFFORDABLE, AUTOMATED AND CONNECTED MOBILITY

3.a KDT for level 2, 2+ vehicles, remotely operated ships

3.b KDT for level 4 vehicles

3.c KDT for level 5 vehicles

4 – VALIDATION & CERTIFICATION FOR SAFETY, SECURITY AND COMFORT FOR AUTOMATED, CONNECTED AND CO_2-NEUTRAL MOBILITY

4.a KDT for validation and certification for level 2+ to 4

4.b KDT for validation and certification of level 5

4.c Validation and certification of integrated mobility

5 – ENERGY OPTIMAL MULTIMODAL MOBILITY

5.a KDT for urban and long distance energy mobility systems

5.b KDT for rural energy optimised mobility systems

5.c KDT for globally energy optimised mobility systems

3.1.7
SYNERGY WITH OTHER THEMES

Mobility is a domain that needs multiple key enablers, as described in other Chapters of this document. It is transversal to almost all chapters, from components to systems.

For instance, semiconductor technologies are evolving rapidly. In the past, silicon was the dominant material, but its performance is now being outpaced by wideband materials such as SiC and GaN. These materials allow reduced packaging, increased operation temperatures, higher switching frequencies and therefore new concepts of compact power electronics modules. This is a major disruption that changes the market for electric mobility.

Closely linked to these semiconductor technology updates are packaging technologies. Moving from standard industrial modules to full heterogeneous integration is the second major disruption. Only adapted packaging can permit the full exploitation of the benefits of such new semiconductor technologies.

1.1 1.2

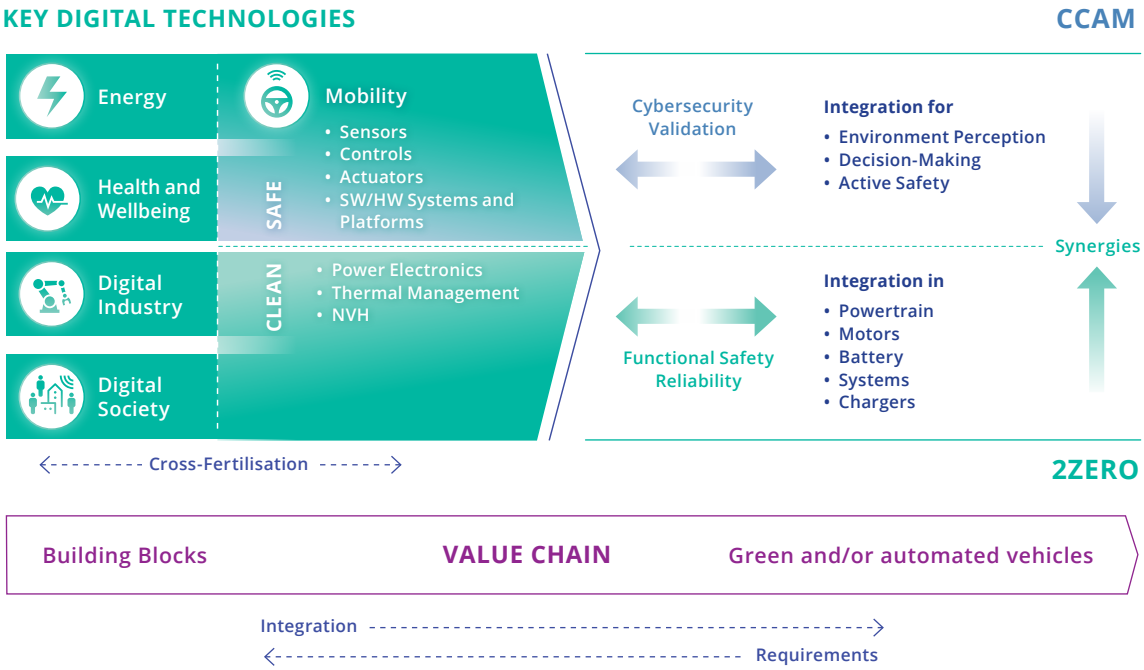
Other components that are of strategic importance are passives, such as capacitors and coils that can withstand higher temperatures and switching frequencies. For these, it is necessary to look at innovative materials that bring improved performance at a lower cost and a high rate of recyclability for the whole system.

A further aspect of mobility is the increasing level of automation, which is also having a huge influence on other in-vehicle components in the area of digital technologies for embedded software, AI, sensors, actuators and trustworthy communication. In this respect, there is a strong need for cybersecurity to protect cars, drivers and the environment. Remote access and OTA updates of rapidly improving complex software for the upgrade of car systems are therefore mandatory. This requires a safe, secure and available infrastructure in cities as well as rural areas.

1.3 1.4 2.1 2.4

This infrastructure includes 5G/6G communication to allow massive transfer of data to and from cars, which can be considered as “data-centers on wheels”. In the back- ground of such operations, a performant (and GDPR-compliant) cloud data system needs to support the mobility of each individual. The overall management of such an infrastructure should include smart grid operations to minimise energy waste and losses through inefficiencies, as is further elaborated upon in the Energy Chapter. It is clear that this requires system developments, from small sensor systems to micro and large grid control, including all aspects of cohabitation of modules and sub-systems. (electro- magnetic compatibility, EMC, and thermal considerations).

2.2 3.2



Synergies with European partnerships

F.46

It should also be noted that synergy potentials exist between the domains of safe and clean mobility, not just at the level of the application in a multimodal urban mobility system but also at the level of the enabling technologies. Examples include electronic architectures for fail-safe power distribution and control within the vehicle, the functional safety and reliability of systems and cybersecurity, and control in power systems. Additional alignment is already in progress with existing or planned programmes for rail (Transforming Europe's Rail System), maritime (Zero Emission Waterborne Transport) and aerospace (Clean Aviation).

3.2

ECS Key Application Areas

ENERGY

3.2.1 SCOPE

3.2.1.1 Change towards the carbon neutral society and challenges for ECS

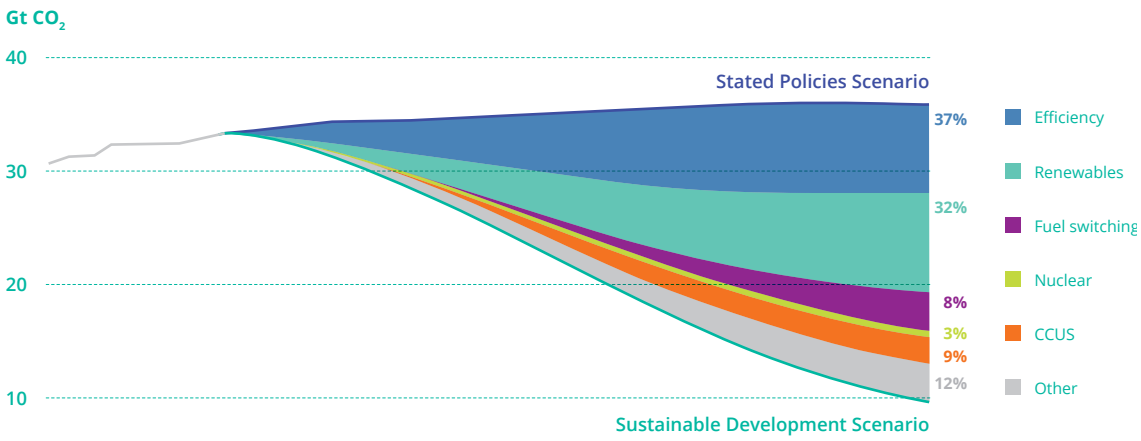
For the first time, the year 2020 marks a crucial milestone within the European transition to clean energy. The renewable energies (solar, wind, hydro, bioenergy) became the main source of electricity and thus, overtook fossil-fired generation. Energy systems *supplying clean, affordable and secure energy* are in the focus of *The European Green Deal*. Although progress is made, the power sector must further be transformed from fossil fuel based to renewable generation and, at the same time, needs to grow in order to enable decarbonization of mobility, industry, and thermal energy supply and reach the climate targets of 55% greenhouse gas reductions by 2030. Because of the increasing residual load resulting from the local mismatch between decentralized renewable generation and load, a digitally controlled transmission and distribution infrastructure is required. Thus, electronic components and systems (ECS) are key to future energy systems being optimized in both, design and operation, for high efficiency, low CO_2-emissions, cost, and security of supply. The development of energy systems is driven by action against climate change, booming decentralized renewable generation (solar, wind), digitalization and AI technologies, as well as cyber security issues.

The Energy Chapter highlights the Major Challenges in the changing energy landscape more and more based on electrical energy generation, supply, conversion, and use. Highest efficiencies and highly reliable, secure solutions are required to achieve the change towards a carbon neutral society in 2050.

3.2.2 APPLICATION TRENDS AND SOCIETAL BENEFITS

3.2.2.1 Application trends

ENERGY-RELATED CO_2 EMISSIONS AND REDUCTIONS BY SOURCE IN THE SUSTAINABLE DEVELOPMENT SCENARIO



F.47 *Efficiency and renewables provide most CO_2 emissions reductions. Source: IEA World Energy Outlook 2019.*

At present, 75 percent of total greenhouse gas emissions in the EU comes from the energy sector. The energy world is undergoing a radical transformation: promoted e.g. by EU and national roadmaps, the global installed capacity of renewable generation has doubled within the past 10 years. This increase is dominated by wind and solar energy being characterized by strongly intermittent, distributed generation. Altogether wind and solar energy made up one fifth of Europe's electricity generation in 2020, with plant capacities ranging from domestic solar (≤ 10 kW) via commercial solar and wind (≤ 500 kW) to power stations at utility scale (≥ 1 MW). At the same time, the levelized cost of electricity (LCOE) from photovoltaic (PV) sources dropped by factor 10. However, the rise of renewables is still too slow - wind and solar generation growth must nearly triple to reach Europe's 2030 green deal target. In the long term, it enables the substitution of fossil fuel-based transportation, domestic heating, and commercial & industrial processes as well as address the strong economic growth of non-OECD countries. Since the pursuit of all economically viable opportunities for efficiency improvement can reduce global energy intensity by more than 3% each year, increasing energy efficiency may be accountable for 37% CO_2 emission-reduction by 2050 (*Figure F.47*), which is in line with the new EU 2030 Green Deal target. Energy supply to all sectors affordably and reliably (reliability, resilience) needs to match the demand (availability) as efficient as possible (energy & resource efficiency).

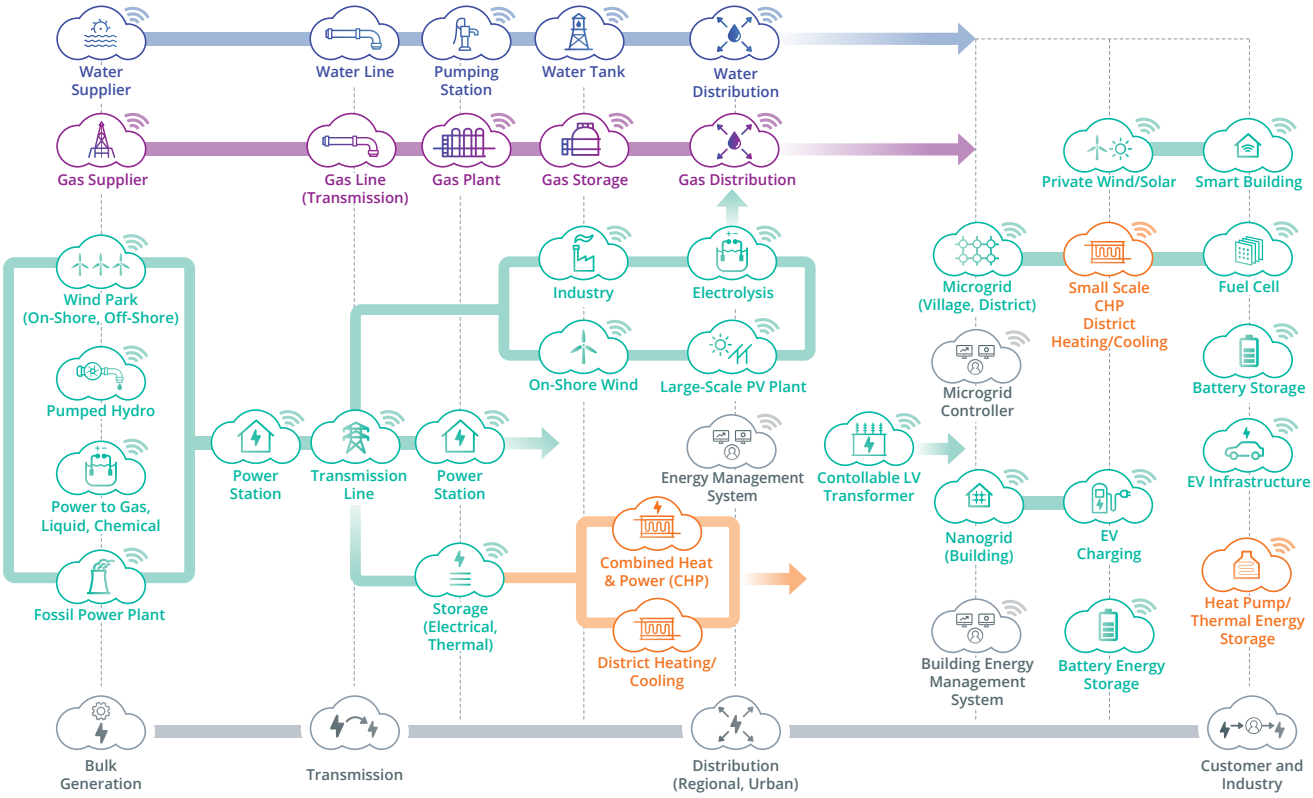
Thus, the power grid architecture developed for centralised, demand driven power generation will be transformed into a multi-modal energy system (MM-ENS) architecture (*Figure F.48*). It will comprise distributed renewable generation, energy conversion units for sector coupling, transmission and distribution grids allowing bi-directional power flow, and energy storage for all modes of energy (electric, thermal, chemical).

1.4

Energy management systems (EMS) will optimize ENS-operation. It will match load and demand at all levels ranging from the nanogrid (behind the meter, building level) and the microgrid (district or community level) to the regional distribution grid, which is connected to the cross-regional transmission infrastructure. Fossil-fuelled power plants, which used to operate on schedules orienting at the demand, will turn into back-up power supply facilities.

The overall reduction of energy consumption in addition to efficiency measures will be always a target, since all energy usage that can be avoided also implies reduction of emissions. This can be achieved by control elements for switching off energy use and zero power stand-by functionality or by transformation to new technologies as in the last decade the transfer to LED illumination had a high impact. Upcoming threats are energy consuming ICT technology related applications like blockchain, AI, data traffic, or digital currencies. The challenge will be to develop highly efficient algorithms and methodologies to decrease energy consumption despite the increased use of these new technologies.

1.3 2.1



Interconnected Energy Infrastructure; Source: Siemens Corporate Technology

F.48

Key to these new energy applications will be smart sensors, networks of sensors, and smart actuators that enable status monitoring on each grid levels as well as smart converters (for all voltage levels). The converters need to use highly efficient and fast semiconductor power devices and modules that enable real-time control of energy system components and grids for optimized operation based on forecasts of generation and demand but also in case of any critical event. The future grid operation requires a sophisticated information and communication infrastructure including cloud services, IT security, and AI technologies. Altogether, they will contribute to significant reduction of energy consumption and, consequently, CO_2 emission.

1.2 2.1 2.4

To achieve the targets of the Green Deal and to have competitive advantages for European based technologies and solutions, research has to be performed in the following areas:

01. Significant reduction and recovery of losses (application and SoA-related).
02. Increase of power density and reduction of losses (e.g. through exploitation of new materials) and a decrease of system size by miniaturisation and integration, on the system and power electronics level.
03. Increased functionality, reliability, and lifetime (incl. sensors & actuators, ECS HW/SW, semiconductor power devices, artificial intelligence, machine learning, monitoring systems, etc.).
04. Manufacturing and supply of energy relevant components, modules, and systems.
05. Management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility. Grid stabilization through e-vehicle charging.
06. Energy supply infrastructure for e-mobility, digital live, and industry 4.0.
07. "Plug and play integration" of ECS into self-organised grids and multi-modal systems, real-time digital twin capability in component and complete system design (to simulate system behaviour).
08. Safety and security issues of self-organised grids and multi-modal systems through smart edge devices and high level IT security (resilient communications and trustworthy AI).
09. ECS for energy storage technologies: production, transportation, storage, distribution, combustion and energy conversion systems.
10. Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.
11. Energy technologies in the circular economy approach: predictive and condition-based maintenance with repair and recycle capabilities.
12. Aligning with standardization of our energy systems.
13. Manufacturing and world-leading technologies for energy relevant applications in Europe.

3.2.3 EXTERNAL REQUIREMENTS AND SOCIETAL BENEFITS

In alignment with the **Parisian Agreements**, the EU committed to substantial reductions of CO_2 emission. In particular, the EU aims to make Europe the first climate-neutral continent by 2050 (EU long-term strategy) while boosting the competitiveness of the European industry. Carbon pricing throughout the EU economy is going to be implemented more strictly. Further climate laws will be introduced and continuing policies will be clarified by the European Commission in 2022. The new policy regarding **"Clean energy for all Europeans package"** was completed by the EU in 2019 as a comprehensive update of its energy policy framework and updated with the new Green Deal in July 2021. It emphasizes renewable energy, energy performance of buildings, energy efficiency, governance regulation, and electricity market design. Smarter buildings with more automation and control systems for effective operation shall be promoted. E-mobility infrastructure is going to be supported further. Energy efficiency targets and energy labels were tightened to encourage the industry to innovate.

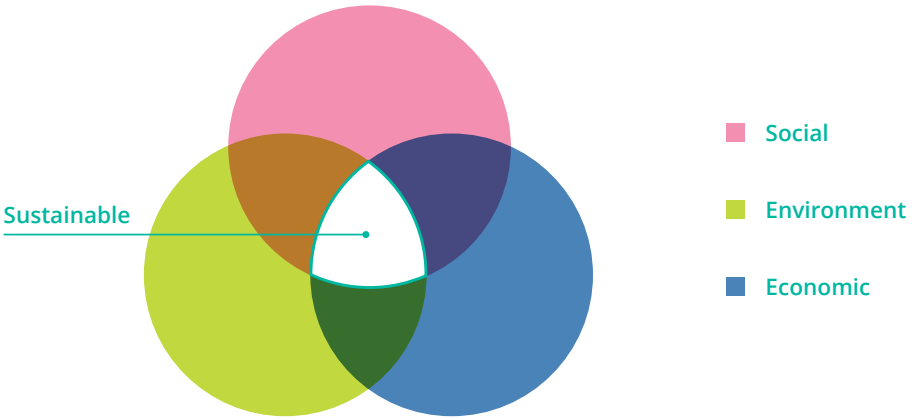
To achieve the **Green Deal** goal of "clean, affordable and secure energy" in all sectors, new laws and regulations will be required. While subsidies and regulations will promote sustainable developments in all application domain of ECS (energy, industry, mobility, communication, consumer goods, and cities), the energy domain with targeted 40% renewables in the energy mix until 2030 is the foundation to all of them.

Additional perspectives are given by the United Nation's "**Roadmap 2050**" addressing sustainable development solutions and implementations towards a carbon-neutral global population.

Energy from renewable sources: Wind turbines and photovoltaic (Source: © Mariana Proenca/Karsten Wurth – Unsplash) **F.49**

All these factors are considered for the roadmaps on research, development, and innovation of ECS for the applications in the energy sector. Potential targets comprise the implementation of electricity storage solutions (e.g. vehicle2grid, battery grid storage), the further increase in efficiency and the reduction in life cycle costs of energy generation from renewable sources (*Figure F.49*) , the electrification of transportation (*Figure F.50*), and the thermal processes in industry as well as the development of secure, self-learning energy management systems for buildings and industrial sites. ECS as enablers support the EU and national energy targets to achieve sustainability (*Figure F.51*) and are essential for a highly developed energy landscape towards a fair, democratic, healthy and prosperous society.

Electrification of the transport sector. **F.50**



F.51 *Three pillars of sustainability, source: Purvis, Mao, Robinson 2018: Three pillars of sustainability: in search of conceptual origins.*

Energy efficiency through ECS fosters economic development towards a circular economy and new employment opportunities. They will have a huge impact on job generation and education if based on the complete supply chain and fully developed in Europe. With more than 11 million jobs in the field of renewable energies[120] and indirectly involved technologies, this is a visible and significant factor for economic and societal stability. The capability of maintaining the understanding of the complete systems as well as the competence from small-scale solutions up to balanced regional energy supply solutions are key to the European competitiveness and success in the global market of energy solutions. Also the consumer itself can contribute its share, thus consumer empowerment to energy savings and efficiency should be taken into account for the development of energy systems.

Societal benefits include access to knowledge, development of modern lifestyle and the availability of energy all the time and everywhere – with a minimum of wasted energy and a minimum of greenhouse gas emissions. Therefore, ECS and its application domains enable Europe to meet the needs of the present without compromising the ability of future generations to meet their own needs.

3.2.4 STRATEGIC ADVANTAGE FOR THE EU

European ECS companies are among the leaders in smart energy related markets, e.g. for electrical drives, grid technologies, and decentralised renewable energy sources. Four European-based power semiconductor suppliers are among the top 20 in the world, having a combined market share of over 22% in 2020. Two of

120 IRENA, Renewable Energy and Jobs – Annual Review 2019.

them amongst the top 5 including the market leader.[121] The major growth driver there includes growth in renewable energy sectors such as wind and solar power generation[122]. Three power modules suppliers are found among the top 10 with one worldwide leader in the automotive, in the discrete power device and in the security-IC sectors, respectively, while the combined market share is more than 35%. Overall, the share of European suppliers in this growing market is increasing, which underlines their competitiveness. The companies invest in Europe and expand Fab capacity or even build up new semiconductor fabs in Europe. This position will be strengthened so that further employment is secured by innovative research within Europe. The technological progress will have a multiplying effect by creating a convergence between semiconductor and other promising future technologies like 5G, IoT, AI, and cloud-edge computing. As a result, EU ECS market prospects are seen very strong[123]. A seamless line from ECS R&D&I to production covering future energy businesses from generation over conversion to distribution and transmission ensures Europe's technological non-dependence.

Since the beginning of the Covid19-crisis, the ECS industry moved to protect employees, and secured supply chains. Despite the crisis, the ECS industry recorded on average a double-digit growth in 2020, with the fourth quarter marking the best quarterly result to date. In contrast to other industries, which had to contend with declining demand, the ECS industry experienced the opposite development and consequently suffered supply bottlenecks for electronic components. In the future, the focus on a strong R&D strategy is essential to emerge stronger from the crisis. Targeted investments in innovation can create a long-term competitive advantage and fill knowledge gaps. Especially the investments in new technologies rather than simply focusing on product variation or optimization to extend the product life cycle leads to the achievement of a pioneering role and should therefore be pushed[124].

ECS enable affordable energy conversion efficiencies of 93% – 99%, which improve the use of renewable energy resources. Involving new materials such as wide band-gap semiconductors, new device architectures, innovative new circuit topologies, architectures, and algorithms, the total system cost can be lowered. The focus on ECS development secures a smooth implementation of renewable energy power plants into the EU grid, a step towards the long-term goal for 2050. To further ensure a competitive, self-sufficient and efficient energy transmission and consumption in the EU, the energy highway through Europe, decentralized intermittent energy sources, bi-directional grid and storage systems, and distributed AC/DC network and grid technologies need to be implemented. These measures will support the EU by reaching its goals of a connected, breakdown and blackout protected, market-based, and yet more consumer-oriented energy market. Consequently, EU's energy system will serve as blueprint for global application.

3.2.5
MAJOR CHALLENGES

Five Major Challenges have been identified for the energy domain:

121 Omdia Power Semiconductor Market Share Database 2020.

122 https://www.marketresearchfuture.com/reports/power-semiconductor-market-1178

123 KPMG GSA Global Semiconductor Industry Outlook 2020 Part 2

124 https://www.mckinsey.com/industries/advanced-electronics/our-insights/how-the-semiconductor-industry-can-emerge-stronger-after-the-covid-19-crisis#

- **Major Challenge 1:** Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems.
- **Major Challenge 2:** Energy Management from On-Site to Distribution Systems.
- **Major Challenge 3:** Future Transmission Grids.
- **Major Challenge 4:** Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply.
- **Major Challenge 5:** Cross-Sectional Tasks for Energy System Monitoring & Control.

3.2.5.1 Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems

3.2.5.1.1 Status, vision and expected outcome

According to the IEA's Efficient World Strategy, digitalization enhances energy efficiency gains in the transportation and industry sectors[125]. Smart and efficient energy systems are drivers of energy savings. Therefore, they are in full alignment with the Green Deal. Alternative ways of energy generation (hydro, photovoltaic, and wind) and the electrification within the industry, the transport / mobility, and the construction / building sectors result in the challenge of creating smart, efficient, and reliable energy generation, conversion, and storage components.

Smart Energy Systems

For operating smart energy systems, all the energy conversion and storage components need to be equipped with smart actuators and sensors for status and health monitoring as well as optimization of grid operation. The integration of sensor, connectivity and edge processing in supplementary/additional parts will enable the creation of intelligent facilities by retrofitting. The creation of secure electronic control units requires development of specific hardware and software.

1.4

Consequently, smart control units need to be developed for all types of energy production, conversion, and storage components comprising smart electronic converters, actuators, sensors, security systems and reference communication interfaces. They shall have plug-and-play functionality and real-time digital twin capabilities in component and complete system design to simulate system behavior for evaluation of its' health status.

1.2 1.3 2.1

For offshore energy generation, such as windfarms and tidal energy generators, fibre optical sensors is an emerging technology beneficial for online monitoring of metal fatigue and excessive turbulences. This technology is currently being developed for such monitoring in aircraft wings and ship masts.

Conversion

Electrification of industry is one of the main implications to reach the 2050 decarbonization targets, mainly via the conversion from fuel-based heating processes to electro-heating solutions. In addition, direct electrification of industrial production processes (such as electro-synthesis of chemicals or electrolysis) is also crucial for replacing present CO_2 emitting solutions[126]. In the case of Heating, Ventilation, and Air Conditioning (HVAC) systems, significant reductions in consumption can be obtained by optimizing the system that handles all the processes of energy management or by changing the use of the Machine-to-Machine

125 IEA Energy Efficiency 2019.

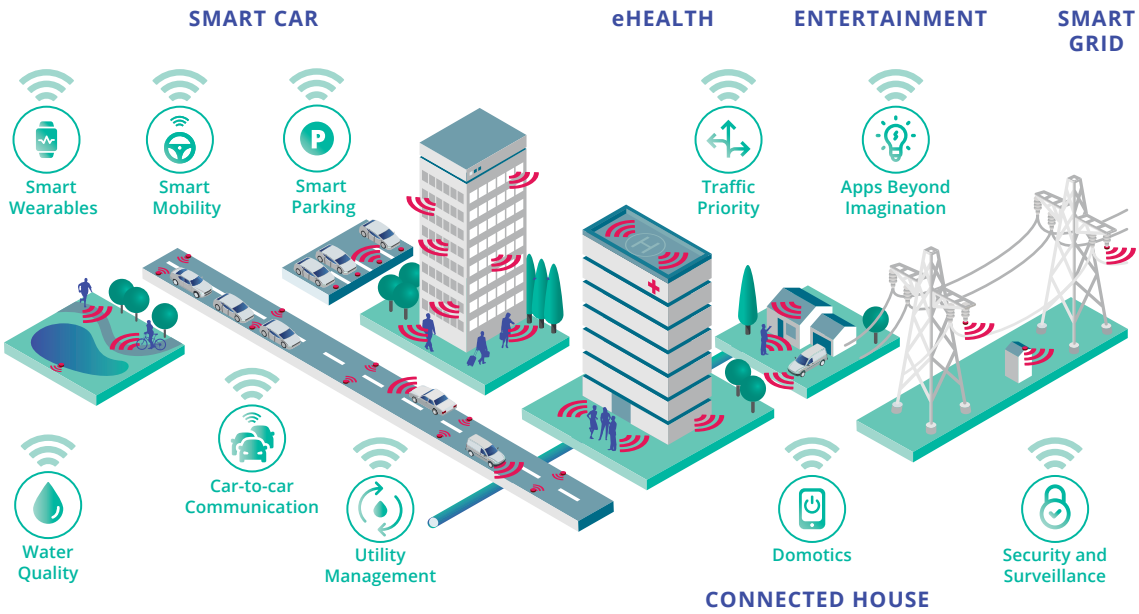
126 In-depth analysis in support of the commission communication, A clean planet for all, European Commission 2018: 773.

(M2M) technologies. For both strategies, efficient ECS are required to obtain optimal control functionality based on sensing, collecting, processing, and evaluating device related data[127].

DC power supply requirements based on advanced semiconductor power devices will provide lower power consumption and thus, feature higher efficiency of the increasing ICT energy consumption (i.e. through data centres) [128]. Investments in the next-generation computing, storage, and heat removal technologies will be required to avoid a steep increase on energy demands and to minimize the implications of unavoidable data centre energy use on the global climate[129]. In data centres and 5G/6G networks, photonic ICs can route information streams from fibre to fibre without conversions into electronics in between. This will be highly efficient and save energy.

The advanced features of 5G and 6G will innovate the use of the technology (*Figure F.52*), but as consequence of larger data rates and through-puts, cost and energy demand will increase substantially. Therefore, energy harvesting capability of sensors and devices in the 5G environment will be one of the crucial aspects, which can make 5G and 6G green and cost-efficient[130].

2.2



5G as enabler of an interconnected smart network. Source: European Commission, Towards 5G.

F.52

Power electronics circuits based on semiconductor power devices are used in all conversion processes. Silicon based power devices are approaching their ultimate limits in terms of breakdown voltage, current, switching frequency and temperature capabilities. Next generation power semiconductor devices will rely

1.2

127 *Energy Management in Smart Buildings by Using M2M Communication, IEEE Xplore*

128 *European Commission Joint Research Centre JRC, Directorate Energy, Climate and Transport. Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency*

129 *Masanet, Eric, Arman Shehabi, Nuoa Lei, Sarah Smith, And Jonathan Koomey. "Recalibrating Global Data Center Energy-Use Estimates." Science 367, No. 6481 (2020): 984-986.*

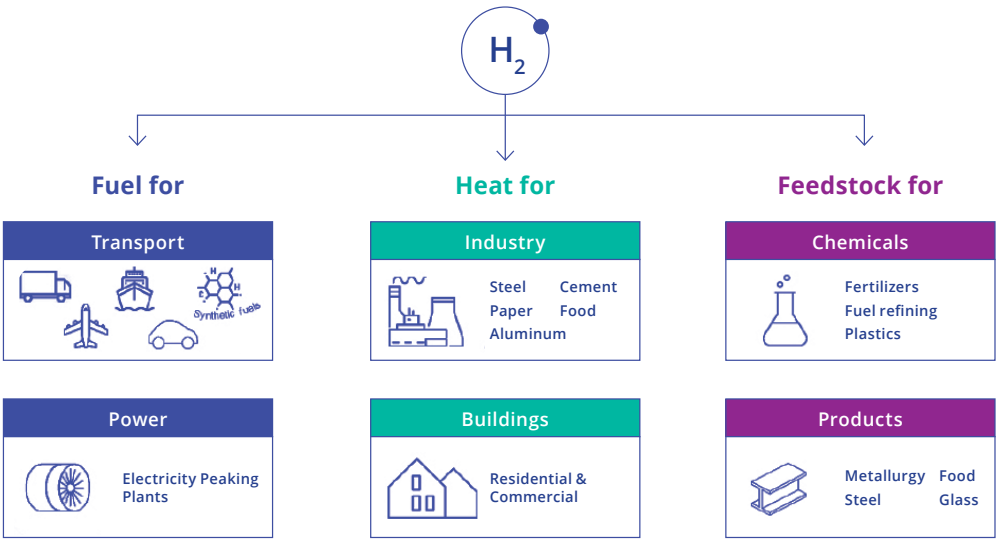
130 *S. K. Routray and Sharmila K. P., "Green initiatives in 5G," 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, 2016, pp. 617-621.*

on Wide Band Gap (SiC, GaN) and Ultra WBG (diamond, Ga_2O_3) technologies. Due to this unstoppable trend, research on device reliability, packaging and assembling methods suitable for very high electric fields and high temperature, is strongly required. A focus also needs to be set on the medium voltage grid (< 45 kV).

Storage

Energy storage deployment provides energy system flexibility[131]. Looking at further storage possibilities, different options for various capabilities need further efficiency improvements. As an example, optimized converters, sensor solutions for monitoring, and battery management systems need to be developed for storage options, all including ECS.

In power generation, hydrogen with its many uses (*Figure F.53*) is one of the leading options for storing renewable energy. Hydrogen can be used in gas turbines to increase power system flexibility. In combination with fuel cells, it is also a great vector of clean energy since it allows to produce electricity directly onboard of EV or in areas, which are cut off from the power grid. With declining costs for renewable electricity, interest is growing in electrolytic hydrogen.[132] ECS will be employed in electronics for electrolyzers, fuel cells, as well as power management and health monitoring.



F.53 *The many uses of Hydrogen, source: Bloomberg NEF.*

3.2.5.1.2 Key focus areas for increased efficiency and smart energy generation, conversion and storage components

- Increased efficiency at all levels:
  - Power conversion and wide-bandgap semiconductor power devices.
  - Power supply.
  - Energy harvesting.
  - Energy management.

131 *IEA Tracking Energy Integration, 2019.*

132 *IEA The Future of Hydrogen, 2019. https://www.iea.org/reports/the-future-of-hydrogen*

- Residential, commercial, and industrial demand side management (scheduling and load adaption):
  - Sensors, actuators, drives, controls and innovative components.
  - Full monitoring in adaptive and controlled systems.
  - High efficiency electric drives, heat pumps, cooling, HVAC, data centres and other consumers of electricity for variable load operation.
  - Solutions for increasing power demand of 5G/6G systems.

- Development of Energy Management Systems including:
  - Optimization module.
  - Demand and generation forecast.
  - Customer preferences.
  - Weather forecasts.
  - Price/tariff information/forecast for scheduling controllable loads and generators.
  - Smart sensor network: internal and external physical parameters that influence energy conversion efficiency.
  - Resilient and smart communication and edge devices.
  - Deployment of Trustworthy AI.
  - Fiberoptic sensors for fatigue detection.
  - Converters for power quality improvement (e.g. electronics filters to manage resonances).

- Conversion of industrial processes:
  - “Industrial electrification” (Replacement of CO_2-emitting processes by others based on “clean” electricity).
  - Electric drives for commercial & industry applications.
  - Industry 4.0 with combination of Cyber-Physical Systems (CPS), Internet of Things (IoT), Artificial Intelligence (AI).
  - DC subsystems for industrial production / data centre applications and DC distribution grids.
  - Photonic routing in data centres from fibre to fibre without conversion to electronics.

- Development and application of storage optimized for residential, commercial, industrial utilization:
  - Control, interfaces to batteries, fuel cells, hydrogen storage electrolysers.
  - Integrated battery driven applications (e-car charging, PV – system local storage).
  - Power Storage to "buffer" net fluctuations and to avoid long distance transmission.
  - Smart storage technologies from low to medium voltage.

3.2.5.2 Major Challenge 2: Energy Management from On-Site to Distribution Systems

3.2.5.2.1 Status, vision and expected outcome

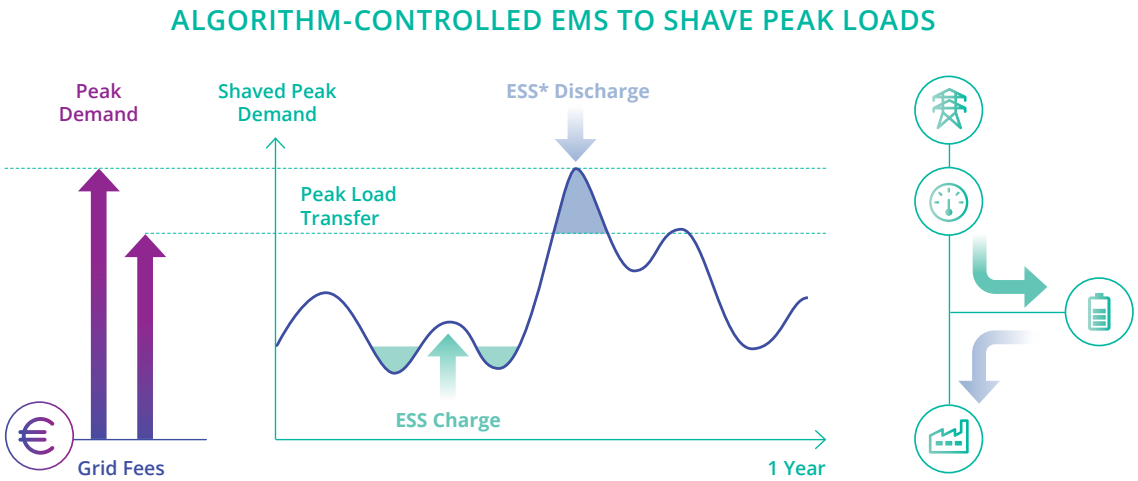
The distribution grid comprises commercial scale renewable generation as well as private smaller renewable power generation units, conversion between different energy modes, storage, control and protection systems for the grid infrastructure together with all kind of consumption.

Autonomous Control Systems

In the future distribution grid, generation and consumption by power electronics systems will surpass the share of synchronous generation. This leads to potential grid instabilities due to lack of inertia. Therefore, autonomous control systems need to be implemented to control the high demand loads. These control systems should be organized hierarchically to adjust the heavy loads according to the actual local production and storage capabilities so that import or export of power is minimized. Price control systems such as TOU (Time of use) can help to prevent grid violations. Storage devices, such as local community storages or e-Vehicles, can be charged when the price is low and discharged when the price is high, to provide flexibility as well as to ensure stability and reliability in the grids.

1.4 2.1 2.3

For industry or larger groups of buildings, control methods increase the flexibility of the total system and can be set up using hierarchical and intelligent control methods to minimize costs and to provide peak-shaving (*Figure F.54*). For larger power production facilities, hybrid generation and storage solutions are also discussed, which integrate the power production facilities with storage devices to have the best arbitrage cost. Novel grid architectures for manufacturing strive to increase topological and energy flexibility within production cells to enable adaptive production optimization.



F.54 *Visualization of an algorithm-controlled energy management system to shave peak loads. An energy storage system predicts load peaks and charges/discharges a battery accordingly. Source: EDF Renewables.*

Security, Reliability and Stability of Energy Systems

For stable, resilient on-site energy systems, multi-modal energy management systems allowing integration of electricity, heating & cooling, and transport (e-vehicle charging incl. Vehicle-2-Grid) will be developed. Their features comprise high level IT security, energy trading via local energy market platforms, renewable energy certification, development of solutions for low voltage electronic systems that are easy to setup, as well as support for self-learning against evolving needs.

1.4 2.4

Energy Management Systems for industrial and residential customers include optimization module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast. They require beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles. Furthermore, the interface to the grid might be used for additional power quality services based on power electronics converter technologies beyond state-of-the-art reactive power compensation (e.g. virtual inertia and balancing).

3.2.5.2.2 Key Focus Areas for on-site or behind the meter systems

- Security, reliability and stability of total energy system:
  - Automation of grids.
  - Storage of data.
  - AI and machine learning for optimized operation of the grid.
  - Machine-learning based forecasting algorithms for generating accurate generation profiles of expected power production and consumption.
  - Deployment of sensors and edge computing devices to health-check grid assets to increase lifetime and optimize operation.
  - Converters for power quality improvement (e.g. electronics filters to manage resonances).

- Stable and Resilient On-Site Energy Systems: Multi-modal Energy Management:
  - Integration of electricity, heating & cooling, and transport (e.g. e-vehicle charging systems).
  - Coupling with energy trading systems, e.g. local energy market platforms.
  - High level IT security.
  - Renewable energy certification.

- Hybrid solutions:
  - Integrating power production facilities with storage devices.
  - Arbitrage cost, keeping level of production according to market bid.

- Virtual markets:
  - Flexibility in demand & supply.
  - Aggregation of Energy consumption and production.

- Electric energy supply for manufacturing:
  - Higher uptime using novel industry grids and UPS.
  - Stable power supply using novel electronics converter technologies.

- Plug-and-play capability for components, self-learning:
  - Integration of low voltage systems using flexible planning rules.
  - Cost effective solutions to minimize set up-time and manual parametrization.
  - Reduced physical size and weight of individual transformer stations with equivalent power ratings.
  - Development of solid-state transformers with.
    - New functions for the operation of power systems.
    - Avoidance of infrastructure extensions caused by increasing share of distributed generation.

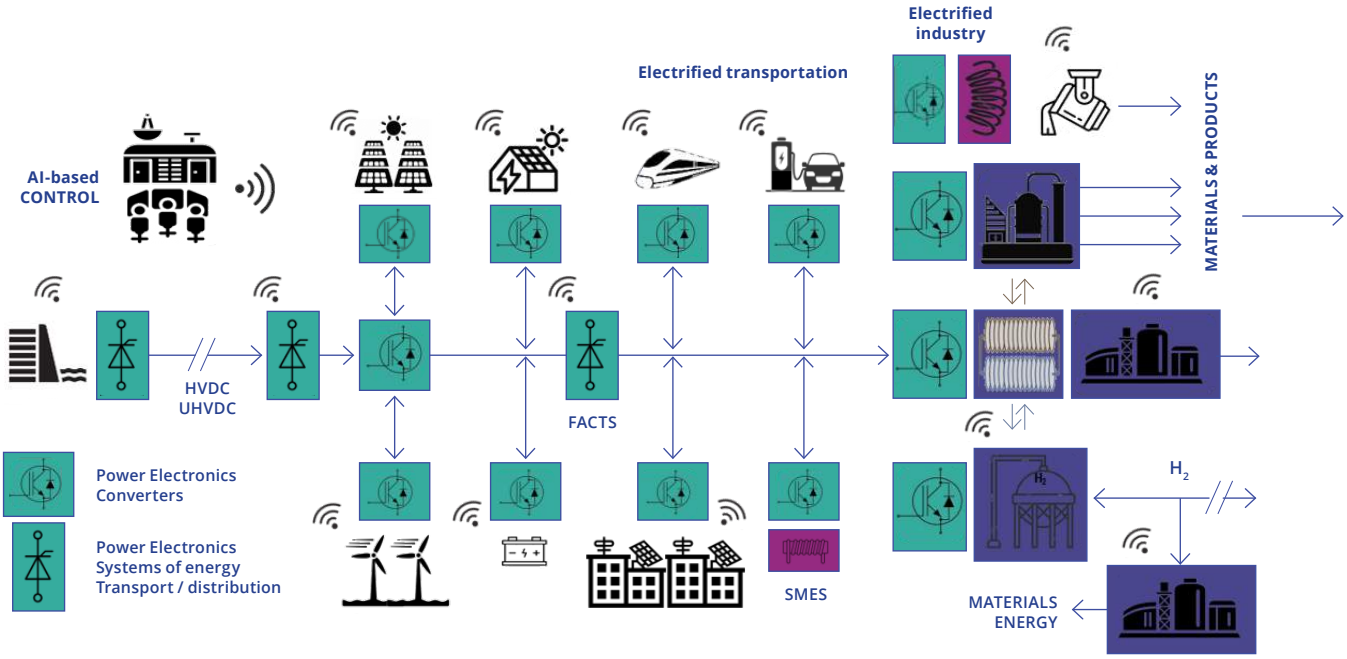
3.2.5.3 Major Challenge 3: Future Transmission Grids

3.2.5.3.1 Status, vision and expected outcome

New grid challenges

Future transmission and distribution grids will remain an integral backbone of energy systems. Coupling of different domains like electricity, thermal, gas etc. will enable new business opportunities which require new technological solutions for high power electronics, combined with sensors and ICT for monitoring, control and prediction.

The energy generation and energy consumption pattern will drastically change as the industry and society at large will be highly electrified. Base industries such as steel and cement production will completely change production technology to enable fossil free production and will require extreme amounts of electric energy. New industries such as giga volume battery production factories are planned in several places in Europe. This together with a massive expansion of supercharger station for private passenger cars and heavy trucks with individual charge capacity of more than 1 MW will put severe challenges on the grid capacity in both networking and electronic components to manage highest possible efficiency. Therefore, further ECS R&D needs to work towards improvements of the grid capacity with the highest possible efficiency (*Figure F.55*). Thus, continued development of components for HV transmission for 1.2 MV or even higher voltages are needed to roll out an efficient energy transmission over Europe. In addition, new business models must be developed for the electric energy market enabled by the smart grid technology.



F.55

Power ECS at each point of the future transport and distribution grid.
Source: CSIC Scientific Challenges: Towards 2030, Volume 8.

Resilience

To account for adverse conditions caused by climate change, the new national and transnational grids must include autonomous electricity generators based on fuel cells or local storage systems for communications and network information management as well as water-resistant components or modules. Also, sensors need to be placed at critical points to immediately alert authorities in case of unexpected incidents. To be able to quickly react to an electricity line fault, the system will benefit from powerful switches and AI to successfully reroute the systems. Additionally, predictive maintenance (e.g. with digital twins) of the energy supply sensors provides further safety and resilience. Due to the weak tectonic movement in most of the parts in Europe, transmission grids could become much more resilient and loss-less when buried in the ground. Thus, extra isolation technology needs to be considered and critical points equipped with smart ECS for monitoring, control, and prediction.

1.2 1.3 1.4 2.1

Key Focus Areas

- Grid stability during the industrial transition:
  - Efficiency increases.
  - Development of medium voltage grid.
  - Development of components for HV transmission for 1-2 MV or even higher voltages.
  - New solutions for high power electronics, combined with sensors and ICT for monitoring, control and prediction.
  - Development of new business models to foster innovations regarding grid stability.

- Development of a Trans-European energy infrastructure:
  - Secure, cross-regional transmission infrastructure .
  - Multi-terminal HVDC systems connecting remote energy generation sites.
  - Interaction between distribution systems on community and district level.
  - Development of components for HV transmission for > 1.2 MV.
  - Minimize Losses.

- Requirements on ECS by disruptive changes in transmission and use:
  - Flexibility in system design and operation.
  - Water-resistant components/modules.
  - Autonomous electricity generators based on fuel cells.
  - Modelling, sensing and forecasting weather conditions and thus, supply and demand.
  - Intelligent power devices, systems, and switches.
  - Status-/health-monitoring (e.g. ice sensor/detection) for transmission lines.
  - ECS for multi-modal energy systems.

3.2.5.4 Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply

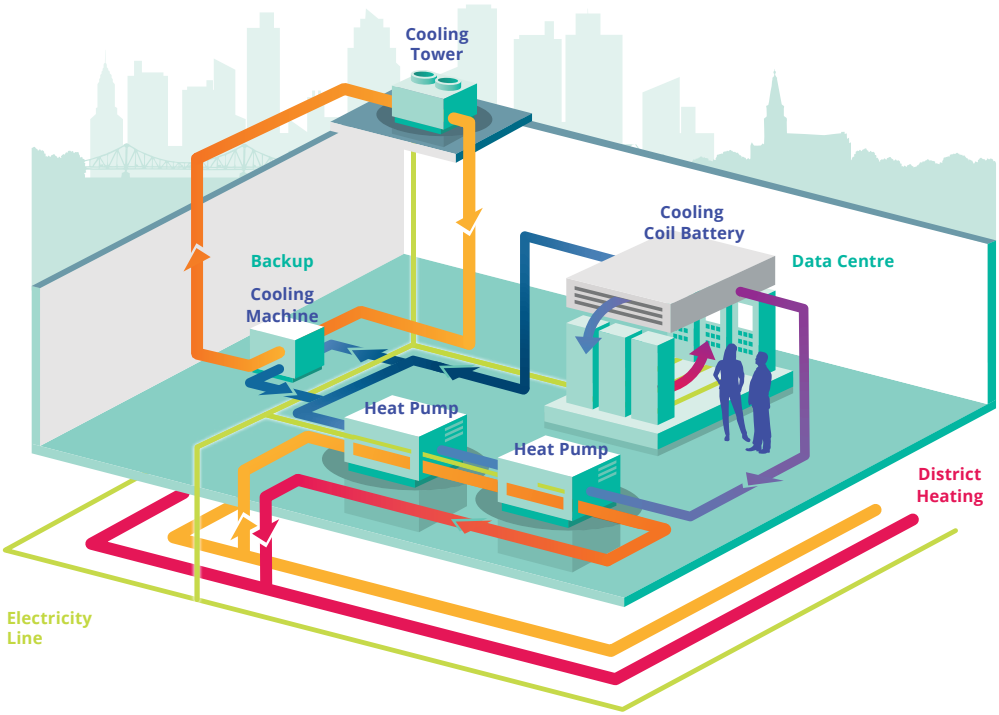
3.2.5.4.1 Status, vision and expected outcome

A 40% renewable energy share in the electricity sector in Europe by 2030 needs decentralized, intermittent energy sources, bi-directional grid and storage for energy supply in transport, industrial and smart cities applications.

Multi-energy Systems (MES)

MES help to achieve optimized energy management. All sectors are integrated to maximize overall system efficiency. Energy flows between sectors and their storages ensure the highest use of renewable energy while balancing fluctuations.

Heating supply uses district heating, supported by heat-pumps and boilers, using thermal storage in the district heating system (*Figure F.56*). Integration with industry makes use of waste process energy using heat pumps to boost from low (40-50 deg) to high temperatures in the pipe (80-90 deg). Electrolyzers add to the gas system or transport. Water treatment uses excess power from renewables adding further flexibility.



F.56 *A Combination of heat pumps and district heating. Source: IEA HPT.*

Local communities use MES concepts on regional level. Different local inputs are gathered for an overall aggregated control for the larger regions as well. Autonomous controllers are used behind the meters to support overall control. A clear hierarchical set up, control structure and knowledge of market interactions are necessary. 1.4

Complex integrated control systems use AI, machine learning and comprehensive communication grid/IoT platforms (including edge computing) to get all data for control and optimization. Risk and security analysis provide resilience and ensure stability of MES. 2.1

Urban Transformation

Emission free cities use electrification and decentralised storages to improve efficiency and reliability. ECS as indispensable components ensure efficient management of data and data storage. AI approaches and the ECS supply chain for integrated applications in energy are key enablers for smart power grids. Electrification of urban mobility supports individual and public transport (incl. utility EV) and furthermore, contributes to the stabilization of the grid. The first needs household and public charging, the latter uses well defined charging points on (bus) lines or at terminals. Powers vary from 10 kW (LV) to 600 kW (MV). Reservation and optimization are based on ICT.

Other, crucial aspects of emission free cities are an efficient urban energy infrastructure, low carbon and smart residential and service buildings, low carbon mobility, smart water systems and smart waste management. Even the shift to LEDs without any smart functions can result in energy savings of ~50% in an industrial setting[133].

133 *Muneeb A, Ijaz S, Khalid S, Mughal A (2017) Research Study on Gained Energy Efficiency in a Commercial Setup by Replacing Conventional Lights with Modern Energy Saving Lights. J Archit Eng Tech 6: 202.*

Storage Solutions

In households, battery energy storage devices can used to increase self-consumption. Some regions will use heat/cooling storage. Algorithms/models for optimal use of storage (community/private/ industrial) are based on technical parameters, demand and generation forecasts, customer preferences, in order to reduce power peaks and to support integration of RES into existing infrastructure.

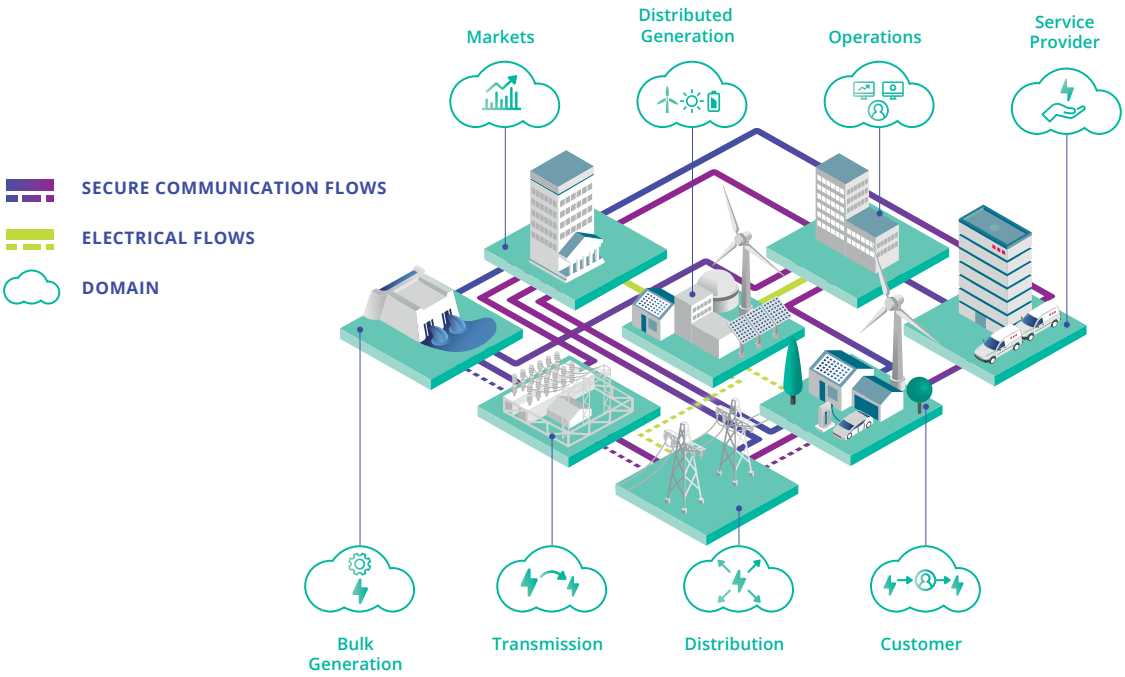
MES in larger communities with different kinds of storage possibilities (electrical, thermal, gas, water etc.) play an important role. V2G is used as huge distributed electrical energy storage. Systems with electrolyzers might use storage tanks for gas production. Thus, development of grid-supporting control algorithms and supporting regional energy management for communities (e.g. P2P trading via storage systems, self-consumption optimization) are needed.

3.2.5.4.2 Key focus areas for achieving efficient community and regional energy management

- Electric Energy Supply for urban mobility:
  - Development of household and public charging infrastructure.
  - Creation of charging points along the (bus) line or at fleet terminals, for public transport.
  - Reservation and optimization services implemented with ICT solutions.
- Electric Energy Supply for urban life:
  - Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimization.
  - Local DC-coupling of various technologies for fast charging at home.
- Regional Energy Distribution infrastructure:
  - Communication infrastructure to support self-organized local energy communities.
  - Sustainable off-grid supply with power electronics-based grid forming capabilities.
  - Virtual power plant functionality optimizing match between generation and demand.
- Operation of connected energy systems:
  - Connectivity, Security, Integrity, Resilience, Variability.
- Storage systems:
  - Development of grid-supporting and peak shaving control algorithms.
  - Support for regional energy management for communities.
  - Peer-to-peer trading by using storage systems.
  - Self-powering systems for small IoT nodes.
  - Local energy harvesting to substitute battery powered devices and eliminate the high demand of energy for the battery manufacturing and distribution logistics.

3.2.5.5 Major Challenge 5: Cross-Sectional Tasks for Energy System Monitoring & Control

3.2.5.5.1 Status, vision and expected outcome



F.57 *Interaction of actors in different Smart Grid Domains through secure communication flows and electrical flows. Source: NIST Framework and Roadmap for Smart Grid Interoperability Standards.*

Focusing on current energy management platforms, they still have shortcomings in terms of automation, interaction and intelligence. Thus, when the traditional energy grid is evolving into a smart grid, it needs to integrate ICT and power electronics massively. The ECS empower the electrical utilities providers and consumers, improve efficiency and availability while constantly monitoring, controlling, and managing the demands. The huge complex networks need cross-sectional approaches for monitoring and control to achieve efficiency, security and reliability of the communication and electrical flows (*Figure F.57*) - all based on new ECS technologies.

Optimization in Monitoring and Control

To ensure security, reliability and stability of the total energy system, it is important to know the current state of the system at all times. Therefore, observability and state estimation together with forecast of expected production and consumption play an important role. This requires automation of the grids, use of sensors at different levels, storage of data, AI and machine learning to operate the grids in an optimized way and at the same time obeying data security and GPDR. Data collection within the grid needs to be limited on chosen parameters to avoid unnecessary costs and complexity.

2.1 2.3 2.4

The IoT technology as application in the smart power grid can help to achieve sustainable energy, low latency, and reliability.[134] Machine-learning used for forecasting energy demand in smart grid

134 *Jaradat, M., Jarrah, M., Bousselham, A., Jararweh, Y., & Al-Ayyoub, M. (2015). The Internet of Energy: Smart Sensor Networks and Big Data Management for Smart Grid, https://hdl.handle.net/10356/81241*

environment contributes to medium-term and long-term prediction of consumption and production and is able to solve energy management issues through improved accuracy of prediction[135]. It allows administrators to optimize and plan their resources and manage energy inconstancies and variations. Nevertheless, security concerns and vulnerabilities need to be identified in today's electricity grid and sufficient solutions implemented to reduce the risks to an acceptable secure level.[136]

1.4

Energy Management Platforms for integrated energy systems

The European electrical power system is undertaking a transformation process driven by targets towards renewable energy sources. Different energy sources from different operators can be managed through ML, algorithmic trading, agile transformation, etc.. In this way, challenges of current and future applications like the energy transition and the digital revolution can be faced appropriately.[137] Energy Management Systems (EMS) are required to enable efficient and combined operation of multiple energy systems and components. Within a study that quantitatively examined 98 scientific papers dedicated to EMS in buildings and households, the identified focus areas were mostly the reduction of energy costs or peaks, as well as the increase of comfort.

1.4 2.1

Results show that high computation time is a significant weakness of current EMS. A possible solution to that could be heuristic algorithms. Furthermore, the study suggests that stronger focus on high uncertainties and robustness is needed in order to transfer EMS with operational management and scheduling into practice. The integration of forecast methods also needs further attention. Regarding sector coupling (e.g. heat and electricity), major challenges exist due to great complexity and uncertainties over longer optimization horizons. Moreover, multi-level EMS in combination with cloud computing offer exciting approaches for new research questions.[138]

Hardware

Electrical grids aim to become more distributed, smart, and flexible to meet the increasing electricity demand. For new grids, the trend is to design energy generation and consumption areas together, in distributed form. Therefore, especially power electronic devices play a crucial role to regulate distributed generation and dispersed energy-storage devices together and into the grid. Future power converters also act as edge devices actively contributing to a stable grid either in grid forming devices, virtual inertia and other functions. Hence, the intensive use of power electronic converters in the microgrid brings their control methods to the forefront, which should meet good dynamic response and high reference tracking characteristics[139]. The domain of combining low power and high power components does require fundamentally new HW solutions. It necessitates heterogeneous integration at the highest and most diverse levels, which leads to unprecedented EMC and thermo-mechanical concerns. It may open the door to developments possible in no other application field. Exemplary, while sensors (e.g. for self-monitoring) placed directly into power switches controlling the energy flow to an entire city, two heterogeneous worlds meet (e.g. kV and pW, MA and nA). The sensors must be able to withstand strong magnetic field changes and temperature fluctuations (300 degrees +), thus requiring research and innovation.

1.1 1.2 1.3 2.3

135 Ahmad, Chen 2018: Potential of three variant machine-learning models for forecasting district level medium-term and long-term energy demand in smart grid environment. https://www.sciencedirect.com/science/article/abs/pii/S0360544218313811

136 Aloul, Al-Ali, Al-Dalky,Al-Mardini,El-Hajj 2012: Smart grid security: Threats, Vulnerabilities and Solutions.

137 Camponesci et al. (2020). ENEL Energy Management Evolution in a growing complexity of the Italian market context. https://ieeexplore.ieee.org/document/9241132

138 Schminke (2021). Overview of the current state of research on characteristics and algorithms of energy management systems in households and buildings. https://doi.org/10.1002/er.6738

139 Bayhan, Abu-Rub (2020). Smart Energy Mangement System for Distributed Generations in AC Microgrid. Quatar Environment and Energy Research Institute, Hamad Bin Khalifa University; Texas A&M University at Qatar, Doha, Qatar.

3.2.5.5.2 Key focus areas in the cross-sectional tasks

- Self-adaptive control based on Artificial Intelligence / Machine Learning:
  - Data driven analytics (descriptive, diagnostic, predictive, and prescriptive) in smart grid.
  - Fraud detection.
  - Design, development, and application of deep learning in smart grid.
  - Artificial intelligence in advanced metering infrastructure.
  - Predictive and condition-based maintenance concepts resulting in reduced maintenance costs and increased lifetime for equipment and infrastructure.

- Algorithms for status, prediction & demand:
  - Multiobjective optimization algorithms in smart grid; e.g. forecasting of generation and consumption.
  - State-estimation based on measurement values, simulation values, trained models (machine learning).
  - Optimal utilization of storage systems (community storage, private storage, industrial storage systems) based on technical parameters, demand and generation forecasts, customer preferences.
  - Short/long-term demand and generation forecast algorithms for different energy domains (electricity, warm water consumption, etc.) and integration into overall systems.
  - New theories and applications of machine learning algorithms in smart grid.
  - Data management, weather forecast, energy use forecast with a time horizon of 24 hours and with resolutions of at least 15 minutes (prevalent use of renewable solar, wind, hydroelectric sources according to demand profiles and use cases).

- Flex Offer – to address flexibility (mathematical tool).- how much energy can be produced in a certain time – aggregated and deliver to the market (alternative to blockchain, etc.):
  - Demand response in smart grid.
  - Peak load management approach in smart grid.

- IT security, connectivity, integrity:
  - Artificial intelligence techniques for security.
  - Smart, secure edge devices for secure data management and control.
  - Energy management systems for low-power/low cost devices.
  - Smart edge computing and AI for autonomous energy control.

- Hardware Innovation:
  - H-bridge quasi-impedance source inverter (qZSI) for PV Systems.
  - Three-phase back-to-back inverter for Wind Energy Conversion Systems.
  - Ultra-capacitor with high efficiency (95%) and high power density.
  - New generation of Smart Meter.

3.2.6
TIMELINE

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: managing energy generation, conversion, and storage systems smart and efficiently	**Topic 1.1:** smart electronic control systems for energy conversion and storage	• High efficiency converters, smart actuators & sensors, Plug-and Play Functionality, Real Time Digital Twin, Integrated Security System, Status & Health Monitoring, Integrated reference communication interface, self-powering systems for off-grid operation
	Topic 1.2: optimized storage possibilities	• Control interfaces to batteries, fuel cells, electrolizers; • Optimized converters • Sensor solutions for cell and module monitoring • Battery management systems • Self-powered electrochemical energy storage systems (SEESs)
	Topic 1.3 electric drives for domestic, commercial & industry application	• Heat pumps, cooling devices, HVAC development, innovation and installation
Major Challenge 2: energy management from on-site or behind the meter to distribution	**Topic 2.1:** stable and resilient multi-modal energy management systems	• Distributed Generation, Interconnectivity:Renewable energy sources and grid connection;
	Topic 2.2: energy management systems for industrial and residential customers	• Development of beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles; • Handle uncertainties at industrial sites throguh ECS
	Topic 2.3: autonomous control systems	• control of high demand loads for efficient energy distribution
Major Challenge 3: future transmission grid	**Topic 3.1:** grid stability during the industrial transition	• Development of components for HV transmission for 1-2 MV or even higher voltages • • New solutions for high power electronics, combined with sensors and ICT for monitoring, control and protection
	Topic 3.2: resilient systems for the European transmission grids	• Water-resistant components/modules • • Autonomous electricity generators based on fuels cells • • Modelling • • Intelligent power devices, systems, and switches

MEDIUM TERM (2027–2031)	LONG TERM (2031–2037)
• Further development of intelligent power devices and electronic control towards higher system energy efficiency, lower system costs and integration or newly developed device technologies. • - 55% GHG emissions	• Getting closer to zero emissions (due in 2050)
• Grid Integration • Further development based on the needs and opportunities by larger volumes	• Development of excellent storage possibilities to balance energy generation volatility; efficient energy distribution and usage
• Supplying clean, affordable, and secure (made in Europe) energy to these applications;	• "In all cases, the 2050 target is to electrify these [...] processes with technical solutions based on renewable ("clean") sources." (Green Deal)
• Integration of electricity, heating, cooling, and transport • Virtual power plant functionality optimzing match between generation and demand; • Secure gateways allowing energy trading, • Coupling with energy trading systems (e.g. local energy market platforms) • Renewable energy certification (labeling through ECS)	• Efficient energy distribution and usage; cost efficiency; high level IT-security
• optimization module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast; • Demand side management for buildings • Virtual Energy Market	• Energy Management Systems optimizing operation of components for lifetime &revenue
• Price-control systems • Storage devices provide flexibility, stability and reliability in the grids	• Minimize costs, provide peak shaving; hybrid solutions; novel grid architectures for manufacturing to enable adaptive production optimization
• Further improvements on grid capacity with highest possible efficiency • Development of business models that encourage new technological solutions	• European Energy transition to zero-carbon emissions
• Modelling, weather forecast, sensing data • Digital twin • ECS for multi-modal energy systems (cooling with excessive energy, use thermal capacities)	• Multi-Modality across Europe

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 4: achieving efficient community and regional energy management	**Topic 4.1:** regional energy distribution infrastructure	• Secure Cross Regional Transmission Infrastructure • communication infrastructure to support self-organized local energy communities;
	Topic 4.2: electric energy supply for urban life and mobility	• Development of household and public charging infrastructure; charging points on bus lines or terminals • Reservation and optimization services implemented with ICT solutions.
	Topic 4.3 Storage systems for urban communities	• Development of grid-supporting and peak shaving control algorithms • Battery energy/ heat/ cooling storage devices for households
Major Challenge 5: cross-sectional tasks for energy system monitoring & control	**Topic 5.1:** AI, machine learning and algorithms for status, prediction and demand	• Data driven analytics and deep learning in smart grid; AI in advanced metering structure; smart sensors with improved data processing; stream processing for real time application
	Topic 5.2: IT security, connectivity, integrity	• Smart, secure edge devices for secure data management and control
	Topic 5.3: hardware	• Improvements in robustness of HW devices to withstand strong magnetic field changes and temperature fluctuations.

MEDIUM TERM (2027–2031)	LONG TERM (2031–2037)
• Sustainable off-grid supply with power electronics based grid forming capabilities	• Energy flows between sectors and their storages ensure the highest use of renewable energy while balancing fluctuations
• Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimization • Local DC-coupling of various technologies for fast charging at home.	• Emission free cities with electrification and decentralised storages to improve efficiency and reliability
• Peer-to-peer trading by using storage systems; • Self-consumption optimization	• Support for regional energy management for communities
• Innovative approaches ensuring clean, secure and affordable energy for EU citizens; multiobjective optimization algorithms in smart grid; optimal utilization of storage systems; short-/long-term demand and generation forecast algorithms for different energy domains	• Safe and interconnected smart grid netword; cross-sectional approaches for energy monitoring and control; integrated energy systems; optimal match between generation and demand; energy flexibility
• Artificial intelligence techniques for security	• Eliminate security vulnerabilities as best as possible
• good dynamic response and high reference tracking characteristics of power electronic converters; new HW solutions to combine low power and high power components;	• Optimal regulation of distributed generation and dispersed energy-storage devices; robust devices able to control high energy flows;

3.2.7
SYNERGY WITH OTHER TOPICS

Energy supply and energy efficiency are fundamental for all other applications from **mobility** and **industry** to societal sectors. The requirements on the ECS for the energy applications Strongly spark the technology developments in (high-) power electronics but also for sensors, photonics, signal processing, and communication electronics along the full supply chain, i.e., from design to processing to integration. Hence, the **"Energy"** Chapter has close links to the **"Architecture and Design"**, to the **"Process Technological Equipment and Manufacturing"** and to the **"Components, Module, and System Integration"** chapters. Energy applications have specific and often particularly high requirements in terms of reliability, safety, and security, so that they are instrumental for the definition of the research work in the transversal Chapter on "**Quality, Reliability, Safety and (Cyber-) Security"**.

Due to recent progress in automotive propulsion concepts based on batteries, fuel cells, and hybrid engines, the synergies to the **"Mobility"** Chapter are particularly high. The new technologies requested for those applications require higher efficiency and reliability, which shows a strong connection to the high priority R&D&I areas listed in Chapter 3.2 **"Energy"**. The strongest interface is seen in the subjects of charging and storage infrastructure.

Finally, the Power Supply scenario with the availability and integration of several renewable sources with variable power generation profile, can be considered as an example of **"System of Systems"** (SoS), enabling the synergy with the related transversal SoS Chapter. Power management is fundamental for modern and future factories driven by Industry 4.0 concept, where digitalization plays a key role. Industrial IoT (IIoT), big data, artificial intelligence (AI) are enabling factors for energy-aware systems with full exploitation potential of synergy across several chapters. Furthermore, a synergy with the **"Connectivity"** Chapter is fruitful to discuss future energy needs for 5G and 6G infrastructures.

3.3

ECS Key Application Areas

DIGITAL INDUSTRY

3.3.1 SCOPE

To be able to manage everything in a machine, factory or company network, industries have divided the necessary ECS technologies into levels or technology stacks. In these levels or stacks, sensors and actuators are closest to processing materials or handling items, and therefore seen as the lowest element in the hierarchy in the Edge-to-Cloud Continuum. Moving up the levels, you find super-sets and/or System of Systems and/or interconnected IoTs like devices, unit processes, production or manufacturing lines, operations control, company or enterprise business processes, and an increasing amount of machines, lines, proprietary HW and electronic components has become more networked, complex, dynamic and global.

The Industry 4.0 changes to the mode of operation have a profound impact on how the factories, construction zones and processes are managed and operated. Powerful networked digital tools are needed to achieve the necessary Situational Awareness and control of autonomous vehicles, robots and processes at various autonomy levels. The technological tools that are part of the 3D Internet concept can encompass such complex non-hierarchical environments .

The European Industry 4.0 movement needs an open source based, stable and extensible 3D Internet to overcome user interface, networking and communication challenges. The 3D Internet is an overarching concept containing multiple technologies, such as such as Industrial Internet of Things, Augmented and Virtual Reality (AR /VR). The 3D Internet can be seen as an expanding set of interconnected virtual and augmented worlds, accessible from AR/VR head mounted displays, desktop computers and even mobile phones. The entities that are present in the 3D Internet may be humans, devices, and autonomous physical and virtual machines such as Digital Twins and AI agents.

This SRIA addresses the digitalisation of the major European industrial sectors, promoting the European strategic autonomy in the internal manufacturing ecosystem. These include discrete manufacturing (e.g. manufacturing of automobiles, trains, airplanes, satellites, white goods, furniture, toys and smartphones), process industries (e.g. chemical, petrochemical, food, pharmaceuticals, pulp and paper, and steel), provisioning, and also production services, connected machines and robots. Emphasis is also given to any type of factories, productive plants and operating sites, value chains, supply chains and lifecycles.

Digitalisation continues to be regarded as a key enabler for the future success of European industry. This Chapter will address the potential for the development of topics such as responsive, smart and sustainable production, Artificial Intelligence (AI) in digital industry, industrial services, digital twins and autonomous systems. Nearly all of the topics in the Technology chapters of the SRIA are of vital importance to industrial applications. These include standardisation, engineering tools, cybersecurity and digital platforms. To digitise European industry, potentially all enabling technologies will need to be employed to realise the required competitive edge, and of course a focus on digital industry would not be complete without them.

Today, the digital landscape remains fragmented, with significant challenges in areas such as standardisation, interoperability, and translating research to real commercial impact. These challenges must be met effectively if we have to achieve a strong, greener, resilient, responsive European economy, where sustainable, human-centric solutions help Europe achieve strategic autonomy into the future.

3.3.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

As stated in the new industrial strategy for Europe ("Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: A New Industrial Strategy for Europe", Brussels)[140].

Europe needs an industry that becomes greener and more digital while remaining competitive on the global stage. The twin ecological and digital transitions will affect every part of our economy, society and industry. They will require new technologies, with investment and innovation to match. They will create new products, services, markets and business models. They will shape new types of jobs that do not yet exist which need skills that we do not yet have. And they will entail a shift from linear production to a circular economy.

The digital sector will also contribute to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint. Scalability is key in a digitalised economy, so strengthening the digital single market will underpin Europe's transition. Europe must also speed up investment in research and the deployment of technology in areas such as AI, 5G, data and metadata management.

European factories and machines already have a high level of automation and digitisation. Many of the leading end-user companies are European based, and Europe also has a number of significant system and machine building, engineering and contracting companies that have a competitive edge in automation and digitisation. The business environment is changing. Through specialisation in new or niche end products, production is becoming more demand-driven and agile, while it is increasingly geographically distributed. In addition, the outsourcing of auxiliary business functions such as condition monitoring and maintenance is gaining in popularity, leading to highly networked businesses. There are many opportunities for energy, waste, material, recycling optimisation, etc., over the value chains and across company boundaries. Such advantages can only be realised by having a significant increase in digitisation.

This transition should include the adoption of applications that do not require to be kept internal or confidential, as solutions based on web/cloud services allow for the mediation of key factors such as their use by non-AI professionals, off-line development of advanced criteria models and inferential engines through the expertise of specialised centres.

The exploitation of AI for core business functions generally requires a complete rethinking of data management and their use and tracking inside the supply chain. Instead, the implementation of a system of system (SoS) framework enables the data to be to capitalised on through appropriate actions, in which analysis and analytical tools usually reach their limits.

The actual value chain will come from existing installations, as it is unusual for new factories to be built. As new, fast and secure communication protocols will provide easy connectivity and interoperability across systems, this will enable the potential for extensive integration. Easy access to a secure internal network will provide all existing information to users at anytime and anywhere within the plant. Moreover, new interesting features could be accessed through cloud or edge-based computing systems. However, this will

2.2

140 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102

require new hardware infrastructure to be added to the plant, along with greater processing power to handle larger amounts of data.

Digital infrastructure and micro services will help evolve business models towards selling added value as a service. Investment in projects will create networks between vendors and providers. In modern business-to-business (B2B) relationships, ongoing R&D and industrial pilots will aim to deliver a range of after-sales services to end customers. Typically, such services will include condition monitoring, operations support, spare parts and maintenance services, help desks, troubleshooting and operator guidance, performance reporting, as well as the increasingly required advanced big data analytics, prognostics-based decision support, and management information systems.

Industrial services often represent 50% or more of industrial business volume, and this share is steadily growing. The share of services is generally higher in high-income countries than in low-income countries. The importance of service businesses in the future is obvious, since they also enable sustained revenue after the traditional product sales, with the service business being typically many times more profitable than the actual product sale itself.

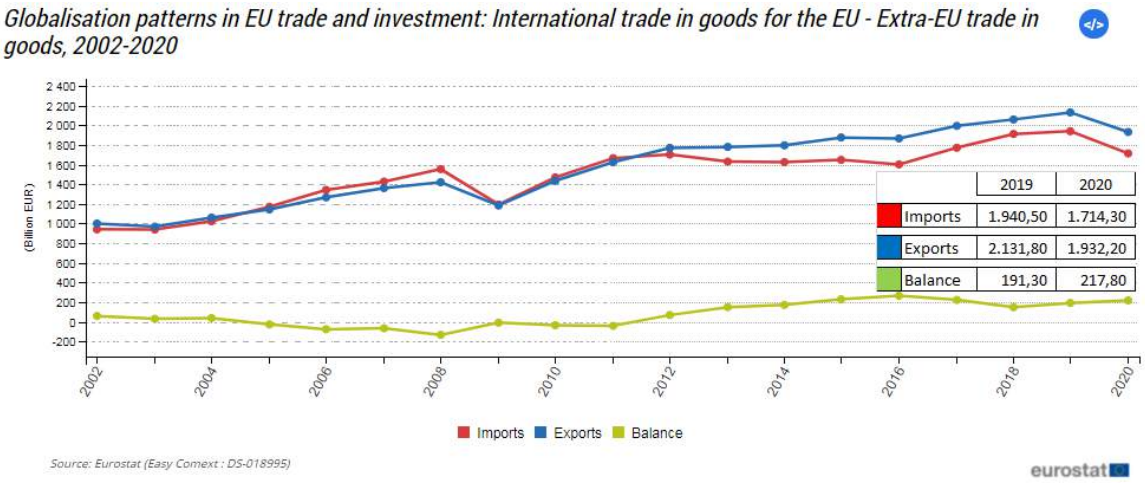
3.3.3 STRATEGIC ADVANTAGE FOR THE EU

It is important here to note the view of manufacturing from the recent Science Europe report, "Guidance Document Presenting a Framework for Discipline-specific Research Data Management".[141]

Europe is home to a competitive, wealth-generating manufacturing industry and of extremely comprehensive manufacturing ecosystems which accommodate complete manufacturing supply chains. Europe's manufacturing industry is the backbone of the European economy, bringing prosperity and employment to citizens in all regions of Europe.

The EU is a global market leader for high-quality products, and European Industry is the world's biggest exporter of manufactured goods, which represent 83% of EU exports. Thanks to the strengths of its manufacturing industry, the EU annually achieves a considerable trade surplus in the trade of manufacturing goods as depicted in the below diagram. This healthy surplus generated by the manufacturing industry allows the EU to finance the purchase of other, non-manufactured goods and services, such as raw materials, energy (oil and gas), and services. The surplus in manufactured goods thus compensates the deficits which are generated by purchasing non-manufactured goods. However, the surplus generated by EU's manufacturing sector cannot fully compensate these deficits anymore: the overall EU trade balance (considering manufactured goods) changed from a balance of €191,3 billion export surplus over imported manufactured goods in 2019 to a lightly higher value of €217,8 billion in 2020. From a macro- economic perspective, this is not a healthy situation in the long run. Nevertheless, this shows the importance of a strong manufacturing industry, because this happened during the pandemic period corresponding also to the first decrease of exports as depicted in the below picture of about €200 billions.

141 https://scienceeurope.org/our-resources/guidance-document-presenting-a-framework-for-discipline-specific-research-data-management/



F.58 *Trends according to Eurostat in International trade in goods for the EU – Extra-EU trade in goods in the period 2002 - 2020*

Although Europe's industry is a worldwide technology leader in most manufacturing market segments, this position is constantly being challenged by international competitors. While being highly competitive, statistics show that EU manufacturing industries constantly need to keep up with worldwide competition. Competitors, especially from Asian economies, have reached advanced levels, often supported by state-supported programmes and plans. Furthermore, industrial structures are changing with significant foreign investments, including those by emerging economies, in Europe and in the US. And finally, large-scale digitalisation, changes in trade rules, and global environmental concerns create new challenges, demanding EU industries to strongly invest in new technologies and reinforcing synergies internally to the EU rich supply chain.

In addition, it is worth noting the perspective of the recent P4Planet 2050 Roadmap of SPIRE, "Transforming the European Process Industry for a Sustainable Society".[142]

Process industries are an essential part of the European economy. Process industries are crucial components of numerous value chains that deliver goods and services to our society and to European citizens. The materials produced by the process industries ultimately aid in providing shelter and housing to families, transporting passengers or freight, offering comfortable working spaces, producing and preserving food and beverages, and producing the sophisticated devices needed in modern healthcare and high-tech digital world. In other words, process industries enable the life we are living. Currently the process industry provides about 6.3 million jobs directly and 19 million indirectly. Process industries continuously attract talents and incite academia to train the next generation of experts. Process industries contribute about €565 billion/year to GDP, drive innovation, and develop solutions for societal problems.

Focused innovation efforts will transform the European process industries, which will adapt existing processes and develop disruptive new digital ones to fulfil the needs of this society in transition, both in the short and the longer term. New solutions (both technical and non-technical) are crucial. As major technological challenges are similar across process industries, increased collaboration is needed inside

142 https://ec.europa.eu/info/sites/default/files/research_and_innovation/funding/documents/ec_rtd_he-partnerships-industry-for-sustainable-society.pdf

EU industrial supply chain in a empowered Edge-to-Cloud Continuum landscape. Europe and its process industries can only succeed in solving the puzzles of climate change and circularity if they jointly define and implement ambitious research, innovation, industrial and financing policies enabling fast and smooth transitions.

As many process industries compete on a global playing field, the competitiveness of these industries needs to be safeguarded throughout the transition. The transformation of EU process industries requires unprecedented levels of investments. If new technologies come at higher cost without a predominant EU ownership, there is a risk that European process industries lose their competitiveness. This needs to be avoided through an effective policy framework, but competitiveness can also be boosted by innovation and scale (e.g. driving down cost of process technologies or of inputs).

3.3.4 MAJOR CHALLENGES

Six Major Challenges have been identified for the Digital Industry domain:

- **Major Challenge 1**: responsive and smart production.
- **Major Challenge 2**: sustainable production.
- **Major Challenge 3**: artificial Intelligence in digital industry.
- **Major Challenge 4**: industrial service business, lifecycles, remote operations and teleoperation.
  Major Challenge 5: digital twins, mixed or augmented reality, telepresence.
- **Major Challenge 6**: autonomous systems, robotics.

3.3.4.1 Major Challenge 1: responsive and smart production

3.3.4.1.1 Status, vision and expected outcome

Responsiveness, flexibility and smartness is currently considered inside the European productive landscape based on pre-Industry 4.0 automation technology. At the same time, in addition to the critical situations to be handled, European Industry must be much more responsive to any changes that may occur, not only from a scientific and technological point of view.

Current automation solutions are not inherently flexible by their design.
Adaptive and self-learning systems principles must be applied to automation solutions. Thus enabling automation system and solution flexibility, responsiveness and smartness.

Many European initiatives and reports cover this topic:

- European Factories of the Future Research Association (EFFRA[143]) name as a key priority the Agile and robust optimal manufacturing to respond quickly to changing customer demands, fluctuating characteristics of raw materials or components, and advanced emerging technologies that can be potential differentiators ".

143 https://www.effra.eu/sites/default/files/190312_effra_roadmapmanufacturingppp_eversion.pdf

- SMART-EUREKA[144] mentions "intelligent and adaptive manufacturing systems" as a main research and innovation domain.
- ManuFuture[145] claims that "the European manufacturing system in 2030 must be resilient and adaptive to cope with a rapidly changing and unpredictable environment, overcome disruptions and adapt to meet the changing market needs".
- In their 2020 report, World Manufacturing calls to "leverage on AI to detect and respond to disruptions in supply networks".

The main benefits of a more responsive and resilient production are:

- Ability to forecast the evolution of the demand-offer-competition ecosystems.
- Capability to rapidly change production and provisioning.
- Efficiency to become profitable with high-mix, low-volume production.
- Capacity to operate, even with decreased operational capability.
- Enable rapid concrete innovation, not exclusively via rapid integration and product evolution but also re-engineering the overall process and components production.
- Limit deterioration in performance, reliability, maintainability and interoperability when plants face disturbances.

ECSEL and Key Digital Technologies (KDT) will play a lead role in this evolution to more responsive, robust and resilient factories. From sensors integrated in wearables and prosthetics, to SoS that enable self-healing and self-reconfiguration, responsive and resilient manufacturing has always been an important challenge.

Similarly, AI should be used to augment the flexibility of manufacturing systems. Although the current trend of deep learning is opening up limitless possibilities in some areas, it is necessary to apply other AI approaches so that systems are more aware of the environment of the task at hand and themselves.

The impact of Covid-19 has highlighted many of the reasons why a flexible factory needs to adapt better in times of change to be a more useful part of the European response to such crises by:

- Modifying production based on medical needs and exogenous inputs.
- Scheduling production with less human resources and social distancing constraints.
- Empowering agile working and telepresence.
- Adapting to changes in the supply chain, promoting European independence.
- Developing capacity for in-kind, or inside a shorter supply chain for the production of components that usually come from the worldwide market-based supply chain.
- Developing capacity for redesign and re-engineering, due to lack of raw materials and electronic components.

Although automation and digitization are the building blocks for building a flexible, resilient manufacturing industry, the importance of a well-trained and agile workforce cannot be overestimated. Technologies like AR and VR promise to simplify the cross-training of operators, maintenance tasks etc. but these promises have yet to come to fruition.

In terms of standardisation, standards are a significant and necessary part of all industrial applications. The modern digitalisation of industry could not exist without standards, as without standards interoperability would not be possible. They enable extensive industrial projects while ensuring quality, safety and reliability.

144 https://www.smarteureka.com/mediafiles/2/1570714583-20190908-technology-roadmap-en.pdf

145 http://www.manufuture.org/wp-content/uploads/Manufuture-Vision-2030_DIGITAL.pdf

Many engineering methods are standardised, and provide textbook consistency across professional engineering. However, standards must also be supported by the relevant engineering tools, etc., as those required for design or development are different from those required at the operation stage.

3.3.4.1.2 Key focus areas

- Robust optimal production, scalable first-time-right production: future manufacturing plants should become more robust in the sense they can continue production even when facing a disturbance. This will require advances in, for example, self-healing and redundant automation systems, first-time-right, zero-defect manufacturing, and predictive maintenance empowering very adaptable production.
- Mass customisation and personalised manufacturing, customer-driven manufacturing, mastering the complexity of products, processes and systems: progress in recent years towards lot-size-one manufacturing and personalised product design will continue to grow in the next few years.
- Resilient and adaptive production, including the shortening of supply chains and modular factories: resilience is a critical property for systems that can absorb internal and/or external stresses and adjust their functional organisation and performance to maintain even with a reduced productivity the necessary operations without any breaks for accomplishing their objectives under varying conditions and with the ability to overcome such stress for getting back to the ordinary condition of functionality and productiveness.
- Cognitive production: this involves deploying both natural and artificial cognition to enable new analyses and learning that can enable responsive and sustainable adaptable production. For example, real-time monitoring against lifecycle assessment (LCA) criteria can be facilitated by the implementation of AI. More generally, it is important for cognitive production to support the emergence of simplicity rather than the combinatorial growth of complexity when complex cyber-systems are combined with complex physical systems.
- Manufacturing as a service (MaaS): technological advances have the potential to expand the geographical distribution of manufacturing and facilitate manufacturing as a service (a well-known example of that is 3D printing). The trend to move part of labor-intensive production into high value manufacturing exploits MaaS, allowing to heterogeneous excellences to become outsourced parts of production chains, replacing the needs to have dedicate lines and even the same factory (factoryless goods). Another interesting opportunity for manufacturing as a service is moveable factories, which circumvent the need for new industrial infrastructure. The scope for moveable factories is enhanced by the range of manufacturing machines and power sources that are becoming increasingly small and light enough to fit into trucks, trailers, carry cases, etc. MaaS empower the dynamic aspects of outsourcing, provisioning, making the supply chain ecosystem more resilient.
- Embedded/Edge/Cloud architectures: nowadays system architectures mainly consist of three layers of computing devices, see *Figure F.24* in Chapter 2.1 *Embedded computing* reside very close or attached to the machinery or process. *Near Computing* devices (2) are often called *edge computers*, routers, or local servers. Near computer nodes are powerful computers themselves and communicate both to the embedded computing cards and to the *cloud* (3) via internet. A special boost in the picture comes from the 5G technology. There, the 5G communication technology takes care of the edge-to-cloud and edge-to-edge communication which will be faster than anything before. The 5G base stations, called peripheral structures and/or edge nodes, are no longer mere antenna poles but equipped with very powerful computing nodes, and the densely installed 5G base stations will take the role of edge computers. Workload and services

1.4
2.1
2.2

are moved from the centralised data centers (core network) to the proximity, benefiting mainly latency which is crucial for time critical application and services.

- Standardisation: due to the ongoing legacies of the many existing standards and their installed base (number of units of a product or service that are actually in use), focus should be on bridging the systems of the various standards. This should involve developing semantic technologies to master these diverse and numerous standards, including software or platforms that enable effective connectivity at a high application level, as well as respective digital testing, development environments and licencing. This is key to ensure there is wide acceptance and support of software vendors, engineering offices and end-users.

3.3.4.2 Major Challenge 2: sustainable production

3.3.4.2.1 Status, vision and expected outcome

This Major Challenge focuses on how Industry 4.0 should address the future regulation or market requirements emerging from the European Green Deal and zero-carbon (or below carbon-neutral) operations.

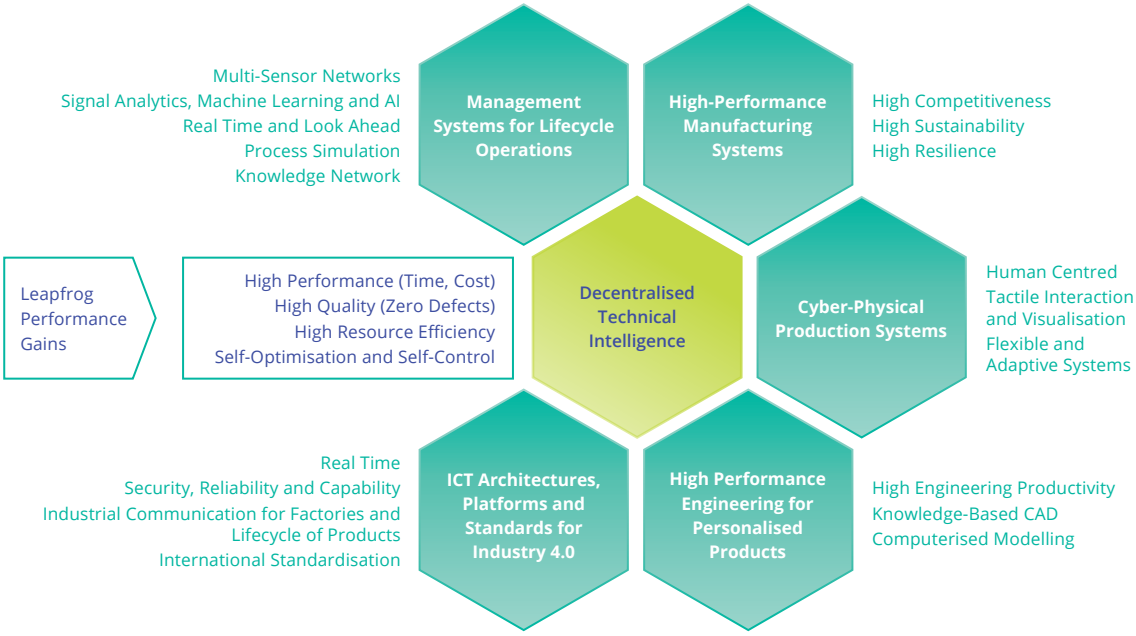
Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2°C. The rapid transformation of all sectors is therefore required. In fact, many European countries have set even more ambitious targets, and European research programs could have a great bearing in reducing environmental impact through sustainable manufacturing, including energy- and resource-efficiency and by applying circular economy strategies (eco-design, repair, re-use, refurbishment, remanufacture, recycle, waste prevention, waste recycling, etc.).

There are some so-called rare earth metals to save, and any kind of careless materials usage can be proven uneconomical and risk to the environment. The vision of Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) categorises the high-level goals discussed above into more practical action, as follows.

3.2 3.5

- Use energy and resources more efficiently within the existing installed base of industrial processes. Reduce or prevent waste.
- Re-use waste streams and energy within and between different sectors, including recovery, recycling and the re-use of post-consumer waste.
- Replace current feedstock (raw material to supply or fuel a machine or industrial process) by integrating novel and renewable feedstock (such as bio-based) to reduce fossil, feedstock and mineral raw material dependency while reducing the CO_2 footprint of processes or increasing the efficiency of primary feedstock. Replace current inefficient processes for more energy consumption reduction.
- Resource-efficient processes when sustainability analysis confirms the benefits.
- Reinvent materials and products to achieve a significantly increased impact on resource and energy efficiency over the value chain.

ManuFUTURE Vision 2030 combines these objectives as shown in *Figure F.59*.



The visionary manufacturing system for adding value over the lifecycle with decentralised technical intelligence (Source: ManuFUTURE, "Strategic Research And Innovation Agenda (SRIA) 2030" [146])

F.59

3.3.4.2.2 Key focus areas

- Monitoring flows of energy, materials, waste and Lifecycle assessment: it is already commonplace in many industry sectors (food, medicine, etc) that material and energy streams need to be fully traced back to their starting point. As more and more products, raw materials, etc, become critical, this implementation strategy must be expanded. Flows need to be monitored. Sustainable manufacturing needs comprehensive environmental data and other measurements that may have been in place when the relevant manufacturing or production was initiated. On the other hand, this is a very typical application for many types of IoT sensor and systems that can be informed by careful LCA. LCA is a prerequisite for holistic environmental evaluation, and it is a simple but systematic method that requires a mixed combination of extensive and comprehensive models and data.
- Virtual AI assistants: discharges or losses mostly happen when production does not occur as planned, due to mistakes, the bad condition of machinery, unskilled operation, and so on. Human factors cause most of the variation in the running of continuous processes. There should therefore be a focus on how an AI assistant or AI optimiser could be used to help operators by providing advice and preventing less than optimal changes.
- Human–machine interfaces and machine-to-machine communications: augmented reality (or virtual reality) will be used to support a number of tasks. Enhanced visualisation of data and analytic results will be required to support decision-making.
- Human operators in more autonomous plants and in remote operations. The relationship between machines and the human factor needs to be rethought. In terms of the logic of human-machine interface, from touch displays, to wearable devices and augmented reality, but also to maintain the centrality of the human factor within the new contexts. The "Skills 4.0" are necessary

1.2 1.3 1.4

146 http://www.manufuture.org/wp-content/uploads/ManuFUTURE_SRIA_2030_Vfinal.pdf

for the management of new technologies for data administration, for privacy, for cybersecurity and much more.

- Human safety: with the localisation of personnel, machines and vehicles, situation-aware safety (sensing of safety issues, proximity detection, online human risk evaluation, map generation, etc) will become increasingly vital.
- Competence and quality of work in an human-centred manufacturing: at a strategic level, the European automation and industrial IT industry depends on its ability to attract skilled personnel to maintain their competence over time. A higher level of formal training may be required for workers in production and maintenance. Greater specialisation is constantly introducing products and processes that require greater company-specific training.
- Green Deal: policy initiatives aimed at putting Europe on track to reach net-zero global warming emissions by 2050 are key to the European Commission's European Green Deal. The Commission the highly challenging objectives of the Green Deal, all industries must focus on high efficiency, low energy usage, carbon-neutrality or zero-carbon usage, zero waste from water, soil and air – all measured, calculated or estimated on product, factory, global and lifecycle levels. European industry must research and discover new materials while paying a great deal of attention to recycling, re-use, and de- and re-manufacturing.

1.3 2.1

Many of these advances will require extensive development in the other engineering, business or social domains, even at the individual level, that are outside of the ECS domain. However, it is also obviously the case that a growing part of these approaches will be implemented through the significant help of electronics and software technologies. The need for ECS/KDT technologies is diverse, and it is not useful to indicate one single technology here. High performance, high precision, careful and professional engineering and decision-making are needed – often at a much higher level than today.

3.3.4.3 Major Challenge 3: Artificial Intelligence in digital industry

3.3.4.3.1 Status, vision and expected outcome

Major Challenge 3 focuses on connected and smarter cyber-physical systems (CPS), industrial internet, big data, machine learning and AI. Local edge-based intelligence is seen as an opportunity for Europe. This Major Challenge extends toward AI-enabled, adaptable, resilient factories, including the human as a part of a "socio-technical" system. AI in combination with (predictive) condition monitoring and maintenance will be applied to not only support reconfigurable first-time-right/zero-defect manufacturing, but also to support human decision-making (considering uncertainties), as well as enabling resilient manufacturing ecosystems based on new business models, increasing safety & security in working environments and improving productiveness and quicker return from investments. An important challenge here is to lead not only the digital transformation of Industry 4.0, but the next generation of ECS/KDT platforms supporting AI-driven human-centric autonomous Industry 4.0 operations. Condition monitoring techniques can be applied to many types of industrial components and systems, although often at additional cost. Commonly, the business value required from condition monitoring depends on the higher availability of equipment and, for production processes, information provision to be able to plan and act on maintenance proactively instead of reactively, as well as to offer decreased cost and improved on-time delivery. Other business values that may be of interest are safety and the optimal dimensioning/distribution of spare parts and maintenance staff. Thus, serious breakdowns and unplanned interruptions to production processes can largely be avoided using condition monitoring.

AI will impact several main areas, all of which are relevant to Digital Industry improving:

- Productivity, by exploiting AI in the design, manufacturing, production and deployment processes.
- Flexibility, by using AI throughout the value stream, from supply to delivery, increasing the autonomy and resilience of each process in the value chain.
- Customer experience, by using AI to make products faster and with better quality, and to provide more efficient services.
- Assistance to human operators in circumstances of rising complexity by using AI to support the decision-making process with ever-increasing levels of complexity and dynamics.

These fundamental impacts will be experienced in all areas of every market sector. In manufacturing and production, AI will deliver productivity gains through more efficient resource, energy and material use, better design and manufacturing processes, and inside products and services, enhancing their operation with more refined contextual knowledge.

The agenda here is cross-sectorial, focusing on AI applied in any domain. However, the impact of AI in Digital Industry is of particular significance. A joint paper by the Big Data Value Association [147] (BDVA) and euRobotics[148] has noted that roughly 50% of the opportunities for exploitation of AI are in manufacturing ("Strategic Research, Innovation and Deployment Agenda for an AI PPP: A Focal Point for Collaboration on Artificial Intelligence, Data and Robotics"[149], Third Release, September 2020).

3.3.4.3.2 Key focus areas

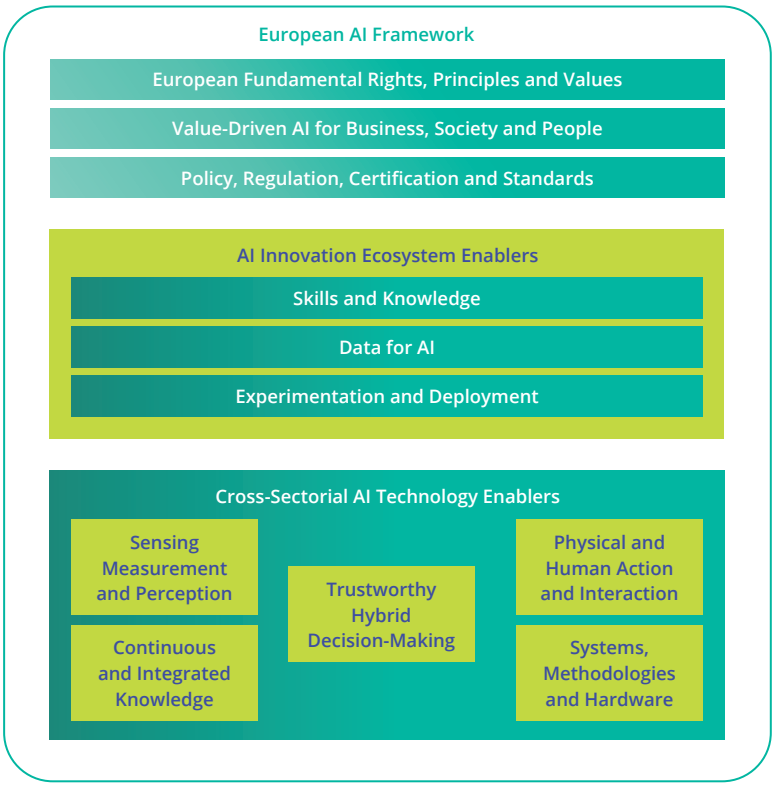
a. European AI framework

Figure F.60 sets out the context for the operation of AI public/private partnerships (PPPs), as well as other PPPs or joint undertakings (JUs). It clusters the primary areas of importance for AI research, innovation and deployment into three overarching areas of interest. The European AI framework represents the legal and societal fabric that underpins the impact of AI on stakeholders and users of the products and services that businesses will provide. The AI innovation ecosystem enablers represent essential ingredients for effective innovation and deployment to take place. Finally, the cross-sectorial AI technology enablers represent the core technical competencies that are essential for the development of AI systems.

147 https://www.bdva.eu/

148 https://www.eu-robotics.net/

149 https://ai-data-robotics-partnership.eu/wp-content/uploads/2020/09/AI-Data-Robotics-Partnership-SRIDA-V3.0-1.pdf



F.60 *European AI framework and enablers –SRIDA on AI, Data and Robotics Partnership*[150]

b. AI in manufacturing:

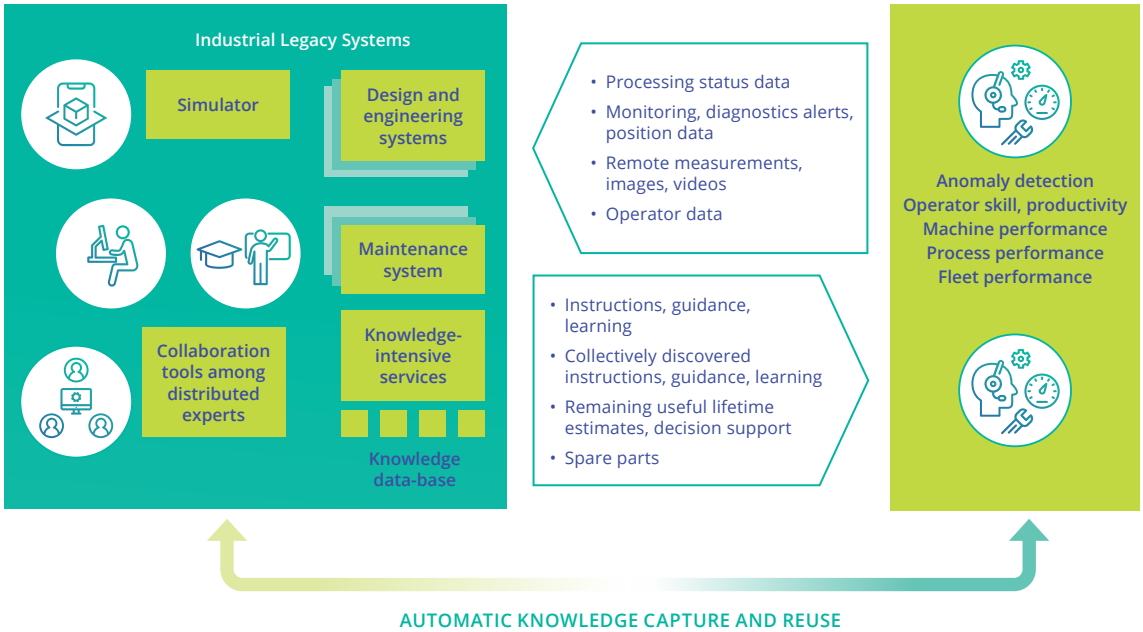
- AI for dynamic production planning and management: this involves taking real-time decisions to optimise the factory operation by quickly modifying the productions schedule, based on the current state of the shop floor, predicted sales orders, unexpected events such as machine breakdowns or changes in job prioritiesc, etc.
- Virtual models spanning all levels of the factory life and its lifecycle: a holistic and coherent virtual model of the factory and its production machinery will result from the contribution and integration of modelling, simulation and forecasting methods and tools that can strategically support manufacturing-related activities.
- AI for green/sustainable manufacturing: the development of software-based decision-support systems, as well as energy management, monitoring and planning systems, will lead to overall reduced energy consumption, more efficient utilisation and optimised energy sourcing.
- AI applied in supply chain management: planning and managing logistics for real-time operations, collaborative demand and supply planning, traceability, and execution, global state detection, time-to-event transformation, and discrete/continuous query processing would therefore be a challenge in view of the distributed nature of these elements. AI for advanced manufacturing processes: The ability to design functionality through surface modifications, functional texturing and coatings, enabling improved performance,

1.4 2.1

150 *https://bdva.eu/sites/default/files/AI-Data-Robotics-Partnership-SRIDA%20V3.1.pdf*

embedded sensing, adaptive control, self-healing, antibacterial, self-cleaning, ultra-low friction or self- assemblies, for example, using physical (additive manufacturing, laser or other jet technologies, 3D printing, micromachining or photon- based technologies, physical vapour deposition, PVD) or chemical approaches (chemical vapour deposition CVD, sol–gel processes) will deliver high functionality and hence high-value products.

- AI for adaptive and smart manufacturing devices, components and machines: embedded cognitive functions for supporting the use of machinery and robot systems in changing shop floor environments.



Industrial service business between a machine or system vendor or service provider and an end-customer. Services or lifecycle businesses deal with, for example, anomaly detection or condition management, operator skills development, productivity issues, machine or system performances, and fleet performances.

F.61

c. AI for decision-making

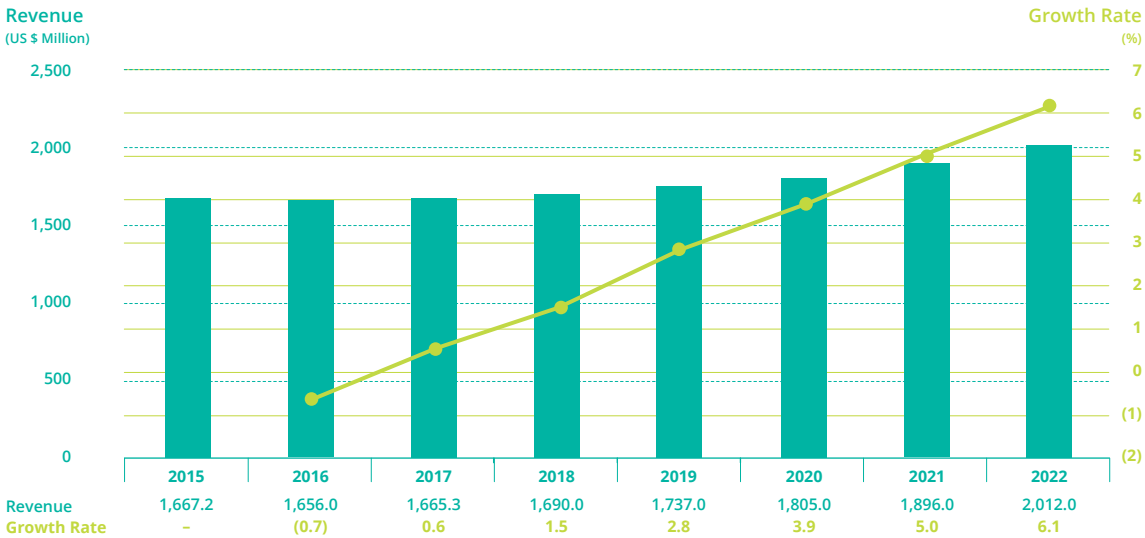
Decision-making is at the heart of AI:

- AI can support complex decision-making processes or help develop hybrid decision-making technologies for semi-autonomous systems.
- Human decision-making, machine decision-making, mixed decision-making and decision support.
- Sliding or variable decision-making, dealing with uncertainty.
- AI for human interaction with machines.

2.4

TOTAL EAM SOFTWARE MARKET: SERVICES REVENUE FORECAST, GLOBAL, 2015–2022

CAGR, 2017–2022 = 3.9%



F.62 *Global Enterprise Asset Management Software Market, Forecast to 2022 (Source: Global Enterprise Asset Management Software Market, Forecast to 2022. Frost & Sullivan, January 2018)*

d. AI for monitoring and control:
   - AI for control technologies.
   - AI for monitoring services.
   - AI for maintenance systems for increased reliability of production systems.
   - AI services for continuous evaluation and mitigation of manufacturing risks.
   - AI for quality inspection.

1.4

3.3.4.4 Major Challenge 4: industrial service business, lifecycles, remote operations and teleoperation

3.3.4.4.1 Status, vision and expected outcome

The volume and value of industrial services are increasing by between 5% and 10% every year. The share of services has exceeded the share of machinery for many machines, system and service vendors – not just for a final assembly factory, but also for companies in supply chains. Companies are willing to take larger shares of their customers' businesses, initially as spare part suppliers, but increasingly for remote condition monitoring, as well as extending this to a number of those tasks previously considered as customer core businesses. From a customer point of view, such a shift in business models lies in the area of outsourcing.

Industry as services is changing the production through use of externalization moving local tasks to external and ever more specialized providers, benefiting of greater flexibility, resilience and adaptability on production; a new proposition of supply chain is embedding all production phases, from the procurement of raw materials and semi-finished products up to the customer services and/or the design of parts or whole final product.

While many businesses have become global, some services are still provided locally, at close to customer's locations, while other services are provided centrally by the original vendor or companies specialised in such services. Similarly, as there may be extensive supply chains underpinning the vendor companies, the respective services may also extend to supply chain companies. The industrial era is becoming a service era, enabled by high-end ECS/KDT technologies. This distributed setting conveniently fits into modern edge-to-cloud continuum innovative architectures as computing power engines and infrastructures enabling emulation, training, machine learning and communication platforms enabling real-time interconnections.

1.4

The importance of service businesses to the future is evident as they enable a revenue flow beyond traditional product sales, and more importantly they are typically much more profitable than the product sales itself.

The service business markets are becoming more and more challenging, while high income countries are focusing on the high-skilled pre-production and lifecycle stages. Fortunately, in the global service business market, Europe can differentiate by using its strengths: a highly skilled workforce, deep technology knowledge and proven information and communications technology (ICT) capabilities. However, to ensure success it needs new innovations and industry-level changes.

3.3.4.4.2 Key focus areas

1.4

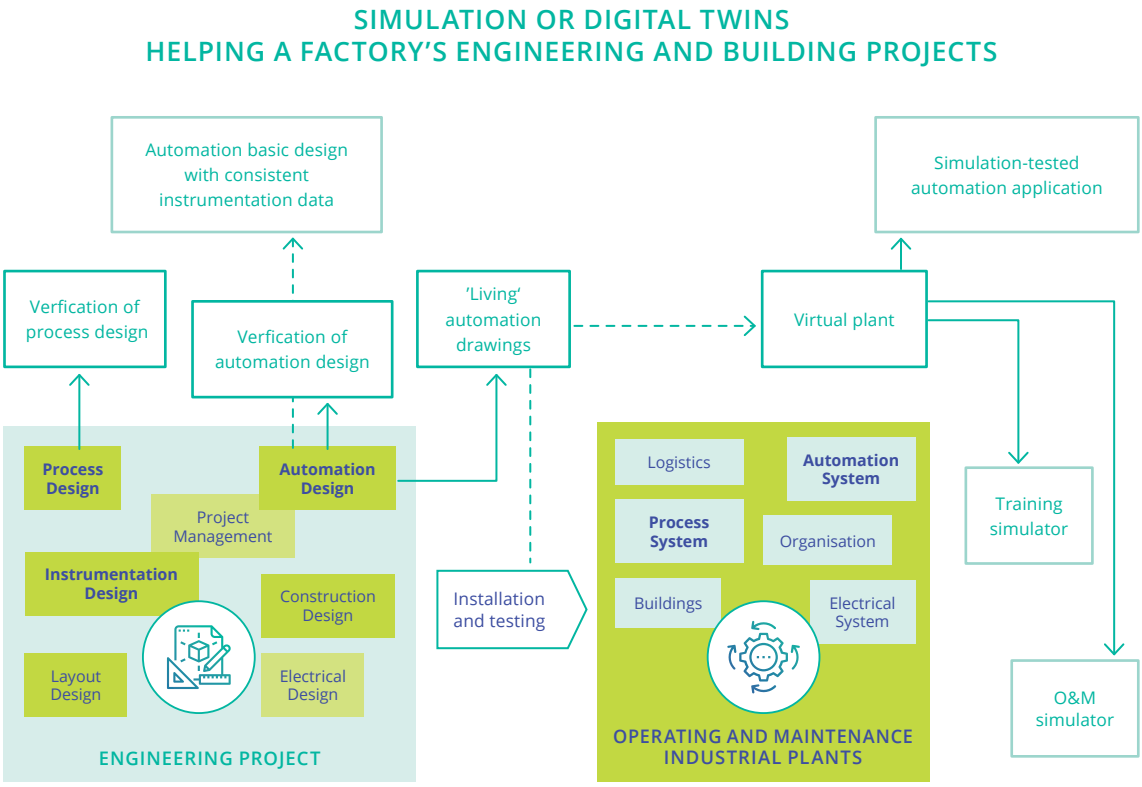
- Remote operations, teleoperation:
  - Remote engineering and operations, telepresence: operating or assisting in operations of industrial systems from remote sites.
  - Edge/cloud solutions: implementing distributed service applications on effective edge cloud systems.
- AI Services for monitoring and collaboration:
  - Collaborative product-service engineering, lifecycle engineering: extending R&D to take into account how products and systems will be integrated into the industrial service programme of the company. This should possibly be enhanced by obtaining further knowledge to provide services for other similar products (competitors!) as well their own installed base.
  - Training and simulation: complex products such as aircrafts, drones, moving machines and any tele-operated machineries need a simulation environment for proper training of the human driver/operator.
  - Condition monitoring, condition-based maintenance, anomaly detection, performance monitoring, prediction, management: the traditional service business sector is still encountering major challenges in practice. It will therefore require an extension to the above, as targets of services are expanded to other topics in customer businesses in addition to spare parts or condition monitoring.
- Fleet management, Edge and local/global decision making:
  - Decision and operations support: in most cases, decision-making is not automatic, whereas in the future it could be based on remote expert assistance or extensive diagnosing (AI-based, etc), engineering, and knowledge management systems.
  - Fleet management: this could benefit on the basis of sold items, by obtaining knowledge and experience from range of similar components and machines in similar or different conditions.
- Business services integration:
  - Local and global services: organising services locally close to customers and centrally at vendors' sites.

– Full lifecycle tutoring: monitoring activities, level of stress and performance-oriented behilityaviour during the product's life, from anticipating its end of life to properly handling its waste and recycling, including improved re-design for the next generation of products.

3.3.4.5 Major Challenge 5: digital twins, mixed or augmented reality, telepresence

3.3.4.5.1 Status, vision and expected outcome

A "digital twin" is a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance and behaviour of their machines, and also to find new revenue streams. Currently, connectivity to the cloud allows an unprecedented potential for the large-scale implementation of digital twin technology for companies in various industries. A physical asset can have a virtual copy running in the cloud, increasing revenue through continuous operational data.



F.63 *Simulation or digital twins helping a factory's engineering and building projects*

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

2.3

In addition to virtual commissioning, modelling and simulation can more widely respond to many digitalisation challenges:

- Visualising physical or real-world phenomena of products, production, businesses, markets, etc.
- Helping designers to perform their core tasks – i.e. studying alternative designs, optimising solutions, ensuring safety, and providing testing for automation and Internet of Things (IoT) solutions.
- The effects of changes can be safely and more comprehensively assessed in advance in a virtual domain rather than using real plants, equipment or even mock-ups.
- Simulators offer versatile environments for users or operator training.
- It is evident that former computer-aided design (CAD)-driven digitalisation is shifting the focus towards simulation-based design.

Simulators may be used online and in parallel with its real counterpart to predict future behaviour and performance, provide early warnings, outline alternative scenarios for decision-making, etc., although they have years of research behind them, such tracking simulators are to be co-designed and improved exploiting also recent investments in computing infrastructures (e.g. HPC EU families, EPI initiative), with a special focus on the industrial context.

Telepresence technologies can also be considered as the predecessor for an extended reality (XR) presence. The combination of new and advanced technology like e.g. XR, AIoT, Edge, HPC, 5G and open integration platforms offers significant potential for innovation, which would benefit the evolution of European digital industry.

1.4

As an example XR is a combination of virtual and augmented reality, and an XR presence is a continuum between a physical reality presence and a virtual reality presence. The main driver here is improving competitiveness through better productivity, more effective worker safety and better quality. The industrial applications have followed the prospects offered by the gaming industry and consumer applications. One of the reasons for its increased take-up is the declining cost of electronic components and sensors.

As some major smart glass producers will provide technology and platform for the consumers, other EU industrial groups could do the same and at EU industrial ecosystem could take benefit of such devices and provide industrial use cases. These can be extended then to state-of-art applications. Back-end services are Digital Twins and Condition Monitoring systems that will provide critical and useful information for the Field Worker. Longer vision for the integration human actions and back-end data servers can be used to build knowledge graphs to help other users to work like experts. As a summary smart glasses can extend human understanding and knowledge if services and information flow can be utilized and formed to usable knowledge.

1.2

3.3.4.5.2 Key focus areas

2.3

- Digital Twin, design process digitalization, telepresence:
  - Heterogeneity of systems: information sharing and standards and means to ensure interoperability of digital twins and their information sources are important to facilitate information synchronisation. Having all relevant engineering disciplines (processes, assembly, electronics and electrical, information systems, etc.) evolving together and properly connected over the lifecycle phases is therefore crucial. This also involves multi-domain simulation, joint simulation of multi-simulation systems coupling.
  - Immersive telepresence for industrial robotics from design toward production lines and any other operational scope.

  - Digital twins applied to sustainability and circular economy: simulate the usage of energy, use of raw material, waste production, etc., with the goal of improving energy efficiency and circular economy performance.
- Virtual commissioning, interoperability:
  - Virtual commissioning: digital twins applied to virtual commissioning to bring collaboration between different disciplines and models from domains of engineering (mechanic, electronic, automation) in the same environment.
  - Interoperability: applications cannot yet be used across platforms without interoperability.
- Simulators: Tracking & Simulator based design:
  - Tracking mode simulation: model adaption based on measurements. Generating simulators automatically from other design documentation, measurements, etc. Generation of simulators from 3D, data-driven models, etc.
  - Simulator-based design: digital twin for testing the designed model by replacing the required physical components with their virtual models. This offers continuous design improvement (the digital twin provides feedback and knowledge gained from operational data), design optimisation, etc.
- Digital twins combined with data-driven models (knowledge and data fusion): combination of data-driven and knowledge-based models along the complete lifecycle (product and production). The real challenge is to combine physics and knowledge-based models (digital twins) with data-driven models (models created using AI from massive acquired experimental data), capitalising on the strength of information present in each of them.
- Humans & Knowledge integration:
  - Human-in-the-loop simulations: methods and simulations for human-in-the-loop simulations and integration of digital twins in learning systems for workers.
  - The 3D Internet platform: to integrate all of the aforementioned aspects into a single powerful networked simulation for humans to get the Situational Awareness for an industrial process as a whole.

3.3.4.6 Major Challenge 6: autonomous systems, robotics

3.3.4.6.1 Status, vision and expected outcome

Machines are usually more precise and efficient than humans when carrying out repeatable tasks. Thus, replacing or aiding work processes susceptible to human errors, quality defects and safety issues with machines will have an impact on quality and redundant waste. In some industries (such as construction, aerospace and automotive), the critical infrastructures of complex systems, and utilities, quality issues and the prevention of hidden defects in structures and/or any mechanical and electrical components are extremely serious. Therefore, substantial losses in terms of legal aspects, safety, potential stresses under critical situations of vehicles and aircrafts, substandard end products, and quality costs in general, are potentially damaging.

There are many kinds of autonomous systems, robots and working machines. These can be categorised by purpose, as follows.

- Industrial machines and robots:
  - Manufacturing (e.g. welding, assembling, spray gun robots).
  - Material handling (e.g. conveyors, warehouse robots, trucks).

- Consumer robots:
  - Domestic (e.g. robotic lawn mowers or vacuum cleaners).
  - Care (e.g. lifting or carrying robots).
- Healthcare and medical robots:
  - Robotic surgery, hospital ward automation.,
  - Medical tests and hospital care, remote healthcare.
  - Medical imaging, exoskeletons.
- Moving machines:
  - Mining machines (e.g. drilling machines, dumpers, conveyors).
  - Forestry (e.g. forest harvester), agriculture (e.g. tractors, appliances).
  - Construction (e.g. excavators, road graders, building robots).
  - Logistics and sorting centres (e.g. cranes, straddle carriers, reachers, conveyor belts, sorting machines, trucks).
  - Military robots and machines.
- Transport:
  - Vehicles, trucks and cars, trains, trams, buses, subways.
  - Aviation (e.g. aeroplanes, helicopters, unmanned aerial vehicles, UAVs).
  - Marine (e.g. vessels, ships, auto-piloted ships), submarine (e.g. auto-piloted submarines).
- Utilities and critical infrastructures:
  - Extraction (e.g. drills for gas, oil).
  - Surveillance (e.g. quadcopters, drones).
  - Safety, security (e.g. infrared sensors, fire alarms, border guards).
  - Energy power plants sensors and actuators (e,g, production and distribution).
  - Transportation (e.g. moving bridges, rail exchanges).

The main aims and evolution trends of robots and autonomous systems in digital industry are oriented toward:

- production efficiency, speed and reduced costs,
- higher precision and quality,
- safety in working conditions.

As is evident from the above, robots and machines are involved in several application Chapters of this SRIA in addition to Digital Industry – i.e. Digital Society, Health and Wellbeing, Mobility, and Agrifood and Natural Resources.

3.1 3.4 3.5 3.6

There is undoubtedly a move to increase the level of automation and degree of digitalisation in industry, which will ultimately lead to fully autonomous systems. Moreover, there are some outstanding flagship programmes already launched (for autonomous driving, for example). Also, some mature manufacturing phases, or even entire production lines, are already practically fully autonomous.

However, between the two extremes of entirely manual and fully autonomous there will always lie a large area of semi-autonomous equipment, units, machines, vehicles, lines, factories and sites that are worth keeping somewhat below 100% autonomous or digitised. The reasons for this include:

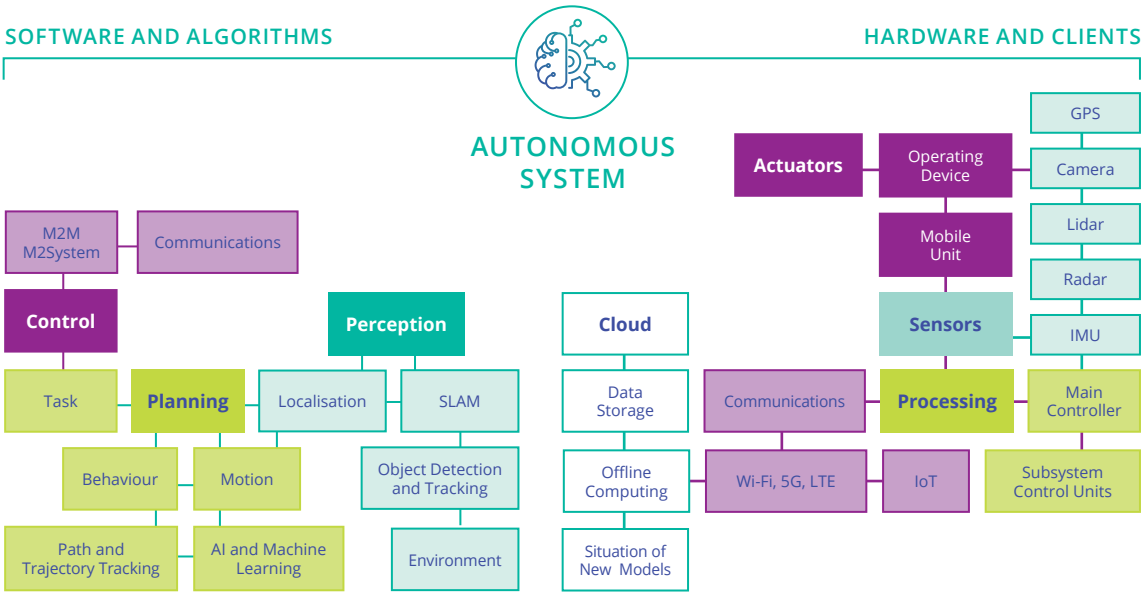
- A fully autonomous solution may simply be (technically) near to impossible to design, implement and test.
- If achievable, they may be too expensive to be realised.
- A fully autonomous solution may be too complex, brittle, unstable, unsafe, etc.
- A less-demanding semi-automatic solution may be easier to realise to a fully satisfactory level.

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

3.3.4.6.2 Key focus areas

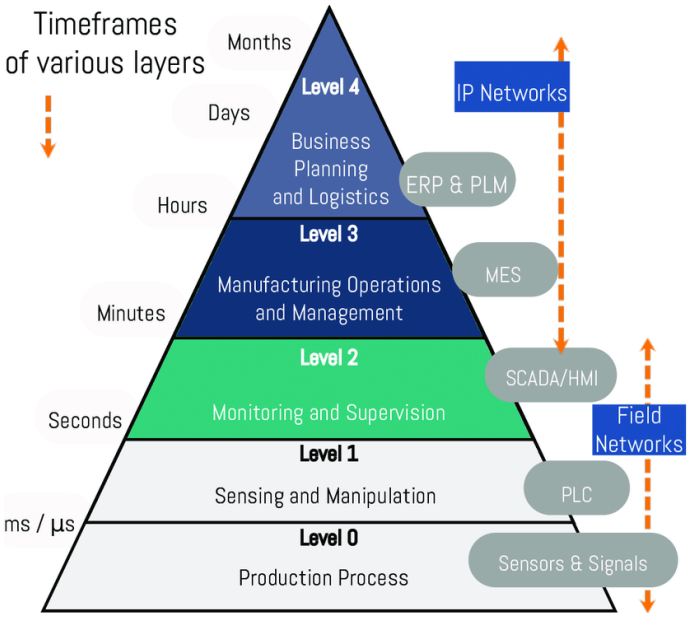
a. Autonomous functions of systems:

- Fully autonomous vehicles are expected to play a key role in the future of urban transportation systems. Such a challenge in a so complex scenario will promote significant advances in any autonomous functions of the many systems which are integral part of the Digital Industry ecosystem. Autonomous robots are key enabling systems towards implementation of autonomous functions shopfloors. Immediate benefits will be additional safety, increased productivity, greater accessibility, better efficiency, and positive impact on the environment. The strong technological demand to complement and follow the human intellectual effort is the need for available computing power and reduced cost in sensing and computing technologies. Here follows a modified picture from giving a generalized view of autonomous systems technologies and functionalities focused on autonomous vehicles, but with a rich affinity with any sort of autonomous system.



F.64 *A generalised overview of autonomous system (AS) technologies and functionalities. Adapted from Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). "Perception, Planning, Control, and Coordination for Autonomous Vehicles. Machines", 2017.*

The following picture shows matching of ISA95 standard that define control functions and other enterprise functions with building blocks of autonomous systems. The autonomy is expected to increase in the level 2 and Level 3 of ANSI/ISA95[151].



ISA95 Hierarchy Model with building blocks of Autonomous Systems according to the 5 levels of the conventional automation pyramid[152]

F.65

b. Safety and security in autonomous systems:
   - Current standards of safety requirements for autonomous machines categorise safety into four approaches.
   - On-board sensors and safety systems for machines that work among humans and other machines but is restricted to indoor applications.
   - An isolated autonomous machine that works in a separated working area, mostly an intensive outdoor environment where other machines or humans are monitored.
   - Machine perception and forecast of expected and/or unexpected human activities aimed at: (i) assisting human activities and movements with a proactive behaviour; (ii) preserving human health and safety; and (iii) preserving the integrity of machinery.
   - An operator is responsible for reacting to a hazardous situation encountered by the autonomous machine when being provided with enough time between alert and transferring responsibility.

2.4

c. Requirements management and conceptual modelling of autonomous systems:
   - With the increasing complexity of autonomous functionality in both AV and ADAS systems, traditional methodologies of developing safety critical software are becoming inadequate, and not only in the autonomous driving, but in any industrial field of application of autonomous systems. Since autonomous systems are designed to operate in complicated real-world domains, they will be expected to handle a near endless variety of possible

2.3

151 https://www.isa.org/standards-and-publications/isa-standards/isa-standards-committees/isa95

152 https://www.researchgate.net/figure/The-conventional-automation-pyramid-according-to-the-ANSI-ISA-95-model-The-five_fig1_343473533

scenarios. meeting expectations from various stakeholders such as the internal engineering teams, people involved in the autonomous systems managements (e.g. passengers, drivers, workers, e-Health patients), regulatory authorities, and commercial autonomous vehicles/ robots fleet operators.

d. Human–machine interaction in autonomous systems:
- Human–robot interaction or human–machine cooperation.
- Transparency of operations between human and advanced machine systems (AMS) in uncertain conditions.
- Remote operation and advanced perception, AS oversight and tactical awareness.
- Autonomy intended to enhance human capabilities.
- Natural human interaction with autonomous systems.
- Assisted, safety-oriented and proactive robot interaction with humans.

e. Verification and validation, digital verification and validation (V&V):
- Automatic or semi-automatic V&V.

f. Digital design practices:
- A digital design environment, digital twins, physical mock-ups.
- Sub-task automation development, generation of training data and testing solutions and field data augmentation, according to a handful of global machine manufacturers.
- Machine state estimation (assigning a value to an unknown system state variable based on measurements from that system).

g. Simulators and autonomous systems:
- 3D models of the product with solid bodies, environment and object models and simulation tools.
- Early design phase simulators.
- Robotic test environments.
- Empirical or semi-empirical simulators, making use of both real and simulated data collected from previous experiments.
- Off-road environments.

h. Autonomous capabilities development in a digital environment.

3.3.5 REQUIREMENT OVERVIEW

The most obvious requirement for Digital Industry is the availability of all technologies, components and systems as described in other parts of this document both as foundation technologies and cross sectorial areas serving and enabling the European Digital Industry mission.

It is extremely important that also a number of societal and policy needs are met, particularly the following aspects of EU legislation, related to working environments:

- Adoption of AI, XR and robotics.
- Adoption of any type of technology safeguarding safety and security of workers.

And the following aspects related to EU policies for the promotion of:

- **Resilience** of EU production capabilities and supply chain toward Industrial EU strategic autonomy.
- **Sustainability** of EU manufacturing renovation and evolution toward a greener and safer EU .
- **Digitalization** of EU Industry toward a quicker and better Innovation vocation, cost production and energy consumption saving and capacity to forecast market and societal needs.

3.3.6 TIMELINE

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035

R&D&I TOPICS IN KEY DIGITAL TECHNOLOGIES FOR DIGITAL INDUSTRY

MAJOR CHALLENGE 1: RESPONSIVE AND SMART PRODUCTION

Robust optimal production, scalable first-time-right production

Mass customisation and personalised manufacturing, customer-driven manufacturing, mastering the complexity of products, processes and systems

Resilient and adaptive production, including the shortening of supply chains and modular factories

Cognitive production

Manufacturing as a service

Embedded/Edge/Cloud architectures

MAJOR CHALLENGE 2: SUSTAINABLE PRODUCTION

Monitoring flows of energy, materials, waste and Lifecycle assessment

Virtual AI assistants

Human–machine interfaces and machine-to-machine communications

Human operators in more autonomous plants and in remote operations

Human safety

Competence and quality of work in an human centered manufacturing

Green Deal

MAJOR CHALLENGE 3: ARTIFICIAL INTELLI-GENCE IN DIGITAL INDUSTRY

European AI framework

AI in manufacturing

AI for decision-making

AI for monitoring and control

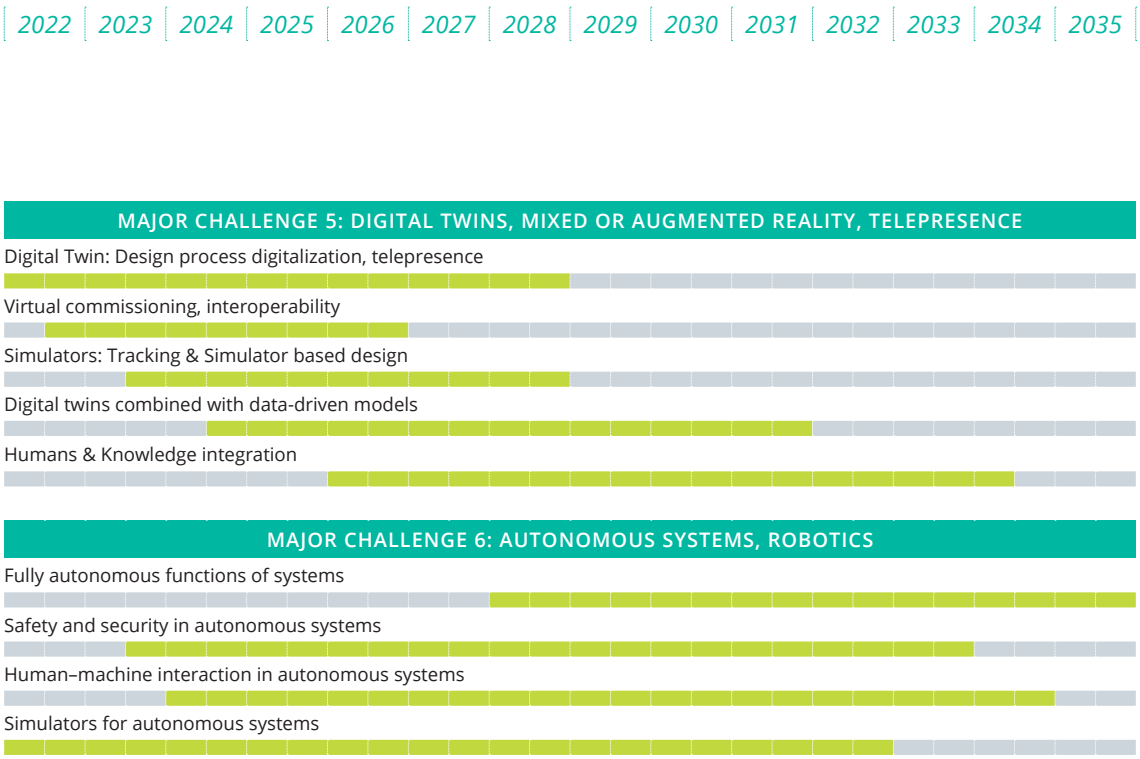
MAJOR CHALLENGE 4: INDUSTRIAL SERVICE BUSINESS, LIFECYCLES, REMOTE OPERATIONS AND TELEOPERATION

Remote operations, teleoperation

AI Services for monitoring and collaboration

Fleet management, Edge and local/global decision making

Business services integration


2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
MAJOR CHALLENGE 5: DIGITAL TWINS, MIXED OR AUGMENTED REALITY, TELEPRESENCE
Digital Twin: Design process digitalization, telepresence
Virtual commissioning, interoperability
Simulators: Tracking & Simulator based design
Digital twins combined with data-driven models
Humans & Knowledge integration
MAJOR CHALLENGE 6: AUTONOMOUS SYSTEMS, ROBOTICS
Fully autonomous functions of systems
Safety and security in autonomous systems
Human–machine interaction in autonomous systems
Simulators for autonomous systems

3.3.7 SYNERGY WITH OTHER THEMES

3.3.7.1 About engineering tools

Digital twins are commonly characterised by modelling and simulation (the finite element method, FEM, computational fluid dynamics, CFD, etc.) or virtual or mixed reality techniques, and their numerous applications. However, the product processes, manufacturing design and management of the operative lifetime of a product or factory is much broader. Typical examples of these are: managing the multi-technologies (mechanical, electronics, electrical, software); safety, security and reliability engineering; managing interactions with the contexts of the target (humans, environment); managing testing and quality; the various types of discharges or footprints; managing projects, logistics, supply chains, etc. These tasks are increasingly being managed by software tools and systems, and through the use of standards, regulations and engineering handbooks, which generally require extensive domain knowledge and experience.

2.3 2.4

The respective engineering disciplines are well distinguished, developed and understood. Key examples here – such as factory design, electronics design, engine design and car design – are well known and significant as regards success. These disciplines are going through a tremendous and demanding digitalisation process, and are sometimes called the "other twins" to underline their importance and high value. A narrow focus on digital twins will certainly play a growing role in implementing the concomitant increase in types of "other twin".

There is also a notable discipline called "systems engineering", which describes both aspects and the whole of the instantiated subfields such as factory design and engine design. Similarly, many notable software tools – such as product lifestyle management (PLM), supply chain management (SCM) and CAD – are actually families of tools with significant versions for the actual subdomains:

1.4 2.3

- Parallel joint engineering of products, processes, safety, security, cybersecurity, human factors, sustainability, circular factors, etc.
- Mastering the deep linkage and complexities in multiple engineering domains and technologies, along with product and process lifecycles in the digital domain.
- Multiplying the engineering extent, efficiency and quality in the digital world.

3.3.7.2 About trust, security, cybersecurity, safety, privacy

2.3 2.4

Increasingly, industrial technologies are being regarded as critical applications by law, meaning that extensive validation, verification, testing and licensing procedures must be in place. Security must also be embedded in all engineering tools, which strongly suggests that safety is not achieved by testing alone, but should be built or integrated into every lifecycle stage.

Security and cybersecurity are the other side of the coin in the distributed, remote or networked applications that contemporary communication technologies effectively enable. Lacking useful security could easily be a showstopper.

Since safety or security is difficult to achieve and prove, industries prefer to talk about trust and how they expect (and assume) safety and security will be in place for their business partners. Nevertheless, there must be no nasty surprises between trusted partners in terms of security issues.

As regards privacy, there is much idealistic urging by researchers, software enthusiasts, etc., for open data and open software from industrial actors. However, certain data must be kept private by law. In addition, critical applications have been sealed and protected once they have been finalised, otherwise their safety, security, functionalities, etc., cannot be guaranteed. Most industrial applications also involve a great deal of engineering effort and creativity, are very extensive and constitute the core asset of companies that must be protected. Competitive business situations could therefore result in a cautious attitude towards open data and software. Nonetheless, industries sometimes do not entirely know what data, etc., it is beneficial to keep private and what should be open. In the era of AI, it may be a challenge to know in advance what could be discovered, for example, in the vast amount of factory or machine data available. It is better be safe than sorry! Open interfaces, standards, etc., are good examples of practical openness.

3.3.7.3 About digital platforms, application development frameworks and SoS

1.4

Analysis of the different roadmaps confirms that the platform landscape is still very fragmented, with open and closed, vertical and horizontal platforms, in different development stages and for various applications. There is a strong need for interoperability/standardisation and the orchestration/federation of platforms. The trend is towards agile, composable, plug-and-play platforms (also that can also be used by SMEs), and more decentralised, dynamic platforms supporting AI at the edge. In addition, future (ledger-based) technologies could provide common services on trusted multi-sided markets/ecosystems.

Existing gaps can still be found in the following topics:

- Moving the focus to industrial and engineering applications. It is important to win the global platform game in various application sectors (which are strong today), and to effectively develop high-level outperforming applications and systems for actual industrial and business requirements.
- Preparing for the coming 5G era in communications technology, especially for both its manufacturing and its implementation within the edge-to-cloud continuum.
- Long-range communication technologies optimised for machine-to-machine (M2M) communication and the large numbers of devices – low bit rates are key elements in smart farming, for instance.
- Solving the IoT cybersecurity and safety problems, attestation and security-by-design. Only safe, secure and trusted platforms will survive in industry.
- Next-generation IoT devices with higher levels of integration, low power consumption, more embedded functionalities (including AI capabilities) and at a lower cost.
- Interoperability-by-design at component, semantic and application levels.
- IoT configuration and orchestration management allowing for (semi)autonomous deployment and operation of large numbers of devices.
- Decision support for AI, modelling and analytics, in the cloud but also in edge/fog settings.

3.4

ECS Key Application Areas

HEALTH AND WELLBEING

3.4.1 SCOPE

The healthcare industry is facing radical change, enabled by its current digital transformation in combination with a change towards a personalized medicine. Related developments will progressively generate a new ecosystem. New players will come to the fore, either from within the industry or through newcomers accessing the healthcare industry ecosystem.

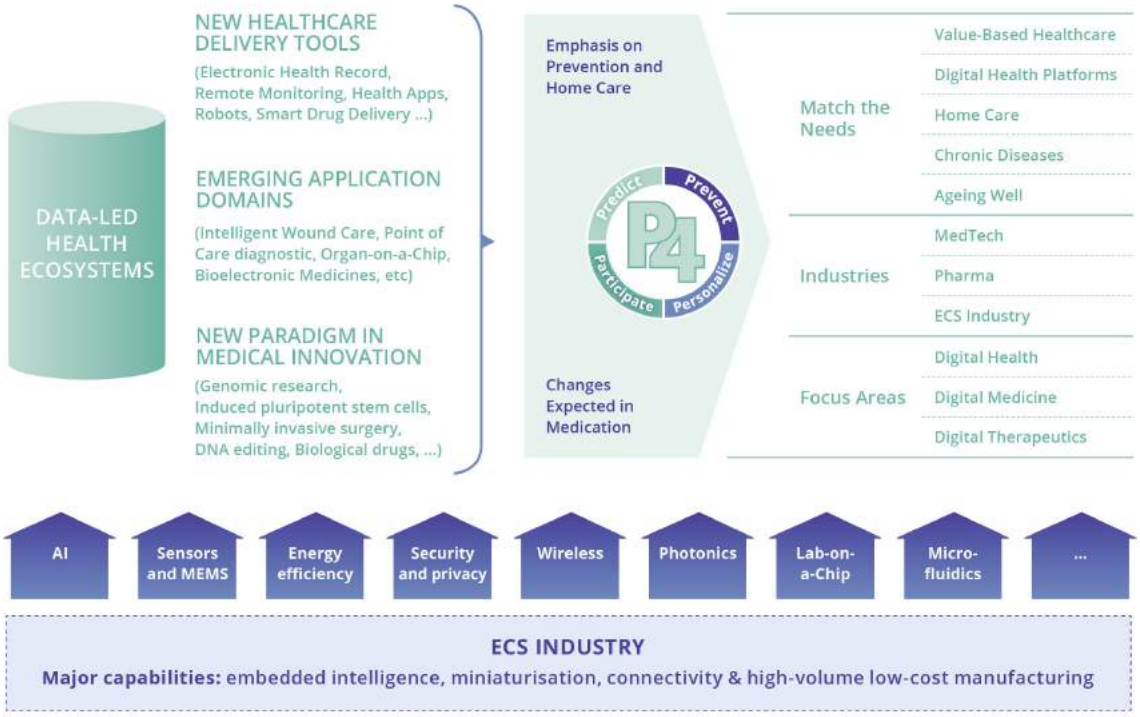
Data will play an increasingly important role in providing a better understanding of consumer needs in terms of health, and to enhance and tailor a more cost-efficient health offering that delivers the right care at the right time and in the right place. The interconnections made possible by being able to access pools of data not previously available (worldwide database, data clouds, apps, etc) are creating a major shift in healthcare provision.

A few years ago, the big techs (especially Google, Apple, Facebook, Amazon and Microsoft, GAFAM) started to move into healthcare, which is a heavily regulated industry. The spread of digitalisation and innovative information technology (IT) is giving them the chance to enter the medical market. Data are everywhere, and healthcare practitioners need to cope with new and emerging digitalised delivery tools. Health tech companies, whether large corporations, small and medium-sized enterprises (SMEs) or start-ups, bring extensive expertise in using data and analytics, will be the dominant catalyst of these trends and are likely to drive change in the healthcare industry.

The Covid-19 pandemic is accelerating the adoption of telemedicine, initially at the most basic level (i.e. consultation by telephone), something that governments are also taking the opportunity to roll out, and this type of consultation is likely to further enable the digitisation of auscultations for medical diagnoses. Also, in a post Covid-19 era, regulators – usually seen as the main inhibitors – are also expected to be more favourable towards accelerating the current healthcare digital transformation.

The emergence of so called P4 healthcare – predictive, preventive, personalised, participatory – as opposed to reactive healthcare, is blurring the lines between medical technology (medtech), the pharmaceutical industry and electronic components and systems (ECS) industry, opening the way for healthcare innovation. This is a huge opportunity for the European ECS industry, its worldwide medtech and pharma market leaders, as well as the 25,000 SME medtech companies across Europe, since the new healthcare ecosystem will rely[153] on digital instruments, advanced electronic sensors and photonics, micro-electromechanical systems (MEMS), and the large volume, high-quality, low-cost production capabilities of the ECS industry.

153 Emerging Medical Domains for the ECS industry – Health.e lighthouse: www.health-lighthouse.eu Medtech Europe: www.medtecheurope.org



F.66 *ECS Industry impact in Healthcare Digital Transformation*

3.4.2 APPLICATION TRENDS AND SOCIETAL BENEFITS

3.4.2.1 External requirements

Healthcare electronics represents approximately 5% of global electronic equipment production, amounting to €91 billion in 2017 versus a total of €2,000 billion for the industry as a whole [154] (according to Decision Etudes et Conseil, "Study on the Electronics Ecosystem": Annex 4, Health & Care). This report shows that healthcare is now the seventh biggest market in terms of electronic production worldwide, and is expected to benefit from a robust growth rate of over 5% over the next few years.

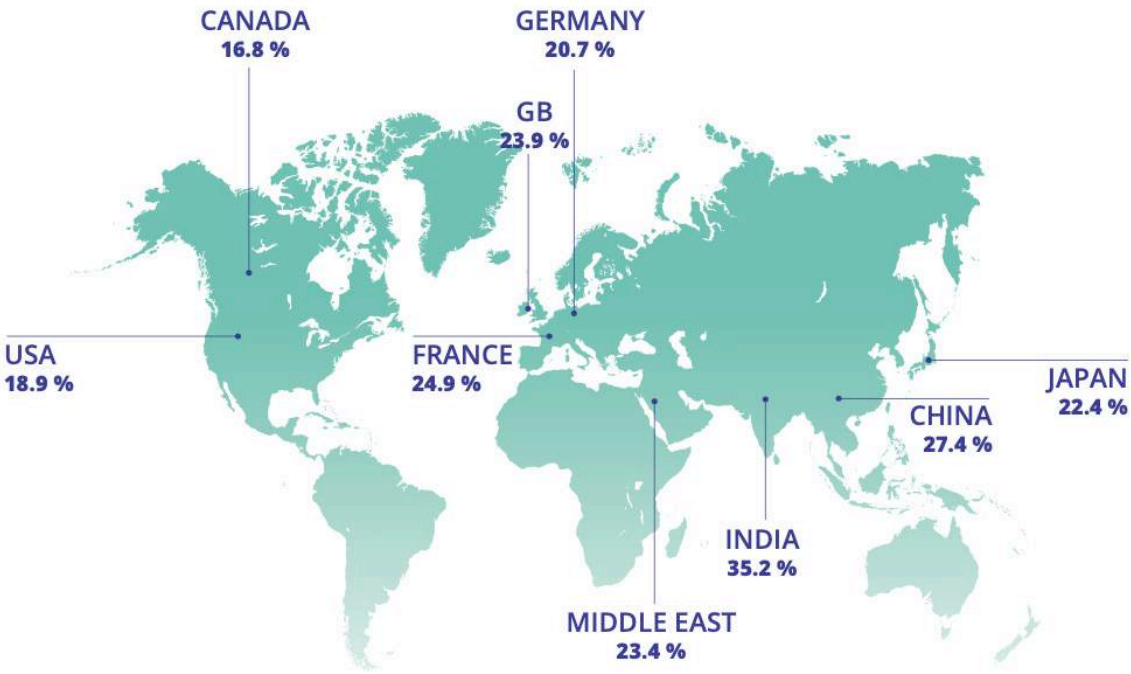
Within the industry, the current major innovation is the "big data" healthcare market. The market is exploding: the volume of generated data in healthcare is predicted to more than triple from 2017 (700 exabytes, e.g. 700 1018) to 2025 (2300 exabytes), according to a survey by BIS Research. This is supported by other studies, such

154 Study on the Electronics Ecosystem – Overview, Developments and Europe's position in the world – Annex 4, Health & Care – Decision Etudes Conseil / CARSA

as the "Stanford Medicine 2020 Health Trends Report", which identifies the rise of the (digital) data-driven physician as a direct consequence of how data and technology is transforming the healthcare sector.

Of course, this big data trend in healthcare relies on government initiatives to encourage the adoption of digital health, and it is interesting to note that Europe – represented in *Figure F.67* by three countries behaving similarly – is well in line with the global trend.

These trends in healthcare electronics, healthcare data and healthcare technologies will continue to impact the healthcare value chain. The graphic in *Figure F.68* highlights how the healthcare digital transformation is gradually positioning the "healthcare consumer" at the centre of the value chain. It also shows how healthcare electronics – from research and development (R&D) to design and manufacturing – will digitalise the application segments, and how the care pathways – from prevention to treatment – will be transformed. As a consequence, healthcare will increasingly occur at the "point-of-need", in most cases at home, whether for wellbeing, preventive measures or post-hospital intervention (e.g. rehabilitation) centred around the patient and taking place away from a clinical environment. Such a transformation will be enhanced by less of an obvious division between the ECS industry and the medtech and pharma ecosystems.

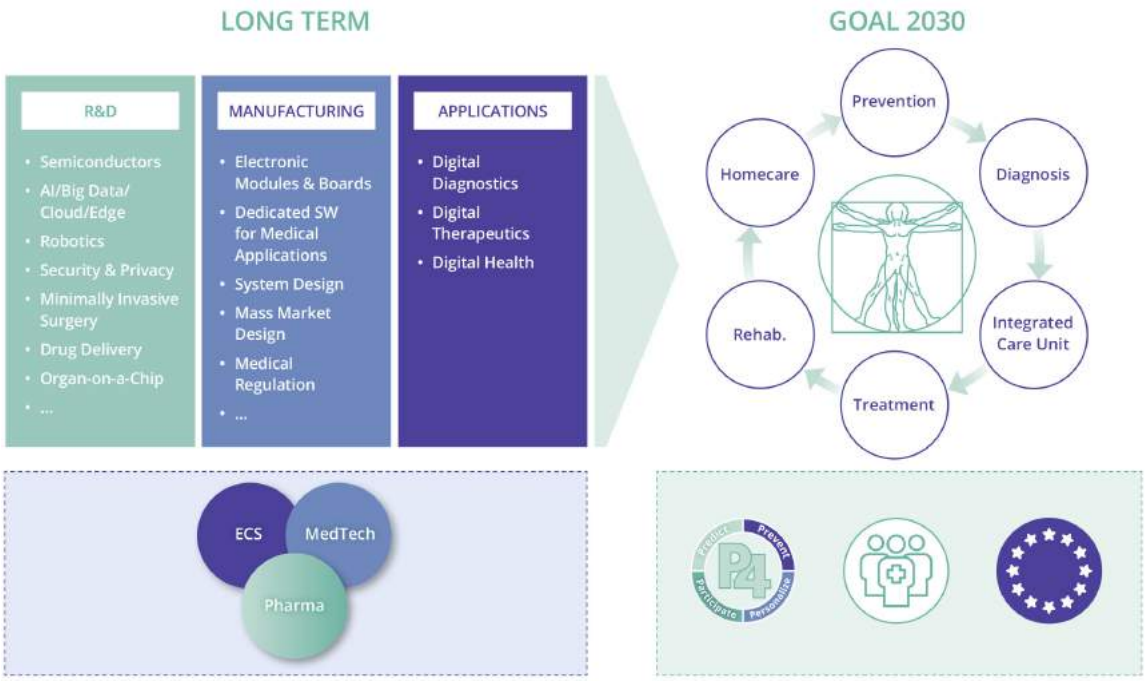


Healthcare Data CAGR 2017–2025 (Source: Bis Research-2020) F.67

3.4.2.2 Societal benefits

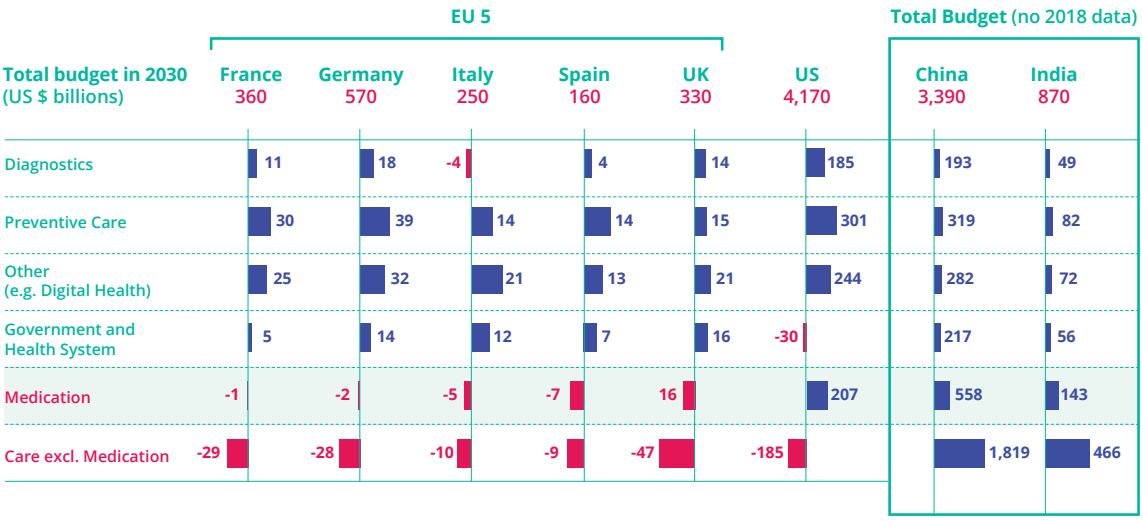
According to different projections, healthcare budgets around the world are expected to increase by 10% in aggregate by 2030. Healthcare spending will be driven by ageing and growing populations, rising labour costs, and also by clinical and technology advances. Consequently, by 2030 healthcare is expected to be centred on patients being empowered to prevent disease rather than seek treatment, as highlighted above.

Healthcare consumers will receive personalised health solutions provided within a healthcare system that is organised and regulated in an entirely new way (see *Figure F.69*).



F.68 *Continuum of Care Value Chain*

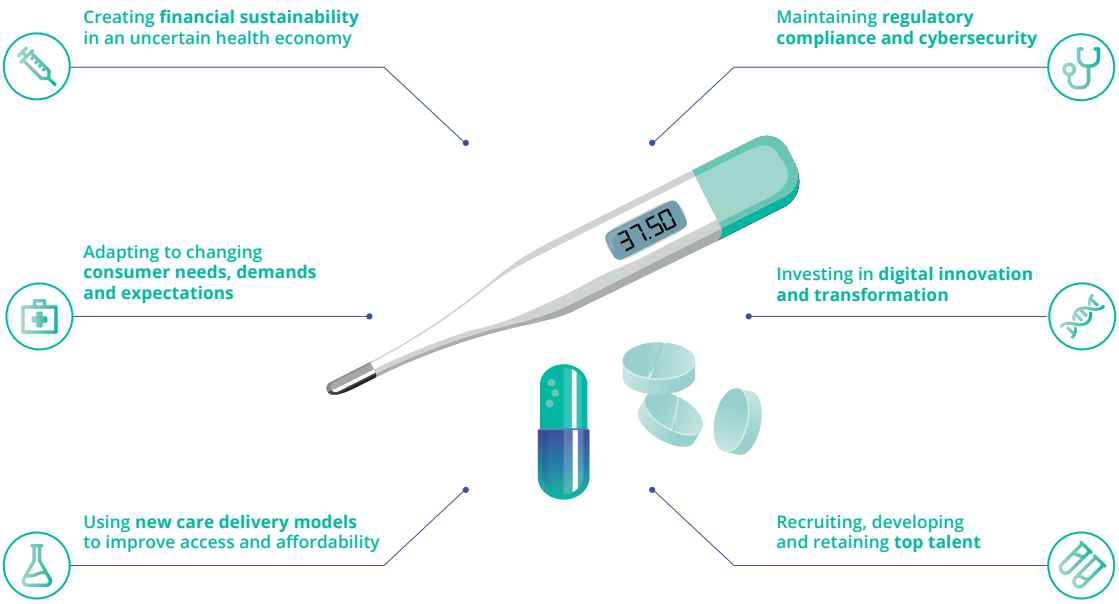
HOW NATIONAL HEALTHCARE BUDGETS WILL SHIFT BY 2030 (2018 VS. 2030)



F.69 *How national healthcare budgets will shift by 2030 (2018 vs. 2030) (Source: OECD data; The Lancet; Strategy & analysis)*

Healthcare budgets in Europe will therefore shift towards novel areas such as digital health and more advanced prevention and rehabilitation options, for which homecare will play a key role. Money is expected to be redirected toward personalised medicine for the most complex diseases, and preventive, early stage treatments. This split is likely to lead to significant changes and require new R&D strategies for many industry players. The expectations will lie in those areas summarised in the *Figure F.70* which is taken from a Deloitte report.

Another societal benefit relates to medical education, an area rapidly progressing due to computer-assisted learning, student medical apps, digital games, simulation and wearable technologies increasingly being embedded in the curriculum, although the pace has not yet been fast enough to meet the clinical need. The Covid-19 crisis has exemplified the need for greater investment in technology to facilitate this. For example, recent events have highlighted the crucial role of anaesthesia in airway management to reduce fatalities, yet clinical airway management is constrained by insufficient training time. Simulation training in airway management is recommended by the Royal College of Anaesthetists, but in recent years less than half of NHS consultants in the UK have access to adequate training.



Source: "2019 Global health care outlook – Shaping the future", Deloitte

F.70

In addition to technical skills such as attention and manual dexterity, some non-technical skills (including situation awareness and cognitive communication) have been highlighted as contributory factors in airway management. Multidisciplinary team training has been advocated, but Covid-19 has highlighted the need for rigorous preparation for airway management through the inclusion of checklists and cross-checks, in addition to the need for highly skilled experienced airway operators to perform first-pass tracheal intubations. Although team-based training and simulation are critical to maximising successful outcomes, training that was previously considered to be occasionally necessary has gained in importance in critical care. Clinical engineering, simulator training and objective performance measures through non-invasive wearable sensors in training and practice is becoming progressively important for patient safety, with further key roles being in extended realities, robotics, Internet of Things (IoT) and Artificial Intelligence (AI). The clinical

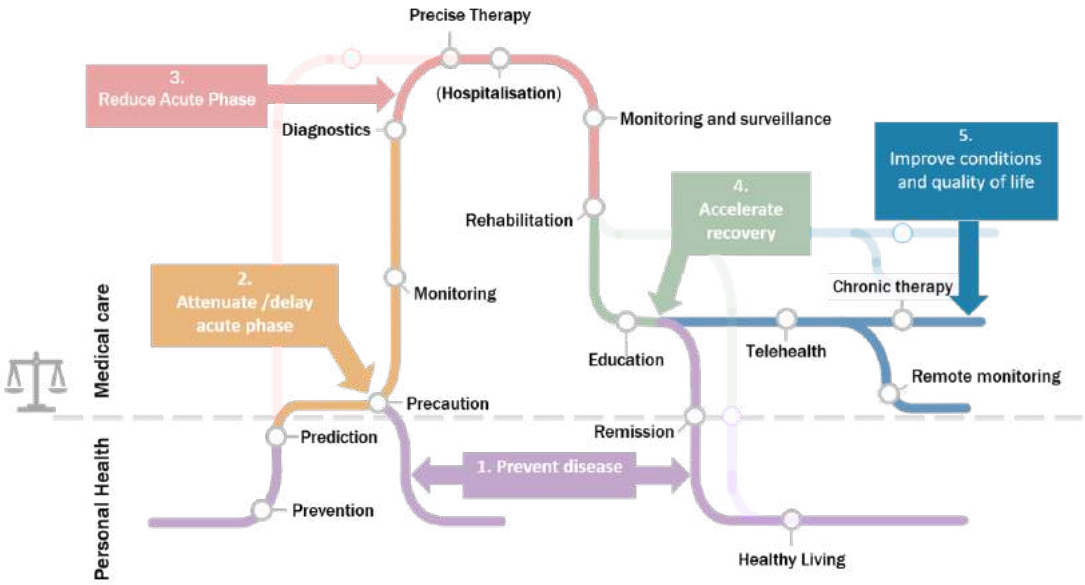
need and potential applications extend across clinical skills in areas such as needle intervention, surgery and radiology, as well as in non-technical skills in all areas of medicine.

Fostering the convergence of technologies will enable the development of cross-sectoral innovations more able to respond to people's needs. Such an approach will also facilitate the integration of health interventions developed by different industrial sectors along the health care pathway. The goal is a more targeted intervention strategy leading to personalised treatments and improved individual health outcomes.

In total, research and innovation regarding ECS for health and well-being will play its part and is also indispensable for realization of specific objectives in healthcare as defined in the Strategic Research and Innovation agenda of the Innovative Health Initiative:

- Contribute towards a better understanding of the determinants of health and priority disease areas.
- Integrate fragmented health R&I efforts bringing together health industry sectors and other stakeholders, focussing on unmet public health needs, to enable the development of tools, data, platforms, technologies and processes for improved prediction, prevention, interception, diagnosis, treatment and management of diseases, meeting the needs of end-users.
- Demonstrate the feasibility of people-centred, integrated health care solutions.
- Exploit the full potential of digitalisation and data exchange in health care.
- Enable the development of new and improved methodologies and models for comprehensive assessment of the added value of innovative and integrated health care solutions.

In total those objectives will contribute to the effort to both shorten the time a patient is actually in acute medical care and improve his or her conditions and quality of life (see *Figure F.71*).



F.71 *Patient's status in Health Care*

3.4.3
STRATEGIC ADVANTAGE FOR THE EU

Like the rest of the world, Europe is going through a healthcare digital transformation, creating a fundamental evolution in care delivery mechanisms. Digital innovation based on the EU's ECS, medtech and pharma industries can support Europe's response to some of the key technological challenges that will be discussed later in this Chapter, as well as the societal challenges lying ahead, as summarised above.

Europe is well-positioned in terms of electronic equipment dedicated to health and care (with 19% of global production in 2017). The European healthcare industry has a number of competitive advantages in a range of economic sectors related to health and social care, as well as digital technology. For example, some of the market leaders in medical equipment (Philips Healthcare, Siemens Healthineers) are Europe-based companies. The pharmaceutical industry is a major contributor to the European economy, with an estimated 1.4% of the EU's combined GDP and 0.9% of the region's employment (Source: EFPIA, 2019).

Programmes such as "EU4Health", which is based in Brussels, are designed to ensure that the EU remains the healthiest region in the world, offering tools promoting innovation in the health sector – making medicines, medical devices and other crisis-relevant products available and affordable, supporting innovation and addressing other important long-term challenges for health systems. This particularly includes obstacles to a broader uptake and the best use of digital innovations, as well their scaling up, as Europe needs to become faster in the translation of ideas and valid technology into economically viable solutions.

Regulators are approving a growing number of digital health therapies, unleashing innovation in digital medicine and also in AI, which has the potential to transform the key steps of clinical trial design – from study preparation to execution, towards improving trial success rates – thus lowering the pharma R&D burden. For instance, in November 2019 Germany passed a law to allow doctors to prescribe health apps, with costs being reimbursed by insurers.

The European Commission has also adopted a Recommendation on a European Electronic Health Record (EHR) exchange format. This Recommendation seeks to facilitate the cross-border interoperability of EHRs in the EU by supporting members states in their efforts to ensure that citizens can securely access and exchange their health data wherever they are in the EU.

However, as we have recently seen, Europe still faces difficulties in reaction to pandemic situations, as for instance required protective goods are not available in number required to cope with the situation. This calls for a better integration of medical resources for pandemics, as the Covid-19 crisis has provided a big impetus for enabling digital health, prompting changes that are helping tech companies and data innovators play a greater role in service delivery. Nonetheless, the digital transformation of healthcare is only at its beginning.

Europe needs to maintain this momentum and build upon digital health technologies that will support this healthcare transition to reach market maturity and wide acceptance. They can help the EU to become faster in translating ideas into economically viable solutions, and which can be further scaled up in daily health practice. These are some of the main questions that have to be addressed to achieve this:

- How can the EU prepare its healthcare system to undertake digital transformation, managing a shift in focus from acute, hospital-based care to early prevention?

- How can the EU contribute to delivering cost-effective and high-quality healthcare, maximising the patient's overall outcomes?
- How can the EU contribute to strengthening where and how healthcare is delivered, supporting home-based care?
- How can the EU support a much stronger participation of citizens in their own care process, enhancing patient engagement?
- How can the EU contribute to supporting its clinical workforce and healthcare consumers to embrace technology-enabled care?

This Chapter on the ECS health applications of the ECS-SRIA will provide recommendations to answer these questions from the perspective of technology, with the aim to establish Europe as a global leader:

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

3.4.4 MAJOR CHALLENGES

Five major challenges have been identified for the healthcare and wellbeing domain:

- **Major Challenge 1:** enable digital health platforms based upon P4 healthcare.
- **Major Challenge 2:** enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies.
- **Major Challenge 3:** support the development of the home as the central location of the patient, building a more integrated care delivery system.
- **Major Challenge 4:** enhance access to personalised and participative treatments for chronic and lifestyle-related diseases.
- **Major Challenge 5:** ensure more healthy life years for an ageing population.

3.4.4.1 Major Challenge 1: enable digital health platforms based upon P4 healthcare

3.4.4.1.1 Status, vision and expected outcome

The medtech industry is in the process of transitioning from an industry primarily producing high-end hospital equipment to one that will increasingly serve point-of-care (PoC) professionals and "health consumers", thereby moving from a product-based approach to the provision of "integrated services".

Electronic medical technology, such as the Internet of Medical Things (IoMT), minimally invasive implants, energy-efficient devices, advanced analytics, cognitive computing for advanced clinical decision support,

cybersecurity, enhanced network capabilities for continuous data access (to mention only a few of those listed below in the section "Key focus areas"), will support the deployment of P4 healthcare in a data-led environment.

The P4 healthcare vision is therefore not only placing doctors and other health professionals at the centre of the care process, but all those relevant to the health consumer. Even if the healthcare ecosystem is operating in a highly regulated environment, by 2030 we can expect this trend to progressively become the norm. The ECS community should participate in the development of dynamic healthcare systems that learn in real time from every result, achieve a better understanding of treatment response and prognostic heterogeneity, and introduce more refined, patient-tailored approaches to disease detection, prevention and treatment.

The P4 healthcare vision, enabling for instance early diagnostics based upon merged data and machine-learning techniques through the detection of weak signals, allows preventive treatments that are far less intensive than acute treatments and increase the chances of survival and quality of life. The medtech industry is not alone on this journey. New pharmaceuticals and treatments will be developed for personalised medicine settings by embedding connected devices and exploiting the potential of the IoT and AI.

This is all creating a new industry, one that revolves around digital health platforms. This platform- based new-market disruption will enable the emergence of specialised platforms, and new players will enter the health domain. This will impact current business models in healthcare, using aggregated data to create value rather than devices – supporting, for instance, proactive services, facilitating outcome evaluation for the treatment of different therapies, and paving the way for outcome-based or pay-per-use reimbursements. This is a potential path to reducing the burden of healthcare expenditures.

3.4.4.1.2 Key focus areas

The addition of AI capabilities – person-centred AI-based consumer devices/embedded AI-based medical devices and systems – to Smart Things will significantly enhance their functionality and usefulness, especially when the full power of such networked devices is harnessed – a trend that is often called "edge AI". AI enables much more efficient end-to-end solutions by switching from a centralised to a distributed intelligence system, where some of the analysis carried out in the cloud is moved closer to the sensing and actions.

2.1

This distributed approach significantly reduces both the required bandwidth for data transfer and the processing capabilities of cloud servers. It also offers data privacy advantages, as personal source data is pre-analysed and provided to service providers with a higher level of interpretation. It also offers greater reliability and safety.

A high level of digital trust – for privacy and security by design, hardened and embedded AI models – is of course required for executing transactions in healthcare and wellbeing. Securing the IoT ecosystem is a multiple level problem. Privacy should be "by design". In general, integrating security features into an existing system can become very complex, sometimes impossible, and often increases the cost of the final product significantly. A more efficient approach is to consider those security requirements at the very beginning of a project, and then integrate them in the design and development phase. The ECS industry can assist with end-to-end solutions by providing on-chip security, supplying comprehensive hardware and software services, including authentication, data encryption and access management.

2.3 2.4

Next-generation connectivity – better performing, more ubiquitous, accessible, secure and energy-efficient networks – will contribute to unleashing the potential of digital health. One of the main characteristics of

2.2

future networks will be their increased intelligence to improve the performance of the networks, and offer sophisticated and advanced services to the users, due to edge computing and metadata, for instance.

With the significantly growing number of wearables and other small form-factor, battery-operated devices, very low power consumption is a major technology challenge for product designers. The transition from linear to circular economy will require innovative designs for the lifetime of electronic components and systems, and disruptive changes in ECS supply chains, to reduce the ecological footprint. The ECS industry will contribute to improving energy efficiency – including new, sustainable and biocompatible energy harvesting – to locally process data and the transmission of pre-processed data as opposed to the transmission of high-volume data (such as imaging data).

1.1 1.2

As a result of improved integration and analysis of multimodal data, new tools for clinical decision-making and precision medicine will emerge, supporting early diagnostics, personalised medicine and potential curative technologies (e.g. regenerative medicine, immunotherapy for cancer).

3.4.4.2 Major Challenge 2: enable the shift to value-based healthcare, enhancing access to 4P's game-changing technologies

A major trend in healthcare is the transformation of large healthcare systems to an optimised hospital workflow: a shift from general hospitals treating any diseases towards integrated practice units that specialise in specified disease types. These units, organised around a medical condition, aim to maximise the patient's overall outcomes as efficiently as possible, increasingly through remote access, for patients anywhere in the world.

Pay-for-cure rather than pay-for-treatment can be an effective way to increase the efficiency of healthcare by avoiding unnecessary tests, therapies and prescriptions. Combined with empowered patients, care-givers should be able to make better informed and more effective choices for treatment. To achieve this, outcomes need to cover the full cycle of care for the condition, and track the patient's health status aftercare is completed. This first involves the health status, relying for instance on EHRs supporting precise communication between different care-givers' PoC diagnostic systems or AI-based clinical decisions. Early diagnosis is key for the successful treatment of both modest and challenging medical conditions.

Health outcomes are also related to the recovery and the sustainability of health. Readmission rates, level of discomfort during care, and return to normal activities should be taken into account for both providers and patients. Humanoid robots applying interpreted human body language and emotion in care delivery, sensors, the deployment of companion devices anticipating and contextualising acute or chronic conditions in EHRs involving health models describing the outcome health values for the patients, both in the short term and long term, will have a direct positive effect on readmission prevention.

To achieve this transformation, a supporting IT platform is necessary. Historically, healthcare IT systems have been siloed by department, location, type of service, and type of data (for instance, diagnostic imaging). An innovative and efficient healthcare information infrastructure – integrating IoT with big data learning for optimising workflow, usage, capabilities and maintenance, and of course digital trust – will aggregate the different areas for efficient value- based healthcare, combining prevention tools, early detection and treatment. This will enable better measurement, and facilitate the design and implementation of new bundle-based reimbursement schemes, reducing costs while improving health outcomes. By 2030, value-

1.4

based healthcare will enable the adoption of optimisation practices already supported by ECS technologies in the industry.

3.4.4.2.1 Key focus areas

By 2030, clinical decision-making will be augmented by electronic medical records. Digital centres will enable advanced capabilities for clinical decision-making where AI, real-time data from portable Point-of-Care devices, 3D printing for surgeries, continuous clinical monitoring – including robotics to improve treatments either in the operating room, minimal invasively inside the body, at the general practitioner or at home – will support the integration of specialised care units. A large number of images will be combined with other sensor data and biomedical models to obtain precise, quantified information about the person's health condition, preventing and providing, for instance, early warnings for (combined) diseases supported by patient health models on complex health conditions. Low–latency, massive image processing is a major information source for AI-based automation, visualisation and decision support within the whole care cycle. Precise quantified and annotated imaging is needed at many levels: from molecular imaging up to whole body imaging. The development and use of accurate digital twins of the human body will enable in silico clinical trials, individualised computer simulations used in the development or regulatory evaluation of a medicinal product, device or intervention. While completely simulated clinical trials are not yet feasible, their development is expected to have major benefits over current in vivo clinical trials, which will drive further research on the subject. Moreover, "digital twins" will help in combining all the data on a personal level, and enable personalised clinical decision-making.

Europe is a leading producer of diagnostic imaging equipment. In diagnostic imaging, the ECS industry has begun to place great emphasis on accurate radiation dose monitoring and tracking. Healthcare providers are already applying dose management as part of the quality programme in their radiology departments, and patient-specific computed tomography (CT) imaging and personalisation of scan protocols will be a key aspect of patient- centred care in radiology departments, facilitating the management and control of both image quality and dose with the optimisation of 3D X-ray imaging protocols.

The enormous capabilities of the ECS industry in miniaturisation, integration, embedded intelligence, communication and sensing will have a major impact on the next generation of smart minimally invasive devices:

1.1 1.2

- Historically, the first revolution in minimally invasive surgery was in the early 1980s after a real-time, high-resolution video camera was developed that could be attached to an endoscope, allowing the first laparoscopic cholecystectomy in 1987 (in France, by Philippe Mouret).
- Highly miniaturised electrical and optical systems realised using advanced cost-effective platform technologies will bring extensive imaging and sensing capabilities to these devices, and enable the second minimally invasive surgery revolution, with smart minimally invasive catheters and laparoscopic instruments for faster and more effective interventions.
- Sensing and diagnostics solutions need to achieve appropriate sensitivity, specificity and time-to-result.
- Reducing waste is possible through sensors made of biological materials, combining a biological component with a physicochemical detector.
- The fusion of diagnostics and surveillance will help reducing system and operational costs.
- To realise next-generation smart catheters, a broad spectrum of advanced ECS capabilities will need to be brought together, foremost in dedicated platforms for heterogeneous miniaturisation and integrated photonics. These can be complemented with platforms for embedded ultrasound, low-power edge computing, and AI and digital health platform integration.

- Optical coherence tomography (OCT) is another example where ECS technologies make a critical impact, in shrinking devices and reducing costs, allowing devices to be used in wider fields beyond ophthalmology.

Finally, it should be noted that the development of the next generation of smart minimally invasive instruments will go hand in hand with the development of new navigation techniques:

- Breakthrough innovations in photonics are enabling optical shape-sensing techniques that can reconstruct the shape of a catheter over its entire length.
- MEMS ultrasound technology will enable segmented large-area body conformal ultrasound transducers that are capable of imaging large parts of the body without the need for a sonographer, to guide surgeons in a multitude of minimally invasive interventions.
- Combined with other technologies, such as flexible and conformal electronics, low power edge computing, AI and data integration into clinical systems, new optical and acoustic- based technologies may eliminate the use of x-rays during both diagnosis and interventions, enabling in-body guidance without radiation.
- Augmented reality can be used for image-guided minimally invasive therapies providing intuitive visualisation.

1.1 1.2 2.1

As mentioned above, outcomes should cover the full cycle of care for the condition and track the patient's health status once care has been completed. Biomarkers derived from medical images will inform on disease detection, characterisation and treatment response. Quantitative imaging biomarkers will have the potential to provide objective decision-support tools in the management pathway of patients. The ECS industry has the potential to improve the understanding of measurement variability, while systems for data acquisition and analysis need to be harmonised before quantitative imaging measurements can be used to drive clinical decisions.

Early diagnosis through PoC diagnostic systems represents a continuously expanding emerging domain based on two simple concepts: perform frequent but accurate medical tests; and perform them closer to the patient's home. Both of these approaches lead to improved diagnostic efficiency and a considerable reduction in diagnostic costs:

- Point-of-care testing (PoCT) methodology encompasses different approaches, from the self-monitoring of glucose or pregnancy, to testing infectious diseases or cardiac problems. However, it should be remembered that disposable PoC devices will need to be environmentally friendly in terms of plastic degradation and the replacement of potentially harmful chemicals.
- The key enabling components of current PoCT devices must include smart and friendly interfaces, biosensors, controllers and communication systems, as well as data processing and storage.
- The emerging lab-on-a-chip (LoC) solutions, embedding multiple sensor platforms, microfluidics and simple processing/storage elements, are currently the most promising basis for the realisation and development of accurate, versatile and friendly portable and wearable PoCT devices. Their simplified operation mode eliminates the constraint of molecular biology expertise to perform a real-time reverse transcription polymerase chain reaction (RT-PCR) test, will enable innovative in vitro diagnostic (IVD) platforms, making possible decentralisation from highly specialised clinical laboratories to any hospital lab and near- patient sites, with dedicated sample prep cartridges, a more efficient prevention (referring to the recent Covid-19 pandemic) and prompt personalised diagnosis.

1.2 1.3 2.1

In addition, digital supply chains, automation, robotics and next-generation interoperability can drive operations management and back-office efficiencies. Using robotics to automate hospital ancillary and back-

office services can generate considerable cost and time efficiencies, and also improve reliability. Robotic process automation (RPA) and AI can allow care-givers to spend more time providing care. For instance, robots can deliver medications, transport blood samples, collect diagnostic results, and schedule linen and food deliveries – either as a prescheduled task or a real-time request. Robotic processes also can be used for certain hospital revenue cycle and accounting/finance functions, such as scheduling and claims processing.

3.4.4.3 Major Challenge 3: support the development of the home as the central location of the patient, building a more integrated care delivery system

3.4.4.3.1 Status, vision and expected outcome

The trend towards integrated practice units specialising in specific disease types as described in the previous challenge means that certain procedures can move out of the hospital environment and into primary care and home care (see*Figure F.68*). Medical equipment that was previously used only in the hospital or clinic is finding its way into the home. For example, tremendous progress has been made since the "consumerisation" of the MEMS in developing compact, accurate, low-cost silicon sensors and actuators. This continuous innovation will support diagnostic and treatment in integrated practice units, while supporting recovery and health sustainability at home. This trend will be supported by the integration of solutions and services for specific disease groups with hospital units to optimise patient-generated health data (PGHD: continuous monitoring, clinical trials at home, etc), enhanced by the integration of heterogeneous devices and systems used at home covering parts of the care cycle (smart body patches, monitoring implants, remote sensing, etc). Solutions are needed that can be integrated into secure health digital platforms, portable end-user devices, remote e-healthcare and AI front-ends.

In addition, the pharmaceutical market is experiencing strong growth in the field of biologics (genomics and proteomics, as well as microarray, cell culture and monoclonal antibody technologies) that require preparation prior to administration. Smart drug delivery solutions are now based on innovative medical devices for the automated and safe preparation and administration of new fluidic therapies and biologic drugs. These use advanced ultra-low power microcontrollers that control the process reconstitution of the drug based on parameters identified by the practitioner, together with wireless communication modules to transmit data and ensure the patient and treatment are monitored. Smart drug delivery will improve drug adherence as patients will be empowered to administer expensive and complex drugs in their own home.

In this emerging context, care solutions need to be integrated, combining information across all phases of the continuum of care from many sources – preventing, preparing and providing care based on person-specific characteristics. This will support the development of applicable biomedical models for specific disease groups, for customer groups and for populations, taking heterogeneous data involving history, context or population information into account.

3.4.4.3.2 Key focus areas

Supporting prevention, diagnosis and aftercare with sensors and actuators to ensure efficient medical decision, leveraging edge computing and imaging as described in the previous section, will be crucial. The next generation of devices will incorporate increasingly powerful edge computing capabilities. Analysing PGHD from medical devices can be synchronised with a web- based monitoring system. When aggregated, this data can be then sent to the organisation's health data analytics system to process the results and compare them to previous measurements. If the analysis uncovers negative trends in the patient's health status, it will automatically notify the care team about possible health risks. The ECS industry can play an

important role here in bringing ambulatory monitoring to the next level. The following enabling technology platforms can contribute to this:

- Low-power technology for sensors, microprocessors, data storage and wireless (microwave, optical, sound) communication modules, etc.
- Miniaturisation and integration technologies for sensors, microprocessors, data storage and wireless communication modules, etc.
- Advanced sensing technologies for multiplex, painless sensing with high sensitivity and reliability.
- Printed electronics technology for textile integration and the patch-type housing of electronics.
- Low-power edge AI computing for data analysis and reduction.
- Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis, and with patient follow-up systems for feedback).
- Data security technology for interoperability between security hardware and software components (end-to-end information security).

1.2 2.1 2.2 2.4

The development of next-generation drug delivery systems will form part of the IoMT – medical devices and applications that link with healthcare systems using wireless connectivity. Smart drug delivery will improve drug adherence so that patients can administer expensive and complex (biological) drugs in their home environment. Enabling platforms are required to facilitate a transition from the legacy mechanical components seen in current autoinjectors and wearable drug delivery pumps, to highly integrated, patch-like microsystems. These include:

- High-performance sensors and actuators for drug delivery, monitoring and control.
- On-board microfluidics for in situ preparation and delivery of formulations.
- Minimally invasive needles and electrodes for transdermal interfacing, delivery and diagnostics.
- New materials, containers and power sources that will meet stringent environmental and clinical waste disposal standards.
- Body-worn communication technologies for IoMT integration and clinical interfacing.
- Edge AI for closed-loop control, adherence assessment and clinical trial monitoring.

1.1 2.1

The development of low-cost, silicon-based MEMS ultrasound transducer technologies is bringing ultrasound diagnostics within the reach of the ECS industry. The ECS industry has the instruments and production technologies to transform these into high-volume consumer products, something no other industry is capable of. Personal ultrasound assisted by AI data acquisition and interpretation will allow early diagnoses in consumer and semi-professional settings, as well as in rural areas. As such, they present a huge opportunity for the ECS industry. It is expected that MEMS ultrasound will enable a completely new industry, with MEMS ultrasound transducers being the enabling platform technology that will drive things on.

Among the emerging applications of advanced medtech, “smart wound care” – i.e. the merger of highly miniaturised electronic, optical and communications technologies with conventional wound dressing materials – will allow the treatment of chronic wounds of patients in their home without the intervention of daily nursing and/or constant monitoring of the status of the wound. While much progress has been made in wearable technologies over the past decade, new platforms must be developed and integrated to enable the rapid rollout of intelligent wound care. These include:

- Flexible and low-profile electronics, including circuits, optical components, sensors and transducers, suitable for embedding within conventional dressings.
- Advanced manufacturing techniques for reliable integration of microelectronic technologies with foam- and polymer-based dressing materials.

1.1 1.2 2.1

- Biodegradable materials, substrates and power sources that will meet stringent environmental and clinical waste disposal standards.
- Body-worn communications technologies for low-power transmission of wound status.
- Edge AI to assist the clinical user in data acquisition and data interpretation.

3.4.4.4 Major Challenge 4: enhance access to personalised and participative treatments for chronic and lifestyle-related diseases

3.4.4.4.1 Status, vision and expected outcome

According to the World Health Organization (WHO) definition, chronic diseases are those of long duration and generally slow progression. Chronic diseases such as heart disease, stroke, cancer, chronic respiratory diseases and diabetes are by far the leading cause of mortality in Europe, representing 77% of the total disease burden and 86% of all deaths. These diseases are linked by common risk factors, common underlying determinants and common opportunities for intervention.

One of the crucial means of coping with the prevalence of the chronic diseases is to achieve a more participative and personalised approach, as such diseases require the long-term monitoring of the patient's state, and therefore need individuals to take greater ownership of their state of health. Most chronic disease patients have special healthcare requirements and must visit their physicians or doctors more often than those with less serious conditions. Technological innovation has already been identified as a great medium to engage chronic patients in the active management of their own condition since digital health offers great convenience to such patients. Access to biomedical, environmental and lifestyle data (through cloud computing, big data and IoT, edge AI, etc) are expected to better target the delivery of healthcare and treatments to individuals, and to tailor each decision and intervention, especially for the treatment of those with multiple chronic diseases.

Patients will be connected seamlessly to their healthcare teams, care-givers and family, as treatment adherence will be more efficient with the innovations mentioned in previous sections. Remote sensing and monitoring offer great promise for the prevention and very early detection of pathological symptoms. Remote sensing and monitoring have the potential to become embedded into everyday life objects, such as furniture and TV sets, while bearing in mind the constraints related to security and privacy. Remote patient monitoring will support clinical decisions with a reduced potential for false alarms, especially for the long-term monitoring and data analysis of patients with chronic diseases.

1.4 2.2

3.4.4.4.2 Key focus areas

The ECS industry will need to take the initiative in the development of the next-generation treatment of chronic diseases. The field of remote sensing holds great promise for the lifelong and chronic monitoring of vital signs. The deployment of remote monitoring system relies on sensors integrated into bed or chair. Optical sensing techniques, for instance for remote reflective photoplethysmography, as well as capacitive and radar sensing support this approach. This will be multimodal, with fusing techniques to smart analytics to unify the data into usable information. The strength of remote sensing not only relies on the quality of the acquired signals, but also its potential to reveal slowly changing patterns – possibly symptoms from underlying physiological changes. The analysis of such datasets, currently largely unexplored, will provide new insights into normal versus pathological patterns of change over very long periods of time:

- Treatment of chronic diseases will be enhanced by an upcoming generation of small and smart implantable neuromodulator devices, which are highly miniaturised, autonomous and cost-effective. These will be implanted, wirelessly powered by radio frequency (RF), microwave, ultrasound or energy harvesting with minimal side effects on the selected nerve through a simple and minimally invasive procedure to modulate the functions of organs in the treatment of pain management, brain disorders, epilepsy, heart arrhythmia, autoimmune diseases (immunomodulation), etc.
- Organ-on-a-chip (OOC) platforms, which lie at the junction of biology and microfabrication and biology for personalised and safer medicines, are another treatment approach, addressing, for instance, pathologies currently without effective treatment (rare diseases). Often rare diseases are chronic and life-threatening, and they affect approximately 30 million people across Europe. In an OOC, the smallest functional unit of an organ is replicated. The essential capabilities underlying the OOC field are primarily embedded microfluidics and the processing of polymers in a microfabrication environment. Smart sensors can be used as readout devices, while edge AI will be essential in data interpretation and reduction.

For chronic diseases diagnoses, LoC-based technologies – relying on miniaturisation – show promise for improving test speed, throughput and cost-efficiency for some prominent chronic diseases: chronic respiratory diseases, diabetes, chronic kidney diseases, etc.

3.4.4.5 Major Challenge 5: ensure more healthy life years for an ageing population

3.4.4.5.1 Status, vision and expected outcome

In the last two decades, effort has been made to enhance two important and specific objectives of smart living environment for ageing well:

- Avoid or postpone hospitalisation by optimising patient follow-up at home.
- Enable a better and faster return to their homes when hospitalisation does occur.

The following list includes some typical examples of assistance capabilities related to major chronic diseases covering the first main objective (optimisation of patient follow-up at home):

- Vital signs checker: blood pressure meter, oximeter, thermometer, weight scale.
- Hospital's software interface, the patient's file, the patient's risk alarm centre with automatic call to healthcare practitioners.
- Video communication support (between the patient and their nurse, doctor and family), and interactive modules for the patient (administrative, activities, menus, medical bot chat, etc).
- Authentication and geolocation of patients, with patient or patient's family consent.
- Teleconsultation for nights and weekends at the foot of the bed of patient's hospital or retirement home.

The second objective – smooth home return – relates to suitable technical assistance in addition to human assistance:

- Enhance the patient's quality of life and autonomy.
- Improve the patient's safety and follow-up in their room through a reinforced work organisation.
- Allow monitoring of the patient's progress to motivate them during their rehabilitation period.
- Minimally invasive therapies allowing for shorter hospital stays and improved patient wellbeing.
- First-time-right precision diagnoses to prevent hospital readmissions.

- Prepare for the return home: patient support in appropriating technical aids by integrating these solutions into rehabilitation.

Efforts are being made to enhance medical and social care services through different kinds of robots. The purpose here is to provide advanced assisted living services via a general purpose robot as an autonomous interaction device that can access all available knowledge and cooperate with digital appliances in the home. In this sense, autonomous mobile robots offer several advantages compared to the current (stationary) Ambient Assisted Living (AAL) solutions. Due to sensor-augmented user interfaces, human computer interaction is becoming increasingly natural. As a consequence, robots will come to represent a familiar metaphor for most people.

Neurorehabilitation is sometimes required after hospitalization and is generally a very complex and challenging undertaking resulting in both "successes" and "failures" (setbacks). Neurological patients typically report having "good days and bad days", which affect performance, motivation and stamina, and where cognitive stimulation (AI-based speech producing programs, social robots, etc), for example, has the potential to improve the efficiency of neurorehabilitation and relieve some of the pressure on health systems. Robotics is well suited for precise, repetitive labour, and its application in neurorehabilitation has been very successful. This is one of the main reasons why the rehabilitation robotics market has tripled over the last five years and, today, rehabilitation robotics is one of the fastest growing segments of the robotics industry. This industry is dominated by European companies that can deliver highly innovative solutions with a strong scientific basis and exceptional manufacturing quality. Based on market size and need, it is projected that the compound annual growth rate (CAGR) for rehabilitation robotics will soon reach between 20% and 50%.

3.4.4.5.2 Key focus areas

The ECS industry can significantly upscale the "ageing well" area, as it is enabled by most of the focus topics developed in the previous sections. The industry is playing an important role in bringing ambulatory monitoring to the next level. Important aspects here are reducing costs, improving user friendliness (e.g. easy to wear/use devices, interoperable gateways, reduction of patient follow-up systems) and data security.

The enabling technology platforms detailed below are expected to significantly contribute to this prevalence of the ECS industry in ageing well, taking into account that ageing well is very much related to "ageing in place":

- Low-power technology for sensors, microprocessors, data storage and wireless communication modules, etc.
- Miniaturisation technology for sensors, microprocessors, data storage and wireless communication modules, etc.
- Printed electronics technology for textile integration and patch-type housing of electronics;
- Low-power edge AI computing for data analysis and data reduction.
- Data communication technology for interoperability of (wireless) data infrastructure hardware (wearable device connections) and software (data sharing between data warehouses for analysis and with patient follow-up systems for feedback).
- Data security technology for interoperability between security hardware and software components.
- Robotics systems enabling patients to overcome loneliness or mental healthcare issues.

1.1 1.2 1.3 2.1 2.2 2.4

Interoperability is surely the main challenge faced by the ECS industry in achieving full impact due to the vast heterogeneity of IoT systems and elements at all levels. Interoperability and standardisation need to be elaborated in relation to data and aggregated information. Thus, it is not enough to be able to receive a

message, i.e. to understand the syntax of the message, but it is also necessary to understand the semantics. This requirement implies the development of a data model that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons. It must be based on several relatively simple principles: creation of formats and protocols for exchange of data records between healthcare information systems; format standardisation and connected interface unification; improvement of communication efficiency; a guide for dialogue between involved parties at interface specification; minimisation of different interfaces; and minimisation of expenses for interface implementation.

3.4.5 TIMELINE

The following table illustrates the roadmaps for Health and Wellbeing.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: establish Europe as a global leader in personalised medicine deployment	**Topic 1:** enable digital health platforms based upon P4 healthcare	• IoMT-enabling patient-generated health data • Expansion of AI on the edge • High level of digital trust – privacy and security by design, hardened embedded AI models
Major Challenge 2: lead the healthcare system paradigm shift from treatment to health promotion and prevention	**Topic 2:** enable the shift to value-based healthcare	• Disease detection from biomarkers derived from medical images and sensors • Predictable and repeatable outcome of diagnostic imaging • Digital supply chains, automation, robotics, and next-generation interoperability • Early diagnosis through PoC diagnostic systems
Major Challenge 3: home becomes the central location of the "healthcare consumer"	**Topic 3:** euild an integrated care delivery system	• Use heterogeneous data from more sources (patient-generated health data, edge computing and imaging to ensure efficient medical decisions, etc.) • Remote decentralised clinical trials development (smart body patches, monitoring implants for continuous monitoring, etc.)
Major Challenge 4: ECS industry supports EU strategy to tackle chronic diseases	**Topic 4:** enhance access to personalised and participative treatments for chronic and lifestyle-related diseases	• Accurate long-term monitoring and data analysis of patients with chronic diseases and co-morbidities • Make treatment adherence more efficient (smart drug delivery based on innovative medical devices, etc.)
Major Challenge 5: ECS industry fosters innovation and digital transformation in active and healthy ageing	**Topic 5:** ensure more healthy life years for an ageing population	• Optimisation of patient follow-up at home to support ageing in place (remote patient monitoring, geolocalisation, etc.)

155 Electronic medical record (EMR): A computerised database that typically includes demographic, past medical and surgical, preventive, laboratory and radiographic, and drug information about a patient. It is the repository for active notations about a patient's health. Most EMRs also contain billing and insurance information, and other accounting tools.

MEDIUM TERM (2027–2031)	LONG TERM (2032–2037)
• Development of multimodal data analysis • Improvement of energy efficiency (energy harvesting, etc) • Secure digital health platforms, portable end-user devices, remote e-healthcare and AI front-ends	• New tools for clinical decision-making and precision medicine • Scalable digital health platforms
• Clinical decision-making augmented by a combination of electronic medical records[155], imaging, biomedical models • EHRs supporting precise communication between different care-givers, PoC diagnostic systems or AI-based clinical decisions • Efficient healthcare information infrastructure, lowering costs while improving health outcomes	• Shift from general hospital to specialised integrated practice units • Next generation of smart minimally invasive devices • Disease detection from biomarkers derived from medical images • Outcomes cover the full cycle of care for the condition, and track the patient's health status after care is completed
• Next-generation drug delivery systems (highly integrated, patch-like microsystems) will form part of the IoMT	• Care solutions integrated, combining information across all phases of the continuum of care, preventing, preparing and providing care based on person-specific characteristics • Holistic healthcare involving all imbalanced health situations of the patient
• Development of active or passive implantable medical devices • OOC platforms addressing pathologies currently without for chronic disorders	• OOC platforms addressing pathologies currently without for chronic disorders effective treatment (rare diseases)
• Suitable technical assistance in addition to human assistance (humanoid robots, advanced assisted living, rehabilitation robotics, etc) • Precision diagnosis to prevent hospital readmissions	• Data model diffusion that maps semantic content from the data received from devices into an information system that is usually utilised for collecting and evaluating data from monitored persons

3.4.6
SYNERGY WITH OTHER THEMES

Close collaboration will be useful in all application areas – for example, **Energy, Mobility, Digital Industry, Agrifood and Natural Resources** and **Digital Society** – based on cross-sectional technologies such as **Edge Computing and Embedded Artificial Intelligence, Connectivity and, of course, Quality, Reliability, Safety and Cybersecurity**.

More specifically:

- Related to digital industry, "bio-production", which has the objective of developing an innovative field to produce the biologic products of the future through the implementation of disruptive technologies, should be an important topic to address in future years.
- The relationship between food systems and health is obvious and well-identified, especially in preventative health. This is an aspect that needs to followed up to reinforce health prevention in the long term.
- In terms of energy and connectivity, it is important to consider the impact of innovative wearables and implantables, sensors and actuators in general, as they represent a crucial sector with a direct impact on the further development of digital health.
- Embedded systems are an essential enabler of healthcare digital transformation. The challenges are defined in the transversal Chapter **Quality, Reliability**, **Safety** and **Cybersecurity**, with the aim of ensuring hardware quality and reliability, dependability in connected software, human/systems interaction and, again, the required privacy and cybersecurity to share the necessary requirements to support the expansion of digital health.

3.5

ECS Key Application Areas

AGRIFOOD AND NATURAL RESOURCES

3.5.1
SCOPE

Smart Internet of Things (IoT) systems are vital for the sustainable production and consumption of safe and healthy food, as well as for sustainable practices in agriculture, livestock, aquaculture, fisheries and forestry. They can also foster access to clean water, fertile soil and healthy air for all, in addition to helping preserve biodiversity and restore the planet's ecosystems.

The first two Major Challenges relate to livestock and crop health, and also to farming systems and food supply chain assurance and management. For instance, IoT system technologies can be used in pest management or towards minimising the use of fertilisers and antibiotics. Farming systems and food supply chain management will benefit from smart IoT systems, including the use of traceability frameworks, and from robots and drones, to revolutionise modern agriculture and food production. The third Major Challenge addresses issues such as soil health, air quality and the environment in general, all in terms of smart integrated monitoring technologies, and the use of smart waste management systems and remediation methodologies. The objective is to protect the environment to reduce the destruction of ecosystems caused by a myriad of anthropogenic activities and reduce GHG emissions. The fourth Major Challenge refers to the key role that IoT systems can play in water quality monitoring and access to clean water. An important aspect here is the overall management of water usage, as well as smart treatments to foster the circular use of wastewater, rainwater and storms/floods. In the last Major Challenge, biodiversity restoration for ecosystem resilience, conservation and preservation address how electronic components and systems (ECS) can contribute to the restoration/preservation of a greater variety of crops, and greater fauna and flora species diversity, to ensure the natural sustainability of healthy ecosystems (agriculture, aquaculture, fisheries and forestry) by enabling them to better withstand and recover from disasters.

1.4

All five Major Challenges in this Chapter align with key Horizon Europe missions, as well as the European Green Deal and future digitalisation technologies. To master these challenges significant advances are crucial in the new fields of materials, manufacturing technologies, information and communications technology (ICT), Artificial Intelligence (AI), robotics, electronics and photonics, and other technologies, as well as in circular industries.

3.5.2
APPLICATION TRENDS AND SOCIETAL BENEFITS

External requirements

According to the UN, if the global population reaches an expected 9.6 billion by 2050, the equivalent of almost three Earth planets could be required to provide the natural resources needed to sustain current lifestyles. Increasing food production is driven not only by population growth, but also by more demanding diets as populations become wealthier. On the other hand, productivity is being hit hard by climate change in regions where food scarcity and inefficient resource management is most prevalent. The necessary acceleration in productivity growth is being hampered by the degradation of natural resources, a reduction in biodiversity, and the spread of transboundary pests and diseases of plants and animals, some of which

are becoming resistant to antimicrobials[155]. Investment in changing agricultural practices, incorporating technological innovations, has boosted productivity, but the yield growth is far from sufficient. A more holistic and innovative approach is needed to reduce the strain on natural resources and enhance their quality, while also increasing food productivity. At the same time, food losses and waste claim a significant proportion of agricultural output, whereas poor bio-waste management and packaging is increasing environmental pollution.

F.72 *Main Agrifood and Natural Resources goals and associated challenges*

Addressing the key issues on food security and sustainable production would lessen the need for production increases while improving the natural resource base. For example, mitigating the effect of natural and human pressures on water bodies is a priority, namely by reducing as much as possible general pollution and plastics, eutrophication, acidification and warming up. Less than 2.5% of the world's water is fresh[156], and water pollution in rivers and lakes is occurring faster than nature can recycle and purify. Currently, more than 2 billion people live with the risk of reduced access to freshwater resources[157,] and by 2050 at least one in four people is likely to live in a country affected by chronic or recurring shortages of freshwater. At the moment, 2.6 billion people are economically dependent on agriculture[158] despite 52% of arable land being moderately or severely affected by soil degradation. Air quality has also been deteriorating in both rural and urban areas as a result of the spread of particulate matter in addition to the release of greenhouse gases (GHGs) and their effect on climate.

155 *[FAO UN: The Future of Food and Agriculture, 2017]*

156 *All about water, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull53-1/53105911720.pdf*

157 *UN 2019 The Sustainable Development Goals Report 2019: Goal 6: Clean water and sanitation / https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf*

158 *ibid: Goal 15*

Today, farmers still spread much more fertiliser on their fields than is required. Consequently, nutrients such as nitrates and phosphates, which cannot be absorbed by the plants, accumulate in the soil and filter into groundwater with a dramatic impact on the environment and public health. Therefore, there is increasing pressure on the agricultural industry to find sustainable solutions for reducing environmental pollution caused by fertilisation. On the other hand, smart production processes and intelligent logistic systems across the whole supply chain can yield further optimisations in an effort to reduce or at least to keep emissions constant with increased productivity, while ensuring safe food. Every year, almost one in 10 people will fall ill due to food-borne diseases[159].

Societal Benefits

Due to the challenges that the world is facing, the UN has defined several Sustainable Development Goals (SDGs) that are a blueprint to achieving a better and more sustainable future for all. The SDG implementation plans address the global challenges we face in protecting biodiversity, our natural resources and acting on climate change. Furthermore, it includes actions relating to socioeconomic drivers aiming at eliminating poverty, hunger, inequality, and achieving responsible consumption and production, sustainable prosperity, peace and justice. In Europe, national and EU policies such as "From Farm to Fork"[160] and "Biodiversity Strategy 2030"[161], reflect and amplify the underlying objectives with a set of measures – from regulatory frameworks to incentives and investments for development, and the deployment of holistic innovative approaches in a circular economy, agroecology, agroforestry, climate- smart and sustainable agriculture, bio-economy and the Blue Economy.

3.5.3 STRATEGIC ADVANCE FOR THE EU

Within the next framework programme on research and innovation by Horizon Europe, it is envisioned that Europe will achieve high impact missions on: "adaptation to climate change including societal transformation", "cancer", "healthy oceans, seas, coastal and inland waters", "climate-neutral and smart cities" and "soil health and food".

Innovative solutions based on IoT systems have a significant socioeconomic impact for the EU in rural, coastal and urban areas. For instance, agriculture is being transformed by the IoT revolution, with the use of smart devices allowing farmers to better control the process of raising livestock and growing crops. As a result, quality and safety in food production are rapidly evolving, becoming more predictable and efficient than ever. According to the European Innovation Partnership "Agricultural Productivity and Sustainability" (EIP-AGRI)[162], the digitalisation of rural areas can help to improve the economic and environmental sustainability of the agricultural sector. Moreover, it can make farming more attractive for young people, improve the quality of life of farmers and multiply the number of rural businesses. Consequently, rural depopulation could be greatly reduced.

1.2 1.3 1.4 2.1

159 Food safety - World Health Organisation at https://www.who.int/news-room/fact-sheets/detail/food-safety

160 https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf

161 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN

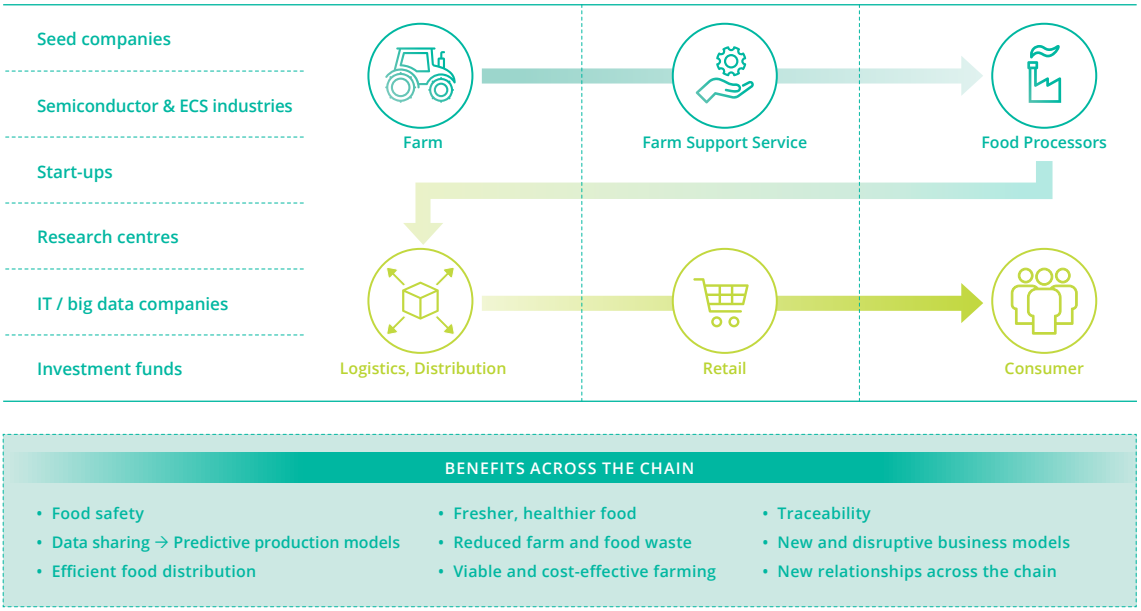
162 https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-seminar-multi-level-strategies-digitising-0

For instance, the Smart Water Management (SWM) project[163] points to an acceleration in the deployment of smart water networks with the aim of upgrading the reliability, efficiency, quality control, sustainability and resilience of drinking water supply services while also educating end-users on the benefits of water conservation. Strategies of this nature could represent the solution for urbanisation-related issues (scarcity, pollution, etc.) by providing a better use of our water resources while protecting the most vulnerable places, and by creating innovative types of economy and management.

Developments in smart IoT systems for agriculture and food production based on innovative and advanced ECS will strongly contribute to reach of the objectives set by the European Green Deal and the EU's Biodiversity Strategy for 2030. These will be enabled the following three sets of main actions and respective targets:

1. **From Farm to Fork**
   Moving towards a fair healthy and environmentally friendly EU food system by 2030 through the targets listed in *Figure F.74*/Topic 1164.
2. **Natural resources**
   Figure F.74/Topic 2: Targets set for natural resources.
3. **EU Biodiversity Strategy for 203**0
   Figure F.74/Topic 3 Targets set in Biodiversity Strategy for 2030165.

Figure F.73 depicts the agrifood value chain and the main actors involved, along with a list of the benefits obtained for farmers and consumers by using smart IoT systems. Moreover, the advanced technology applied throughout the whole chain will bring new market opportunities for the European semiconductor and ECS industries.



F.73 *Agrifood value chain*

163 *https://www.iwra.org/swmreport/*

164 *https://ec.europa.eu/commission/presscorner/detail/en/fs_20_908*

165 *Facsheet EU-Biodiversity-strategy-en.pdf, https://ec.europa.eu/commission/presscorner/detail/en/fs_20_906*

TOPIC	TARGET ACTIONS	MAIN GOALS
Topic 1: from Farm to Fork	**Target actions 1.1:** reduce the use of pesticides in agriculture that contribute to pollution of soil, water and air	• Reduce by 50% the use and risk of chemical pesticides by 2030 • Reduce by 50% the use of more hazardous pesticides by 2030
	Target actions 1.2: the excess of nutrients in the environment as a major source of air, soil and water pollution, negatively impacting biodiversity and climate	• Reduce nutrient losses by at least 50%, while ensuring no deterioration on soil fertility • Reduce fertilizer use by at least 20% by 2030
	Target actions 1.3: antimicrobial resistance linked to the use of antimicrobials in animal and human health leads to an estimated 33,000 human deaths in the EU each year	• Reduce by 50% the sale of antimicrobials for farmed animals and in aquaculture by 2030
	Target actions 1.4: organic farming as an environmentally friendly practice that needs to be further developed in the EU each year	• Boost the development of EU organic farming areas to achieve 25% of total farmland under organic farming by 2030
Topic 2: natural resources	**Target actions 2.1:** optimisation and remediation towards climate-neutrality – first step for 2030 and then 2050, through:	• Reduction of water pollution and GHG emissions, including. methane and nitrous oxide • Reduction of European cumulated carbon and cropland footprint by 20% in the next 20 years, while improving climatic resilience of European agricultural and halting biodiversity erosion
Topic 3: EU biodiversity Sstrategy for 2030	**Target actions 3.1:** establish protected areas	• For at least 30% of land in Europe. • For at least 30% of sea in Europe.
	Target actions 3.2: restore degraded ecosystems at land and sea across the whole of Europe	• Increasing organic farming and biodiversity-rich landscape features on agricultural land • Halting and reversing the decline of pollinators • Restoring at least 25,000 km of EU rivers to a free-flowing state • Reducing the use and risk of pesticides by 50% by 2030 • Planting 3 billion trees by 2030

Targets set in the Farm to Fork strategy, in Natural resources and EU Biodiversity Strategy for 2030.

F.74

3.5.4 MAJOR CHALLENGES

This section discusses five Major Challenges that need to be addressed in the domain of agriculture (food security, food safety, environmental protection, and sustainable production), natural resources and biodiversity, and how smart IoT systems and associated key enabling technologies can help achieve them:

- **Major Challenge 1**: food security.
- **Major Challenge 2:** food safety.
- **Major Challenge 3:** environmental protection and sustainable production.
- **Major Challenge 4:** water resource management.
- **Major Challenge 5:** biodiversity restoration for ecosystems resilience, conservation and preservation.

3.5.4.1 Major Challenge 1: Food Security

To define the difference between food security[166] and food safety[167], *Figure F.75* presents the interrelation between both concepts, as well as their main constituent elements. This section and the next will address the challenges related to food security and food safety from an ECS perspective.

F.75 *Food security vs safety*

166 *Food security has been defined by the FAO as "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life"*

167 *Food safety is an umbrella term that encompasses many facets of handling, preparation, and storage of food to prevent illness and injury. Included under the umbrella are chemical, microphysical and microbiological aspects of food safety*

3.5.4.1.1 Status, vision and expected outcome

1.4 2.1 2.2

Consolidated advances in Industrial Internet of Things (IIoT) have already started to shape smart manufacturing in the food and beverage[168] industry. The access to relevant and role-based information, in real-time or near real-time, is key to ensuring not only the efficient storage and processing of data, but also their appropriate use for optimised decision-making at every level of next-generation automation systems and robotics (e.g. cyber-physical systems, CPS). Therefore, sustainable production, safety and quality do not only depend on the product itself, but on the respective processes and their control as offered by key data gathering and monitoring, smart sensing, data analysis, diagnostics and control systems. Ultimately, intelligent food production can consider the consumer needs of each market, and such systems can provide intelligent recommendations for adjusting the amount and quality of food accordingly, assuring food security (i.e. enough food for each market) and food safety (i.e. healthy food), and also consider environmental concerns and societal impact.

3.5.4.1.2 Intelligent and adaptive food production

To develop intelligent food production systems, solutions are required in (but not limited to) the following fields:

- In-line inspection, networked packaging systems and robot technology in the warehouse to allow for a smart workflow to manage, monitor, optimise and automate all processes accordingly.
- Intelligent control room systems to enable correlations between machine malfunctions and load parameters to be detected immediately, thereby enabling maintenance work to be carried out early and on schedule, with a reduction in costly downtimes.
- Food industry imposes specific requirements (e.g. in food processing) that may take advantage of smart (bio-sensing) for high-quality monitoring to reduce the amount of water and chemicals used in such processes, and to prevent contamination.
- AI/machine learning (ML) and big data models must be devised and used to offer further intelligent decision-making and, whenever possible, should be employed directly at-the-edge for greater energy efficiency.
- IIoT systems, based on AI and digital twin technology, can provide the flexibility to tailor-make new products to help cope with ever demanding diets.

3.5.4.1.3 Re-designing Farming Systems

Precision Farming Systems

Advanced farming machines and robotic collaborative systems are needed for cost-effective land and livestock management, as well as for large-scale arable and fruit crops, as tasks can thereby be performed in parallel, enabling economies of scale. Advanced machines include the following:

- Harvesting robotic systems: autonomous robots or swarms of robots can replace intensive and strenuous labour practices as the worldwide population transitions from rural to urban areas and manual labour declines. Agricultural robots need to be equipped with improved capabilities for sensing and perception. Special attention must be paid to safety aspects for those robots expected to work collaboratively with humans or close to livestock.
- Drones: remotely piloted autonomous unmanned aerial vehicles (UAVs), either flying alone or in swarms, can mainly improve efficiency in two application areas: (i) monitoring large areas with intelligent computer vision devices to provide a higher level of detail and on-demand images, especially as drones can overcome limitations of satellite imagery (e.g. images below forest cover); and (ii) in the use of phytosanitary products to increase efficiency and

168 Beverage will be considered as food in the rest of the document.

reduce environmental impact by avoiding indiscriminate chemical dispersion, and following predetermined prescription maps.

- Satellites: these allow for improved information regarding fields, although a combination of data from further sensors with increased update frequency, improved performance and spatial resolution would also be needed.
- Wireless sensor networks (WSNs) and smart actuators deployed across fields will form the backbone of heterogeneous multi-agents collaborative approaches. Local parameters (e.g., ambient temperature, soil pH, soil salinity, relative humidity, etc.) measured from multiple sensors planted in the soil or attached to the plants could be retrieved remotely by drones and/or robotic systems in order deepen the field analysis provided by image-based techniques. Coupled to the proper AI and decision systems, WSNs will also further help in automatically triggering the appropriate actions (e.g., drones could locally release agrochemicals after interrogating/analysing sensors, water irrigation systems could be activated only in some land areas, etc.).

1.2 2.1

All the proposed solutions should meet important requirements such as cost-efficiency, compactness, reliability, lifetime, low power, interoperability with existing machinery, and human factors. Furthermore, training systems based on virtual, augmented and mixed reality and simulators are needed for training people (e.g., operators) independent of seasonality or safety issues. However, an important challenge remains that all sizes of farms, including small and middle size, have access to these solutions at cost effective and the facilities to easily exploit them.

Horticulture/greenhouses, urban and vertical indoor agriculture

Urban agriculture is being promoted as a promising option for sustainable food, a better quality of life, and community engagement. The goal of this modern version of agriculture is to grow and deliver high-quality food with a minimal waste of resources.

Many crops in vertical indoor farms are often cultivated using hydroponics, a technique where there is no need of soil and fertiliser as the growing plants are supplied with irrigation water. In fact, recent environmental challenges have promoted the intensification of "soil-less agriculture" in an urban context to decrease the negative impact on nature. Even if hydroponics produces quality crops with high efficiency, there is an area of opportunity here to better monitor and control the fertiliser components in the irrigation water, such as through the development of:

1.2 1.3 1.4 2.1

- Novel and low-cost online sensors for optimised control, such as nutrient sensors to enable smaller discharge of fertiliser into natural waters.
- Robots with a high precision level to perform automatic harvesting to reduce the overall production costs, which are currently high, to be competitive with traditional agriculture.
- Autonomous indoor farming systems in which cultivation is controlled remotely via AI, based on measurements of crop properties with the help of intelligent sensors and AI-based digital twin models of such plants.

3.5.4.2 Major Challenge 2: food safety

3.5.4.2.1 Status, vision and expected outcome

Key for the next generation of novel ecology-based agricultural systems is the use of high-tech sensors and AI to monitor, quantify and understand individual plants and animals, as well as their variability, to ensure food safety. This requires smart sensors and monitoring technology that can adapt to the unpredictability and variation of living systems. It will require integrated digital technology solutions such as ecology-based

robotic systems that can control the bio-physical processes (including growing conditions) and understand the biological environment (for plants and animals). However, innovative ecology-based robotic systems' manipulation of operations is a huge challenge in environments that are only modestly defined and structured.

1.2 1.3 1.4 2.1

Furthermore, detection in the supply chain and "at the fork" should be also considered. This implies low-cost compact sensors, connected to information processing systems used in the food supply chain and by consumers, that allow, for instance, freshness and food safety detection for meat and vegetables (such as integrated into a smartphone).

3.5.4.2.2 Crops quality and health

Integrated pest management (IPM)

Novel IPM strategies are needed to detect diseases and prevent their spread on crop production for European organic and conventional agriculture, and to increase organic farming and horticultural systems. Improved IPM will require developments in the following fields:

- Smart systems based on portable real-time pest disease diagnostics and monitoring platforms to provide rapid local and regional disease incidence alerts (georeferenced) e.g., weather/climate information for predictive models providing risk assessments and decision support for IPM.
- IoT devices specialized in pests and disease measurements, such as insect traps and other systems based on image recognition or AI models.

Agro-ecology based: Move from conventional to organic, regenerative agriculture

To support the EU *"From Farm to Fork"* implementation, smart ECS can help farmers to drastically decrease the use of pesticides and their impacts on human health and the environment. This will require:

- Development of cost-effective and intelligent intra-row, herbicide-free weeding techniques using advanced robots and robot fleets for individual plant recognition with high precision based on advanced (vision) sensor technologies and AI algorithms working under in-field conditions.
- Development of smart sensors to monitor the quality of spraying, as this is essential for biocontrol products and contact pesticides.
- Integration into the same framework of decision-support tools and precision agriculture tools to simplify farm management, improve crop quality and reduce costs.

Plant precision breeding and plan phenotyping

The development of smart technologies can support precision plant breeding and phenotyping. This could be nanotechnology solutions or smart sensor solutions to support the following.

- Genomics and transcriptomics: DNA informed breeding, gene editing, genome prediction, breeding optimisation, phenotyping and seed sowing optimization.
- Large scale and high precision measurements of plant growth, architecture and composition: These are required to optimize plant breeding by increasing our understanding of the genetic control and response of plants to their environment. These sensor systems should allow the study of plants in relation to biotic and abiotic factors, including plant-microbiome interactions, plant-plant competition, plant diseases and exposure to a multitude of variable abiotic environmental conditions such as light quality, irradiance levels, nutrient supply, temperature, humidity, soil pH and atmospheric CO_2 levels.

3.5.4.2.3 Livestock welfare and health

Livestock health is crucial for food safety. Healthy animals should not need antibiotics, and their reduced use would decrease the risk of transmission of diseases to humans by healthy animals. Animal welfare is also an important concern for a growing number of consumers.

These two aspects are drivers for investing in better sensing systems for animal monitoring. Combined with data intelligence solutions, this will improve animal health and welfare, resulting in more animal-friendly production, higher efficiency, better quality and improved food control safety.

They should include for instance:

- Wearable sensors at the farm/barn level, and ambience sensors during cattle transport.
- Smart sensor systems to monitor animal activity, such as individual or group behaviour, to provide useful information for the early detection of diseases and to increase animal well-being.
- Smart sensor systems for the rapid verification of bacterial infection and behavioural observations to control disease spread and support clinical and veterinary stakeholders to effect suitable therapeutic interventions when required; body temperature can also be monitored for early disease detection to reduce antibiotics use.

1.2 2.1

3.5.4.2.4 Food Chain

Intelligent logistic systems including sensing and monitoring for food chains

Logistics are a critical component of the food chain. It does not only determine the reach of distribution, but logistics delays and conditions profoundly affect the quality and safety of the products received by consumers and can result in food loss and waste in the supply chain.

Smart real-time sensing, monitoring and control systems in the food supply chain will safeguard food quality and food safety, while eventually reducing food losses in the supply chain. Therefore, technological solutions are required, but not limited to:

- Systems for monitoring and controlling food quality during transport and storage (e.g. temperature in cold chain monitoring, moisture, controlled atmosphere, ethanol, ethylene), which should be efficient and interoperable along the logistics chain.
- Predictive systems of the quality of (perishable) food products in the supply chain, providing real-time decision-support based on actual sensor measurements, supply chain data and AI models.
- Transport route optimisation, considering not only time and cost, but also external conditions and the intrinsic properties of the products being transported.

1.4 2.1 2.4

These needs are strongly related with traceability, as shown in the following section.

End-to-end food traceability

Food and beverage manufacturers and producers are faced with increasingly complex and fragmented supply chains, stricter regulation, and more demanding consumers. Regulatory compliance, competitive advantage, brand reputation and costs have made product traceability a priority and end-to-end traceability a major challenge. In today's globalised world where people of any origin live across every country, the source of food products and ingredients, as well as their certification, are a major concern/priority for consumers. Therefore, traceability should also encompass certifying food origin and not be restricted to tracking across the supply chain. End-to-end traceability solutions are required, but should not be limited to:

- Integrating blockchain into current technology to prevent fraud and counterfeiting.
- Traceability to increase alignment between production and individual consumer demands, leading to more personalised nutrition support.

2.4

- Traceability to optimise distance between farm and fork – although many products are produced preferentially in specific parts of the world, there are also many examples of food that could be produced economically closer to consumers.

To this end, as IoT solutions are increasingly being deployed, integrated hardware systems need to deliver mobility, connectivity, long lifetime autonomous sensing and AI-based intelligence at-the-edge, edge and/or cloud analytics and cybersecurity, complying with privacy regulations when applicable, on a plug-and-play, open, interoperable architecture and platform.

1.4 2.1 2.2

3.5.4.3 Major Challenge 3: environmental protection and sustainable production

3.5.4.3.1 Status, vision and expected outcome

EU regulations, together with consumers' increased interest in organic food, is compelling farmers to drastically decrease the use of pesticides to reduce the risks and impact on human health and the environment, as well as to undercut the maximum residue levels of pesticides. Pesticides are found not only in drinking water[169] but also in food and beverage. Lively debates have shown that our society demands alternatives to pesticides to help preserve the environment and improve food quality.

Drastic reduction in the use of pesticides is one of the major goals of the EU's agricultural policy, with some countries planning to halve their pesticide use by 2025 (e.g. ecophyto plans[170] in France, and the Aktionsplan Pflanzenschutzmittel[171] in Switzerland). The EU Farm to Fork strategy also aims to implement a plan that significantly reduces the risks from chemical pesticides, as well as the use of fertilisers and antibiotics, and to increase the amount of organic farming carried out in Europe.

3.5.4.3.2 Soil Health

The in-situ real-time monitoring of soil nutrients and herbicides

The optimal use of chemical fertilisers and organic manures to deliver the required increase in food production requires a complete understanding of applied nitrogen- and phosphorous-based nutrients with a much greater spatial and temporal resolution than is available today. Current methods of soil analysis do not provide real-time in situ nutrient analysis in fine detail, and delays in receiving soil results are common because of backlogs in commercial labs due to high sample volumes, thus reducing the value of the soil test results for the farmer. Moreover, herbicides are another huge problem due to their environmental and health impact. To solve these issues, the following approaches could be explored:

- Intelligent sensors (with miniaturised and ultra-low power consumption components) must be developed to deliver measurements in situ and in real time of soil nutrients at parts per million (ppm) concentrations. Such devices must have the appropriate packaging to extract water from the soil, soil, ideally, they should be able to be buried in the soil for long periods of time or at least while sustaining operation capabilities for at least the entire growing season. To optimise effectiveness, low proximity sensors should be combined with optical sensors and high proximity sensors to retrieve the maximum amount of information on soil health.

1.2 1.3 2.1

169 https://ree.developpement-durable.gouv.fr/donnees-et-ressources/ressources/cartes/article/nombre-des-pesticides-trouves-par-masse-d-eau-et-leur-classement-selon-le-taux

170 Ministère de l'Agriculture, Le Plan Ecophyto, qu'est-ce que c'est? https://agriculture.gouv.fr/le-plan-ecophyto-quest-ce-que-cest , 2020

171 Aktionsplan Pflanzenschutzmittel, https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/pflanzenschutz/aktionsplan.html

- Likewise, smart actuators could prove to be highly beneficial. Such miniature units could be deposited on or buried into the soil. Coupled to sensing functionalities into the same module, critical actions (e.g., release of agrochemicals) could be triggered very close to the plant roots for maximized efficiency.
- Multidisciplinary approaches for developing novel sustainable smart ECS are needed. Indeed, current ECS contain a variety of toxic materials and chemicals. As such, they cannot be left into the soil. The optimization in the use of agrochemicals should not come at the expense of another ecological burden. New sustainable "green" ECS made of eco-friendly materials that will have benign environmental impact must be created. 1.2
- IoT systems with edge and/or cloud-based data analytics are also necessary to provide farmers with decision support regarding fertilisation strategies, by translating measurements into meaningful agronomic indicators and respective measures. These strategies should prioritise the use of organic fertilisers and the gradual reduction of chemical fertilisers until completely eliminated to restore the biodiversity contribution in the preservation of soil health. Furthermore, this type of system should detect weeds, preserve the “good ones” and eradicate those that are competing with the crop in question. This requires low cost vision technologies (not only red/green/blue (RGB), but also 3D, hyperspectral imaging, etc) and edge AI for in situ real-time recognition. 1.4 2.1

3.5.4.3.3 Healthy air and skies

Sensors and diagnostics for air quality monitoring (indoor, urban and rural)

According to the World Health Organization, the air we breathe is growing dangerously polluted: nine out of ten people now breathe polluted air, which kills seven million people every year. In fact, there has been much progress on identifying and reducing the sources of air pollution at lower concentrations and with higher spatial coverage. This is necessary to provide adequate data on what people are breathing, and to provide localised as well as holistic solutions. Microsensors and/or mini-stations can be used during fieldwork campaigns in cities, but there are technical problems relating to power source, data transmission, data storage, and data handling and assessment. Besides, local measures are not always effective since local concentrations of particulate matter may be influenced by long-range transported pollutants from agricultural activities occurring outside city boundaries.

Similarly, while indoor air quality has been shown to unambiguously impact the wellness and performance of people, there is also a lack of spatial granularity and a significant lag between exposures and sensing, actuation and management interventions for risk mitigation. In addition to indoors, air quality is made more complex by the interaction between indoor and outdoor air, emissions from buildings and their contents (paints, furniture, heating and cooling systems, etc.), human activities (breathing, cooking, cleaning, etc.) and the effects of long-term exposure to low concentrations of volatile organic compounds. These issues necessitate the development and deployment of real-time intelligent multi-sensor technologies with high selectivity and embedded (re-)calibration techniques. These should be combined with a monitoring network (edge-based) as part of the indoor infrastructure to provide the spatial and temporal information needed for specific, targeted and appropriate actions. Such actions should also include public awareness and the promotion of behavioural changes. 1.2 2.1

Smart systems for controlling and preventing GHG emissions

Strong evidence has been accumulated on the climate emergency resulting from human activities that add GHGs to the Earth’s atmosphere. The EU is the world's third biggest GHG emitter after China and the US. Although several measures have been taken since the Paris Agreement, breakthrough technologies and

state-of-the-art deployment is still needed across the transport sector and several industries with a high emission footprint to achieve a further reduction in emissions. These would be facilitated by the following:

- Smart systems and digitalisation to improve industrial processes performance and energy/resource efficiency towards a low-carbon economy, while reducing the impact of mobility and agricultural processes on the environment and human health, thereby controlling and preventing GHGs.
- A focus on the GHG emissions from animals by investigating microbiological sensing technologies on or in animals (in their rumens, for instance) to increase efficiency while reducing environmental impact, as well as performing analysis of the gathered data to support decision-making for mitigation measures (for instance, leading to change in feed).

3.5.4.3.4 Smart waste management

Integrated bio-waste systems

Despite proactive European policies and regulations[172], effective bio-waste management remains a challenge. For instance, 14 member states have been identified as at risk of missing the 2020 target of 50% preparation for the re-use/recycling of municipal waste. Reducing, recycling and reusing food/kitchen waste requires significant progress in technological solutions along with strong policy-making and shifting community behaviour. These solutions could be based on the following:

- Smart monitoring, controlling waste treatment units in real-time as well as gas emissions in landfills and anaerobic digestion monitoring. Data analytics should include gamification for behavioural triggers.
- Smart waste collection bins (radio-frequency identification (RFID) tags, self-compacting bins, fullness level sensors, automated waste segregation), including automated robotic systems and optimised separation systems, which can be complemented by the upcycling of waste streams into usable resources and optimal routing systems, as well as vehicle tracking. These solutions should be integrated and interconnected into the product cycle "from cradle to grave" to enable circular and resource-efficient methodologies.

Intelligent sustainable / biodegradable packaging

Intelligent and biodegradable packaging concepts have been gaining traction in the food industry to improve product safety and reduce environmental impact. Smart sensors of an IoT system can monitor environmental conditions and product quality, while communication devices can store and convey data throughout the product lifecycle. While these concepts need to be further advanced for efficient, safe food production and waste management, intelligent packaging itself needs to become more sustainable. Novel ideas are required to solve the problem of the amount of plastic packaging produced by food manufacturers. The definition of biodegradable packaging should lead to a new generation of food packaging. Such novel ideas include:

1.2 1.3 2.1

- A synergetic interdisciplinary approach to cross the boundaries of novel materials for food packaging and smart sensors associated with analytical methods for the detection of harmful substances that can infiltrate into food, cause water contamination, etc.
- Fabrication and hybrid integration of eco-friendly nanostructured electrodes, sensors, energy harvesting and storage devices on rigid and flexible biodegradable substrates to reduce the waste from embedded electronics in smart packaging.

172 https://www.consilium.europa.eu/en/press/press-releases/2018/05/22/waste-management-and-recycling-council-adopts-new-rules/

3.5.4.3.5 Remediation

Efficient smart networks for remediation

Remediation processes aimed at converting harmful molecules into benign ones can be undertaken in different ecosystems, such as water bodies (e.g., biotic and abiotic farming by-products), air (e.g. GHGs) and soil (e.g. pesticides). Remediation processes are mainly carried out in wastewater treatment plants. Although some pollution sources are static and sufficiently well known that treatment can be undertaken effectively, other pollution sources are more mobile in both time and/or space, making treatment at single points unsatisfactory. Another limiting issue is that remediation technologies are often power-intensive, and can therefore not be deployed for long in remote locations. Alternative high efficiency remediation methods are needed, such as to transform/reduce the levels of CO_2 in chemical products. Current devices are also prone to fouling. This means remediation processes cannot be run constantly in remote locations, and there is thus a necessity to undertake them only when and where they are most required. In this regard:

- A network of smart sensors (an IoT system) that can monitor relevant status in real time, and inform on the necessity of remediation, would provide unique decision support that would be invaluable for efficient water, air and soil management.
- Techniques used in the measurement and analysis of carbon sequestration by soils could also investigate the current potential of soils as a remediation mechanism to improve the sequestration capacity – such investigation should include the initiative of "four per 1000173 presented at COP21 in Paris.
- Likewise, tools and methods able to evaluate the performance of the carbon sequestration techniques employed should be developed to guarantee their efficiency.

1.2 1.4 2.1 2.3

3.5.4.4 Major Challenge 4: water resource management

3.5.4.4.1 Status, vision and expected outcome

The quality of groundwater, surface water bodies (oceans, seas, lakes), waterways (rivers, canals, estuaries) and coastal areas has a great impact on both biodiversity and the water quality that people consume every day. While natural droughts may lead to increased salinity and, along with floods, impact or endanger the quality of water bodies, human activities in energy production, manufacturing and farming industries have a major detrimental effect through thermal pollution, chemical, microbiological and micro-plastic contaminants, and biotic and abiotic farming by-products. Moreover, the outdated and deteriorating water infrastructure is having a detrimental impact on both water quality and the amount of water lost through leakage.

3.5.4.4.2 Access to clean water (urban and rural)

Healthy Water

With the aim of reducing pollution-related problems, water utilities, water associations, academia and private industry have focused on developing new methods, policies and procedures to secure drinking water distribution by detecting in real-time any compound or contaminant that may represent a health risk for the end-users and taking the required measures to mitigate these issues. This necessitates online information on the status of water sources at a larger scale than ever before. To mitigate both accidental and intentional contamination of freshwater resources, the deployment of sensors and diagnostic systems with

173 Researchers from the French National Institute for Agronomic Research, mentors of the project, have observed that by increasing the organic matter in the soil by 4 grams per 1000 - hence its name - it would be possible to limit the current growth of CO_2 emissions to the atmosphere. Promoting good agricultural practice would combat climate change and, at the same time, guarantee the food security of the population.

rapid communication technologies and data analysis capabilities are needed to secure water quality and its distribution over the network. Such actions would provide:

- Connected and highly integrated multi-parameter diagnostic sensors for real-time physico-chemical analysis (temperature, ionic electrical conductivity, pH, turbidity, inorganic pollutants as nitrates or heavy metals, etc.) and biofilm growth monitoring in water pipes.
- Online monitoring systems at the edge, including sensors to monitor biofilm growth in water pipes and AI/ML techniques for data analysis.

1.2 2.1

Integrated systems for demand reduction and conservation of water

According to the UN Development Programme, dwindling drinking water supplies are affecting every continent. On the one hand, increased urbanisation and farming have amplified the demand of water for human consumption and for domestic and agricultural use. On the other hand, an increasing number of countries are experiencing water stress due to longer drought periods and the spread of desertification. In addition, approximately 25% of all urban drinking water is being lost forever[174] in global water systems before it even reaches the end-user. Therefore, there is an urgent need to prevent losses from water abstraction as climate effects intensify. Leak localisation is currently very time-consuming, labour-intensive and costly. Operators have to manually place equipment that "listens" to the water flow during the night. Smart integrated systems can significantly contribute to key measures aiming at affecting consumer practices in water usage, delivering greater efficiency detecting leaks and reducing water waste. Developments are needed in the fields of:

- Smart metering, time-of-use pricing and gamification to control consumption and appliances, along with interoperable solutions for a truly connected smart household (taps, lavatories, showers, appliances).
- Low-cost sensors for flow control, leak detection and auto shut-off, along with inexpensive actuators to remotely control valves for limiting water usage by volume/time. IoT systems can optimise the control of household, agricultural and industrial infrastructure/equipment in water-intensive processes.
- Smart systems able to automate leak localisation, and to respond promptly and cost-effectively. This can be a combination of in-pipe inspection (to locate the leak) and a network of low-cost, fine-grained sensors to allow predictive maintenance of distribution systems.

1.2 1.3 2.1

Efficient and intelligent water distribution

The main challenge for improving the use of water is to guide its distribution depending on its final application (drinking water, water for industry, etc.). However, the existing sanitary regulations always look to optimise water safety regardless of its final use. To apply the most effective measures to make water distribution more efficient, it is necessary to thoroughly review the different supply protocols and quality criteria for each sector. Moreover, by continuously monitoring the quality and availability of water, it would be possible to better regulate its distribution depending on the final use and to adjust the price accordingly. Intelligent systems connected to smart grids will allow water inputs to be made in the network at the right times, optimising the energy cost as a result.

174 Leakage Reduction in European Water Mains; Layman Report https://ec.europa.eu/environment/eco-innovation/projects/sites/eco-innovation-projects/files/projects/ documents/-curapipe_layman_report.pdf

To address these challenges, there is a need for developing:

- Novel smart metering solutions based on various technologies, including electrochemical multi-parameter sensors (pH, chlorine, conductivity, etc.) with high stability, anti-fouling, high accuracy capabilities and cost-effectiveness, as well as optical sensors based on different principles (fluorescence, absorbance, etc.) integrated into miniaturised systems at a low cost.
- IoT systems with the adequate data analysis processing power and AI capabilities to handle the large volume of data generated by the different water management processes to satisfy quality, usage type and associated pricing.
- Efficient year-round water management in terms of storage to deal with some of the most urgent shortages, with better forecasting and warning systems based on extensive measurements – e.g., intentionally flooded areas could be used to store water in times of expected scarcity.

1.2 1.4 2.1

3.5.4.4.3 Resources management

Smart systems for irrigation management

At a global level, agriculture consumes 69% of the world's freshwater[175]. Because of this, precise control of irrigation is essential to guarantee water and food security for all. Irrigation water management is the practice of monitoring and managing the rate, volume and timing of water applications according to seasonal crop needs, considering the soil intake and water holding capacities with the objective of using water in the most profitable way at sustainable production levels. To this end:

- Smart sensors are increasingly required as tools to implement irrigation management and monitor water levels. Sensors should be more intelligent to support real-time applications and/or reduce latency, optimise power consumption of the overall system, and facilitate local (at the edge) cost-effective solutions for both outdoor and indoor use.
- Integration of systems monitoring water deficiency or surplus is also required. These could be based on narrow-band spectral reflectance of water and land surfaces for vegetation/habitat mapping, along with UAV utilisation in remote areas.

1.4 2.1

Smart systems for flood management

Flood management has been gradually integrating smart sensors. IoT systems with water-level sensors can also play a significant role, not only in real-time monitoring but also in predictive/forecasting capacity models in occurring natural hazards. This requires:

- The monitoring of water levels and devising prediction models to identify areas at a high risk of flooding. This is possible through the development and deployment of more intelligent sensors in combination with smart predictive algorithms to integrate information from other sources, such as weather forecasts and regional georeferenced data.
- Key is IoT interoperable systems to provide real-time information to first responders, civilians and companies to proactively take countermeasures.

1.4 2.1

Smart water treatments fostering circular use (wastewater, rainwater, storm water)

Around 80% of all wastewater is currently being discharged into the world's waterways, where it creates health, environmental and climate-related problems. Water from industrial, agriculture and domestic use contains organics, phosphates, nitrogen, cellulose, rare earth elements and other substances. In addition to its domestic use, purifying, distilling or deionising water is essential for many agricultural and industrial uses – both to ensure the consistency of products and to meet strict safety regulations. The global market for water and wastewater technologies reached US $64.4 billion in 2018 and is expected to rise to US $83

175 http://www.fao.org/nr/water/aquastat/water_use/

billion by 2023[176]. Technologies that allow resource recovery from wastewater to be commercially feasible are increasingly being developed, making transitioning to a circular economy an opportunity to accelerate and scale-up the most recent scientific and technological advances that support greater efficiency in the water sector. There is an increasing requirement for:

- A range of sensors in water systems to monitor water levels, the flow of water through different channels, temperature changes, chemical leakage, pressure level, chemical residues, etc.
- IoT-enabled water purifiers that can predict potential system failures to reduce downtime in public water systems, and to enable remote sensing for mapping groundwater resources and monitoring sustainable extraction levels.

1.2 1.3 1.4

3.5.4.5 Major Challenge 5: biodiversity restoration for ecosystems resilience, conservation and preservation

3.5.4.5.1 Status, vision and expected outcome

It has been stated that: "Biodiversity boosts ecosystem productivity where each species, no matter how small, all have an important role to play"[177]. For example, increasing the number of plant species means a greater variety of crops, as greater species diversity ensures natural sustainability for all life forms. Healthy ecosystems can better withstand and recover from a variety of disasters, anthropogenic or not. A healthy biodiversity offers many natural services for everyone.

It should be noted that there are many such services that we already get for free! However, the cost of replacing these, even if possible, would be extremely expensive. It therefore makes economic and development sense to move towards sustainability. From this perspective, ECS will contribute to addressing some of the key challenges relating to biodiversity and sustainability for the four ecosystems described below.

3.5.4.5.2 **Biodiversity restoration** for the **agriculture ecosystem**

Agriculture is one of the economic activities that has the highest dependence on nature and biodiversity[178]. On average, global mean crop yields of rice, maize and wheat are projected to decrease between 3% and 10% per Celsius degree of warming above historical levels. All crops depend directly on soil health and fertility, and more than 75% of global food crop types rely on animal pollination. However, the impact of agriculture activity on the environment must be as low as possible to preserve biodiversity.

In this regard, the EU Biodiversity Strategy 2030 establishes several objectives[179], summarized in sub-section 3.5.5 Timeline. To address these objectives, there is a need to develop:

- Precision farming systems for optimal use of fertilisers and pesticides.
- Sensing and monitoring systems for soil nutrients measurement, connected insect traps and landscape monitoring.

1.4 2.1

176 https://www.bccresearch.com/market-research/environment/water-and-wastewater-treatment-technologies-global-markets.html

177 Anup Shah « Why is biodiversity important? Who cares? https://www.globalissues.org/article/170/why-is-biodiversity-important-who-cares

178 European Commission. The business case for biodiversity. May 2020. https://ec.europa.eu/commission/presscorner/detail/en/fs_20_907

179 European Commission. EU Biodiversity Strategy for 2030: bringing nature back into our lives. May 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX%3A52020DC0380

3.5.4.5.3 Biodiversity restoration for the aquaculture ecosystem

Aquaculture impacts biodiversity negatively in several ways[180]: (i) antibiotics and hormones are used to reduce farm stock mortality and improve growth rates, but their use has side effects for the flora and fauna of water bodies receiving farm effluents; (ii) through eutrophication and changes in flora and fauna in waters receiving effluents from aquaculture facilities; (iii) risk of excessive exploitation of wild fish stocks for use in farm fish feeds; and (iv) transfer of disease and parasites from farm animals to wild animals.

To address these side effects, there is a need to develop:

- Precision aquaculture systems for optimal feeding (minimizing waste and feed residuals), optimal use of antibiotics/hormones, and optimal use of freshwater.
- Smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents.
- Smart systems combining data collected from different sources (IoT, satellite, and drones) and data analysis based on AI/ML techniques to create predictive models leading to more confident decision-making, timely alerts, and automated systems in general.

1.4 2.1

3.5.4.5.4 Biodiversity restoration for the fisheries ecosystem

The EU's Biodiversity Strategy has set an objective of protecting a minimum of 30% of its sea area. Similar to agriculture, fishing is an economic activity with a strong dependence on biodiversity. Keeping fish stocks healthy is critical to guaranteeing ocean biodiversity and thus the economic sustainability of fisheries. According to recent studies, the preservation of marine stocks could increase the annual profits of the European seafood industry by more than €49 billion.

Fishing activities impact biodiversity negatively in several ways, particularly by: (i) increasing fish mortality, so measures must be taken to keep this under maximum sustainable yield levels; and (ii) damaging the ocean ecosystem due to the use of certain fishing techniques, currently the most damaging activity to the seabed. In addition, the effect of by-catching from non-selective industrial fishing methods endangers many species of marine animals not being fished for. It is therefore necessary to evolve towards more selective and less damaging fishing techniques, as well as the more effective control of illegal fishing practices.

To reduce these negative impacts, there is a need to develop:

- Oceanographic sensing and monitoring solutions (including unmanned vehicles, UXVs) for fisheries ecosystem to estimate biodiversity indices, fish stocks and species distribution, and to build fishery management systems consistent with conservation objectives and rules.
- Technologies to make fishing gear more selective and environment respectful.
- Technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc.).

3.5.4.5.5 Biodiversity restoration for the forestry ecosystem

The EU Biodiversity Strategy has set the objective of protecting a minimum of 30% of the EU's land area. At least one-third of protected areas – representing 10% of EU land – should be strictly protected. In particular, the strategy identifies the crucial need to strictly protect all the EU's primary and old-growth forests (see *Figure F.74*), which are the richest forest ecosystems removing carbon from the atmosphere, while storing significant carbon stocks [167]. The strategy also calls for preserving the good health and increasing the resilience of all EU forests, especially against wildfires, droughts, pests and diseases. It is envisaged that the European

180 Claude E. Boyd, What is biodiversity and its relevance to aquaculture certification? https://www.aquaculturealliance.org/advocate/biodiversity-relevance-aquaculture-certification/

Commission will develop a forest information system for Europe that integrates data from multiple sources and providers. To prevent more wildfires, grow rural economies in a sustainable way and manage climate change, a much better understanding and continuous assessment of EU forests is necessary. To this end, there is a need to develop:

- A precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests as well as early detection and prevention of threats to the forests (wildfires, pests, diseases, etc.).
- Smart systems for environment monitoring of forests and fields as well as CO_2 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and provide timely warning upon illegal poaching activity.

1.3 1.4 2.1

3.5.5 TIMELINE

MAJOR CHALLENGE	TOPIC	SHORT -TERM 2022 - 2026
Major Challenge 1: food security	**Topic 1.1:** intelligent and adaptative food production	• Advanced analytical processing based on several data sources. • IoT devices with integrated firmware for implementing big data solutions
	Topic 1.2: redesigning farming systems	• A farm management information system (FMIS) thoroughly integrated with IoT and automated systems; all the data should be gathered automatically and digitalised
Major Challenge 2: food safety	**Topic 2.1:** crop quality and health	• IoT for monitoring the key parameters related to plant health. • DSS for recommendation/decisions related to agrochemical application; health and environmental care
	Topic 2.2: livestock welfare and health	• Advanced indicators of welfare, health and performance monitoring (integration of milking robot, wearable sensors data, etc.) at the individual and herd scale
	Topic 2.3: food chain	• IoT devices monitoring food transport from production to the retailer; end-consumers to have full access to this information; AI (ML/deep learning) models based on the recommendations and decisions that the IoT devices could take to monitor the whole supply chain • Global accessibility for end-consumers to the traceability of the whole value chain – i.e. total transparency
Major Challenge 3: environmental protection and sustainable production	**Topic 3.1**: soil health	• Autonomous recommendations done by the IoT devices directly related to fertilisation and phytosanitary application.
	Topic 3.2: healthy air and skies	• CO_2 capture materials in use
	Topic 3.3: smart waste management	• Forecasting models of potential waste that will be produced by the farm management system
	Topic 3.4: remediation	• Network of sensors for target pollutant with antifouling properties for use in real environments • Development of capture materials for targeted pollutants, including CO_2 capture materials

MEDIUM-TERM 2027-2031	LONG-TERM 2032-2037
• AI applied to food production to define advanced analytical processing related to prescriptive and predictive analysis	• AI applied to food production, not only in pre-harvest areas but also post-harvest – i.e. applied to the whole value chain integrally
• Telecontrol of agronomic systems (irrigation systems, climate control systems, etc.) based on expertise and farmers' decision-support systems (DSS)	• Automation of labour; resource optimisation (environmental care and social impact)
• AI for automatic decisions and action; ML and deep learning related to agronomic models and algorithms	• Robots with AI for managing plant health automatically
• Reduce by 50% the sale of antimicrobials for farmed animals by 2030	• Fully automated herd performance control (growth and milk production, forage efficiency, early disease detection for antibiotics use reduction), and applications for genetic selection to optimise breeding performance and resilience
• Interoperability among all the systems that manage the whole value chain • Normalisation and homogenisation of communication protocols • IoT devices integrated in the food chain where the end-consumers will be able to read them by mobile phone and directly access for complete traceability	• IoT devices making recommendations automatically and take autonomous decisions related to food safety, acting directly with the transport mechanism (cooling mechanism and others that impact food safety) • Systems automatically and autonomously act in all the machinery located at each step of the supply chain
• Combination of several data sources to define key performance indicators (KPIs) related to environmental protection and sustainable production	• Autonomous actions performed by IoT devices directly in the telecontrol systems related to fertilisation and phytosanitary applications
• CO_2 capture and conversion on site	• Low or no carbon fuel sources
• Registration of the traceability related to residues management, including the residue management in food traceability and the environmental footprint	• AI and digital twin models providing recommendations for decision-making related to minimising farms waste
• Coupled sensor and CO_2 capture/conversion system for CO_2 remediation • Solar/thermoelectric in situ driven pollutant removal	• Real-time multiparameter sensing with AI and digital twin decision-support for management • Efficient and low-cost general pollutant removal and conversion systems using energy harvesting towards in situ remediation

MAJOR CHALLENGE	TOPIC	SHORT -TERM 2022 - 2026
Major Challenge 4: water resource management	**Topic 4.1:** access to clean water (urban and rural)	• ICT solutions allowing greater societal involvement in water management through online knowledge of its consumption data (remote meter reading), and quality parameter monitoring for greater awareness about the optimisation of the freshwater as a limited resource • Water quality monitoring systems based on hybrid technology (mono-parameter bulky probes and some miniature chips) • Sensors for basic parameters such as chlorine, conductivity and pH are available for real-time monitoring; more complex parameters require lab analysis • Cost and integration are still challenging for massive deployment in water distribution networks based on current IoT system applications • Limited amount of data (systems are installed only at critical locations) • Centralised control and data analysis based on AI on the cloud
	Topic 4.2: resource management	• Requirements identification and classification for biodiversity protection in the exploitation of aquifers for human supply • Monitoring systems for the water lifecycle, including supply and sanitation through the development of digital tools allowing the intensification circular economy • Progressive transformation of wastewater into raw materials for the generation of products and services
Major Challenge 5: biodiversity restoration for ecosystems resilience, conservation and preservation	**Topic 5.1:** biodiversity restoration for agriculture ecosystem	• Sensing and monitoring systems for soil nutrients measurement, connected Insect traps and landscape monitoring
	Topic 5.2: biodiversity restoration for aquaculture ecosystem	• Smart multi-sensors and smart systems for monitoring water quality in aquaculture facilities and their effluents

MEDIUM-TERM 2027-2031	LONG-TERM 2032-2037
• Smart monitoring systems at home to optimise household water spending and tools to improve performances through KPIs that allow for measuring progress at the microscale; water users must move from passive consumers to active management • New generation of more integrated and miniaturised multiparameter autonomous sensors (e.g. pH, chlorine, and conductivity parameters) • More complex sensors are available for the real-time detection of pollutants in water, such as heavy metals and nitrates • Edge computing and multiparameter devices allowing decentralised data analysis and control • Massive deployment starts being cost-effective with more accurate solutions due to the availability of an increased amount of data	• Use of different water qualities for different usages (at home, industry, etc.) through secure monitoring systems, always guaranteeing the water quality (especially freshwater) • Advanced multiparameter sensors supporting new capabilities, such as stability, antifouling, accuracy, etc. • Real-time microbial- detection and removal are feasible • Large-scale deployment of multiparameter devices allowing advanced data analysis in water distribution networks for more intelligent water management • Freshwater quality prediction based on digital twin technology capabilities considering real-time environmental conditions
• Improvement of knowledge through the accumulation of consolidated and valid data series, on the natural environment through the implementation of monitoring systems, for both the water and natural environment (fauna, ecology, sociological aspects, uses, etc.), as a basis for sustainable management through AI/ML tools, allowing for identification of the correlation between the evolution of the environment quality and water use • Design of environmental evolution models in different use scenarios • Industrial transformation of wastewater treatment plants in bio-factories	• High-performance monitoring systems to identify and quantify the presence of emerging pollutants and high-risk chemical species derived from human action • Integrated vision for all aspects related to water in systemic and non-cyclical areas; process reengineering and redesign of monitoring, control and exploitation systems based on advanced tools for decision-making through the generation of models • Paradigm shift in the vision of water as a cycle to a system that must be optimised
• Precision farming systems for optimal use of fertilisers and pesticides • Reduction by 50% of the use and risk of chemical and more hazardous pesticides by 2030 • Reduction of nutrient losses by at least 50% while ensuring no deterioration to soil fertility • Reduction in fertiliser use by at least 20% by 2030 • Reduction by 50% in the sales of antimicrobials for farmed animals and in aquaculture by 2030 • Boosting the development of EU organic farming areas with the aim of achieving a 25% increase in total farmland under organic farming by 2030	• Reduction of European cumulated carbon and cropland footprint by 20% over the next 20 years, while improving climatic resilience of European agricultural and stopping biodiversity erosion
• Smart systems combining data collected from different sources (IoT, satellite and drones) and data analysis based on AI/ML techniques and digital twin to create predictive models leading to more confident decision-making, timely alerts and automated systems in general	• Precision aquaculture systems for optimal feeding (minimising waste and feed residuals), optimal use of antibiotics/hormones and optimal use of freshwater

MAJOR CHALLENGE	TOPIC	SHORT -TERM 2022 - 2026
	Topic 5.3: biodiversity restoration for fisheries ecosystem	• Technologies for checking compliance and detecting illegal activities (onboard cameras, RFID, traceability technologies, vessel monitoring, etc.)
	Topic 5.4: biodiversity restoration for forestry ecosystem	• Precision forestry system with remote sensing and AI/ML monitoring capabilities to map and assess the condition of the EU forests, as well as early detection and prevention of threats to forests (wildfires, pests, diseases, etc.)

MEDIUM-TERM 2027-2031	LONG-TERM 2032-2037
• Oceanographic sensing and monitoring solutions (including UXVs) for fisheries ecosystem to estimate biodiversity indices, fish stocks and species distribution	• Technologies to make fishing gear more selective and environmentally respectful
• Smart systems for environmental monitoring of forests and fields, as well as CO_2 footprint monitoring, remote monitoring of wildlife behaviour and habitat changes, and provision of timely warnings about illegal poaching activity	• Preserve the protected and restored forestry areas, as well as continuing to restore the remaining degraded forests

3.5.6 SYNERGY WITH OTHER THEMES

The IoT system technologies and related activities prioritised in this Chapter are key to addressing the specific challenges of food, agriculture and natural resources. The Major Challenges of food safety and security, environmental protection and sustainable production, water resource management and biodiversity restoration are in alignment with the European missions on "adaptation to climate change including societal transformation", "healthy oceans, seas, coastal and inland waters", "climate-neutral and smart cities" and "soil health and food". The application needs under those missions can be addressed through the integration of IoT systems into innovative technological solutions, as well as holistic approaches in processes covering the whole supply chain, from resource utilisation and production to food packaging, waste management and remediation. As such, there are potential synergies with the Health, Energy, Mobility and Digital Industry application chapters.

3.1 3.2 3.3 3.4

On the technology side, the envisaged IoT system solutions will require significant advances in terms of functionality. Synergetic topics include advanced multi-sensing and data fusion capabilities, energy autonomy (harvesting, storage, and power management), connectivity, interoperability at all levels, lifecycle properties, reliability, privacy and security. There are also great challenges to make these heterogeneous systems manufacturable at the right cost for market entry while simultaneously achieving miniaturisation, ultra-low-power consumption, adequate packaging considering the environmental conditions and other constraints. To this end, significant collaborative effort will be required in materials integration and process technologies, architecture and embedded software for individual components, devices, systems and systems-of-systems. New designs at different abstraction levels (component, devices, network) and computing (edge, cloud) paradigms, new and interoperable models (e.g., AI/ML/DL and digital twin), design flows and methodologies and their associated tools are also needed. This is required to cross boundaries between domains, e.g., for verification and automated design space exploration, or data analytics and decision-making through AI/ML/DL and digital twin based solutions. Overall, an orchestrated synergetic approach in the areas of advanced materials, circular industries, manufacturing technologies, ICT, AI, digital twin, edge and cloud computing, robotics, electronics and photonics, as well as other key technologies such as new advanced HIM like virtual, augmented and mixed reality, will facilitate technology- push/demand-pull advances in the activity fields of IoT systems for agriculture and natural resources.

3.6

ECS Key Application Areas

DIGITAL SOCIETY

3.6.1 SCOPE

Supporting the digital transformation throughout society

This Chapter describes the type of digital innovations that are essential to stimulate an inclusive and healthy society, and which will in turn contribute to solutions for European challenges in the fields of health, mobility, security, energy and the climate, and consequently to European economic prosperity.

Europe needs digital solutions that support the individual, and at the collective level to empower society as a whole. These (smart) digital solutions will be driven by new technologies such as 5G, Artificial Intelligence (AI) with deep learning (DL), virtual reality (VR) and augmented reality (AR), brain–computer interfaces (BCIs) and robotics. They will shape new ways of how people use and interact with these technological solutions, with each other, and with society and the environment. Digital innovations should facilitate individual self-fulfilment, empowerment and resilience, collective "inclusion" and safety, as well as supportive infrastructure and environment.

However, such a transformation will also introduce a wide range of ethical considerations. Future digital innovations will therefore need to address societal concerns in a sustainable way, guaranteeing participation and reducing inequality. A human-centred approach is therefore a key aspect of the EU's approach to technology development. It is part of European social and ethical values, (social) inclusiveness, and the creation of sustainable, high-quality jobs through social innovation.

3.6.2 APPLICATION TRENDS AND SOCIETAL BENEFITS

3.6.2.1 External requirements

To guarantee economic and societal growth in Europe, digital inclusion requires tools and infrastructures in application domain roadmaps as described in the other Chapters. Technology permeates every aspect of society, and is an important instrument of change (as can be seen in *Figure F.76*, where two distinct rows are shown: current status and future expansion).

People's expectations of the future impact of technology are broadly positive, but also involve specific concerns around employment, income, safety, equality and trust. By 2035 the impact of science and technological innovation will be enormous on prosperity, individual wellbeing, sustainability, fairness and trust (see *Figure F.77*). This underlines the importance of investing in our digital strategy today.

In striving to guarantee European sovereignty to support European digital societal goals (for instance, through the GAIA-X140 project), safety, equality and trust are key requirements. What does this mean for electronic components and systems (ECS) for our society? Ubiquitous connectivity ("everywhere and always on"), online services and social media ("always online") drive people to rely on intelligent applications and the services

they offer. Public and private infrastructures will increasingly be connected, monitored and controlled via digital infrastructures ("always measuring").

Two important further drivers for European society and economy – from a human-centred approach on AI perspective – are lifelong learning and training, as well as being able to work anywhere, anyplace. The trend to work from home whenever possible, which has been triggered by the Covid-19 pandemic, will continue, and people will endeavor to combine work and private life in a better way. In rural areas, as well as in cities, it should be easy to work either from home or remotely in distributed groups/workforces. This can be achieved through living labs and learning factories at both a personal and collective level.

F.76 *Technology permeates every aspect of society (Source: Why digital strategies fail, McKinsey & Company, March 2018; GSMA 2019; Domo; IDC; McKinsey Global Institute analysis)*

3.6.2.2 Societal benefits

All of European society will benefit from a major (AI-based) evolution in intelligent systems, on both the individual and collective levels:

- The benefit of digital inclusion for all individuals will involve employability through lifelong learning and training, and the personal wellbeing of individuals. To achieve these, the key ambition is to maximise the individual development of citizens.
  - How? By ensuring personal resilience, enabling lifelong learning and development, and stimulating employability. Human-centred solutions will optimise services to each individual's needs and level of understanding, for applications in areas such as healthcare, lifestyle,

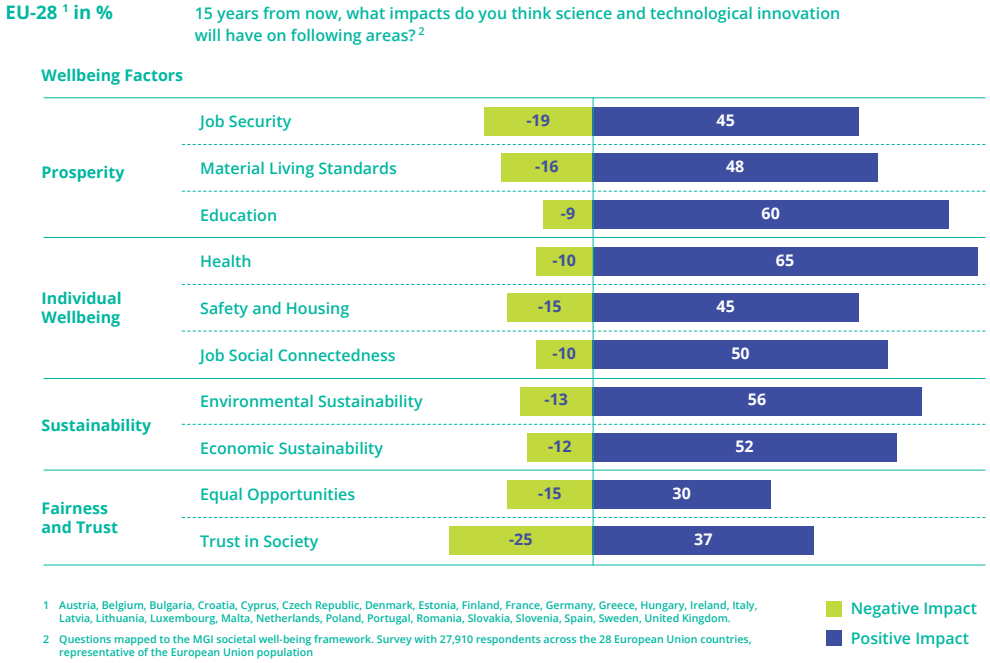
coaching, training, and working from home or remotely collaborating in a "distributed" workforce. This will boost employee productivity, improve their work/life balance and foster better mental health, and reduce pollution from commuters.

- The overall individual benefit is "wellbeing". A factor such as "prosperity" means job security, material living standards and the right to have the optimum education, any time, any place. On an individual level, wellbeing means health for everyone of every age, and also adequate housing, ensured safety, protected privacy, reliable and ubiquitous digital infrastructures, in addition to social connectedness and more intense social cohesion. Our key objective is to empower and protect the individual.
  - How? By ensuring acceptable and trustable AI technologies to increase inclusion and prevent exclusion, protecting citizens against identity theft, and providing a protective environment against new virus infections; in addition, through lifestyle monitoring and coaching, to enable and support healthier lifestyles.

3.4

2.4

PEOPLE'S EXPECTATIONS OF THE FUTURE IMPACT OF TECHNOLOGY ARE BROADLY POSITIVE, BUT WITH PARTICULAR CONCERNS AROUND JOBS, WAGES, SAFETY, EQUALITY AND TRUST.



People's expectation of the future impact of technology (Source: Special Eurobarometer 419, Public perceptions of science, research and innovation, 2014; McKinsey Global Institute analysis)

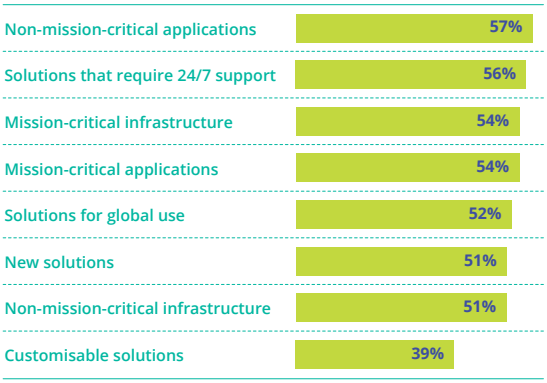
F.77

- The benefits of digital inclusion, a society resilient against setbacks, and the societal acceptance of novel technologies will achieve the key ambition of safeguarding collective society and wellbeing for all.
  - How? By societal and digital inclusion, providing societal access for all, and ensuring collective resilience against setbacks. Also, the elderly will be supported to continue their social participation, which will reduce feelings of loneliness, improve their wellbeing and health, but provide reassurance that their precious experience can still be used.

- On an environmental level, the benefits are a physical and digital sustainable environment, intelligent Infrastructure management, stability and resilience against threats, and agreement on fall-back solutions in times of crises. The main aim is to contribute to a supportive infrastructure and environment.
  - How? By providing reliable and resilient infrastructures, protecting society against destabilising forces, establishing a sustainable environment, and securing controlled climate change. Monitoring and intelligent control of infrastructures will also contribute to a sustainable environment by solutions that address, for example, optimal use of natural resources, reduction of pollution and crisis management.

EXPECTED USES OF CLOUD COMPUTING IN THREE YEARS

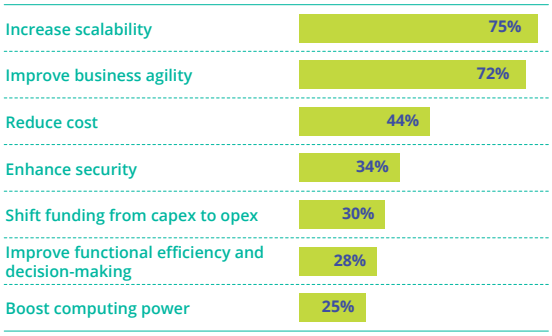
Which of the following areas do you foresee shifting to a cloud-based flexible consumption model in the next three years?



(FIGURE A)

PRIMARY CLOUD DRIVERS

What are the primary reasons for using cloud technology? (select all that apply)



(FIGURE B)

F.78 *Expected uses of cloud computing and their primary drivers (Source: Deloitte 2018 Global CIO Survey)*[181]

"Sustainability" means environmental as well as economic sustainability, and equal opportunities for all people. It is related to fairness and trust in our societies. It must be ensured that AI-based systems will take European-style human values into account by design. A human-centred approach will therefore be a key requirement. As such, "FAIRness" (findability, accessibility, interoperability and re-use) will help shape future applications.

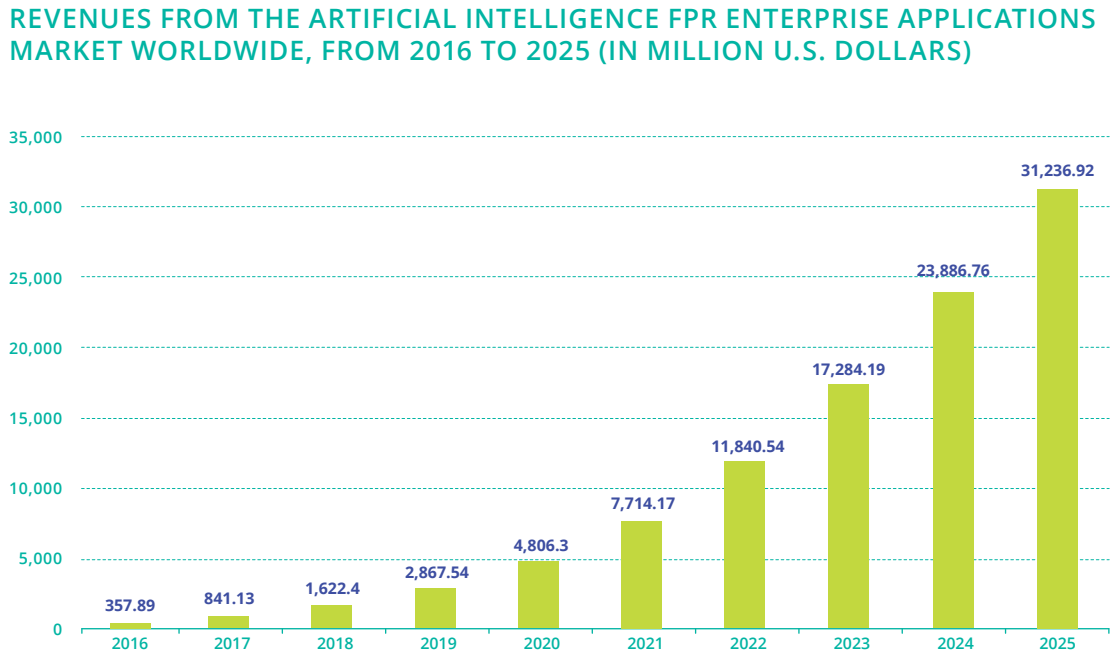
181 *https://deloitte.wsj.com/cio/2018/11/11/ the-state-of-cloud-adoption/*

3.6.3
STRATEGIC ADVANTAGE FOR THE EU

Overall, a strategic advantage for the EU lies in digital solutions and people with high-developed digital skills that can contribute more efficient solutions for European challenges in the fields of health, mobility, security, energy and the climate. A digital "healthy" society will contribute to European economic prosperity. Digital tools, infrastructures, applications and digital skills will offer the following:

- Ensure companies that their labour force will work efficiently, whether they work at the head office or from their homes (i.e. to prevent virus spread, or for other reasons). An advantage here is the widespread empowerment of citizens to work from different locations, taking into account that some jobs will need to be undertaken in the office or factory, but that knowledge workers with computer-based jobs can work remotely.
- Provide people with greater employability and better protection against social or economic exclusion (the possibility of ubiquitous connectivity).
- Support citizens instead of replacing them with robots, as EU technical solutions will be based on human centred AI systems that have a focus on human values. AI solutions applied should be trustworthy (responsible, transparent and explainable).
- Help European governments, companies and citizens to cooperate more easily, and develop reliable societal emergency infrastructures. This will make European societies better prepared to deal with emergency and crisis situations.

Widespread empowerment to work from different locations will require optimal use of (but also drive) the growth of interconnection bandwidth (see *Figure F.78* A). Remote working will also require further use of cloud applications (see *Figure F.78* B), using AI software as a service (SaaS) to automate processes and support employees in decision- making, resulting in the growth of AI (as shown in *Figure F.79*).



F.79 *Enterprise AI market revenue growth worldwide (2016–25)*[182]

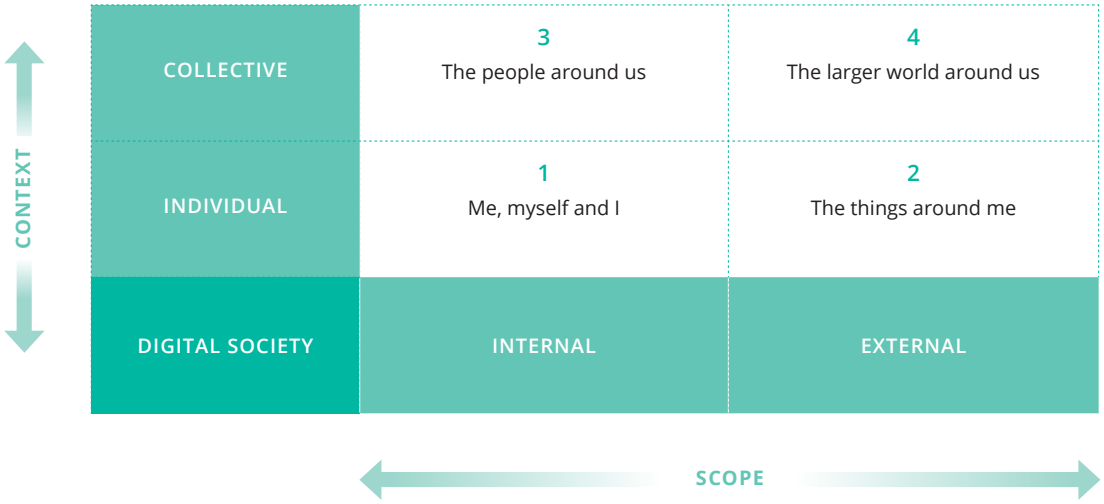
3.6.4 MAJOR CHALLENGES

Enabling and ensuring a digital society implies various aspects will be facilitated by ECS products and services. To structure these aspects, we distinguish between the individual or collective context and the internal or external scope. This leads to the matrix shown in *Figure F.80*.

Each of these four areas relates to one of the following Major Challenges:

- **Major Challenge 1**: facilitate individual self-fulfilment.
- **Major Challenge 2**: facilitate empowerment and resilience.
- **Major Challenge 3**: facilitate inclusion and collective safety.
- **Major Challenge 4**: facilitate supportive infrastructures and sustainable environments.

182 *https://www.forbes.com/sites/ louiscolumbus/2018/01/12/10-charts-that- will-change-your-perspective-on-artificial- intelligences-growth/#31791eef4758*



Structuring the Major Challenges in scope and context

F.80

3.6.4.1 Major Challenge 1: facilitate individual self-fulfillment

3.6.4.1.1 Status, vision and expected outcome

Ambition: to maximise the individual development of citizens.

- Provide empowerment to citizens.
- Ensure personal resilience.
- Enable lifelong learning for both children and adults (serious gaming, including AR/VR).
- Give citizen more freedom to do their work wherever they want/need.
- Stimulate employability.
- Wellbeing (e.g. by gamification[183], connection to others, leisure).
- Improved human–machine interaction solutions for perception, reasoning and autonomy, with interaction being adaptive to the user's abilities.

To maximise the empowerment and self-fulfilment of citizens, Europe has to strive for lifelong learning, employability and the freedom to work wherever one resides, as well as optimal wellbeing in the context of an independent and pluralistic media. These enable lifelong empowerment by keeping citizens informed and facilitate the flow of educational content. Educating through the media is an important means to develop valuable skills that will help to end violence and eradicate forms of discrimination (such as sexism and racism). More fundamentally, the media encourages the acquisition of civic knowledge and facilitates discussion concerning current issues[184], while at the same time entering new frontiers of engagement using on-demand and interactive paradigms, and in employing AR/ VR technologies backed by 5G/6G connectivity.

183 Gamification: The application of game design elements and principles in a non- game context.

184 http://www.unesco.org/new/en/ unesco/events/prizes-and-celebrations/ celebrations/international-days/world- press-freedom-day/previous-celebrations/ worldpressfreedomday200900/themes/ empowering-citizenship-media-dialogue- and-education/

The 30-year career has become a thing of the past. Education does not end after school; individuals need to keep on learning throughout their careers to stay up to date and adapt their skills as the world changes at an unprecedented rate. To better support lifelong learning, technologies are needed that encourage collaboration, foster autonomy and responsibility, and implement learning initiatives. Technological advancements such as cloud computing, mobile devices and web 2.0 technologies are still relatively new additions to the workplace that must be further explored[185].

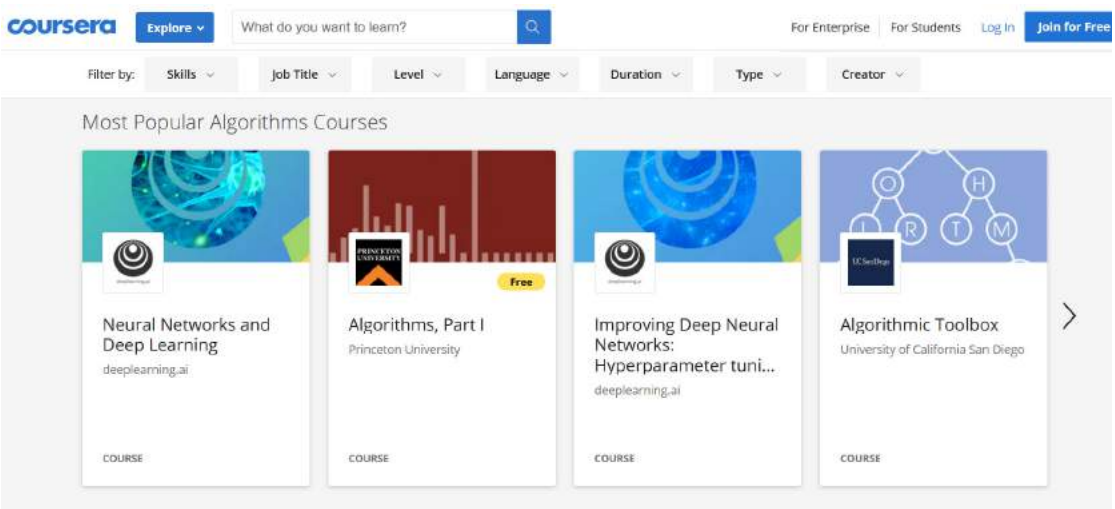
To provide the citizen with more freedom to do their work wherever they want or need, Europe must ensure the availability of high bandwidth secure connections (wired and wireless) at all possible locations one could use to work from. This should be reinforced by easy and secure access to cloud applications, and novel AI-based solutions to automate processes, analyse data, guide the user in decision-making, and to minimise repetitive work.

2.2

Advanced technologies, including smart automation and AI, have the potential to not only raise productivity and GDP growth, but also to improve wellbeing more broadly, as well as offer a healthier life and longevity, and greater leisure time. Studies have shown that, besides income, the following factors contribute to individuals' wellbeing and self-reported life satisfaction: social life, use of leisure, health, spouse/partner, job, flat/house and the amount of leisure[186]. New technologies in the digital society can, and will, influence all these factors.

2.1

An example of the relevant tools is shown in *Figure F.81* for Coursera, which utilizes of gamification to offer the lifelong free and open learning of languages and brings massive open online course (MOOC) platforms to the public.



F.81 *Coursera (Source: Coursera, Inc)*

185 https://www.trainingjournal.com/articles/ opinion/how-promote-lifelong-learning- using-technology

186 https://www.mckinsey.com/featured-insights/future-of-work/tech-for-good-using-technology-to-smooth-disruption-and-improve-well-being

3.6.4.1.2 Key focus areas

High-priority research and development and innovation (R&D&I) areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Online education and examination: VR/AR training and support.
- Improved human–machine interaction (HCI) solutions.
- Support devices: wearables, robots, cobots, chatbots, etc.
- Nudging and serious gaming: for personal development and healthier lifestyles.

To improve the awareness of our body's condition to external or internal stimuli, smart systems can provide support for disabilities, or a personal coach and trainer to identify behaviour to be avoided (wrong body position, bad habits), as well as possible future injuries or disorders. Smart systems can also offer an immersive experience through vision, gaming and sensory interaction by way of VR or AR. Consumers can be offered the immediacy, individualisation, interactivity and immersion they expect from media content consumption ("even better than being there").

2.4

A healthier and more comfortable environment can be offered based on personal preferences (control of temperature, humidity, air flux, etc), in the context of running activities and clothing, and by adapting lighting and acoustic quality to one's own sense of wellbeing. It also provides the capability to comfortably communicate and interact remotely with people, institutions and sellers, possibly without leaving home, saving time for self- development and leisure.

Selective automation, AR at work and a range of feedback tools can help boost satisfaction and give more meaning to work. This is a particularly important element for the millennial generation, which according to surveys tends to place more emphasis on work satisfaction than on income (above a certain income level). Due to the Covid-19 pandemic, large events are becoming more difficult to organise, and many people may prefer to take part in events while not physically being present. Technological advances will make it possible to place audiences in the middle of the action and to offer them immediacy, individualisation, interaction and immersion without it being necessary for them to actually be there in person. This will further change consumption patterns and open up new business opportunities.

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major Challenge 1: Facilitate individual self-fulfilment	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING	COMPONENTS, MODULES AND SYSTEMS INTEGRATION	EMBEDDED SOFTWARE AND BEYOND	SYSTEM OF SYSTEMS	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL	CONNECTIVITY	ARCHITECTURE AND DESIGN: METHODS AND TOOLS	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Reliable, dependable and secure SW and HW	X		X					X
Mature human–systems interaction methods				X			X	X
Trustable AI/ML algorithms					X			X
Energy-efficient HW and SW solutions (e.g. for IoT devices, wearables)	X		X		X			
Seamlessly operating SW (e.g. for IoT devices, wearables)		X	X	X		X		
Ubiquitous, reliable and energy-efficient connectivity	X	X	X			X	X	X

F.82 *Required R&D&I developments within ECS –Major Challenge 1*

Required R&D&I developments within ECS

Taking the above into account, specific R&D developments are necessary within ECS technology, as shown in *Figure F.82*.

3.6.4.2 Major Challenge 2: facilitate empowerment and resilience

3.6.4.2.1 Status, vision and expected outcome

Ambition: empower and protect the individual citizen.

- Increase inclusion and prevent exclusion.
- Protect citizens against cyber-fraud (scams) and identity thefts; provide privacy.
- Enable smart homes with ubiquitous connectivity.
- Ensure acceptable AI technologies.

Diversity and inclusion within societies are increasingly recognised as crucial for equality at work and economic development. Research has established a strong link between gender equality in society, attitudes and beliefs about the role of women, and gender equality in work[187]. Technology can improve equality at work – for instance, by revealing pay gaps and biases, and helping de-bias recruitment. It can also improve equal access to essential services – for example, biometrics and cloud technology can contribute to increasing the diffusion of microfinance to women and underserved populations. Technology can also help enforce inclusive legal rights, policies and social norms. While e-voting still poses a number of cybersecurity challenges, it can support diversity by facilitating the vote for vulnerable and marginalised parts of society. Finally, technology can help with physical security and autonomy for minority groups through objects and digital communications tools that reduce or mitigate exposure to risk – for example, connected devices such as smart bracelets can enable women to signal an assault and call for help.

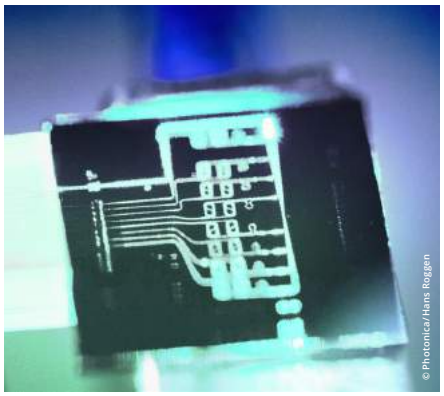
Reliance on technology comes with many benefits, but also brings new risks[188]. The radical nature of the ongoing technology transition could result in risks that are not just an extension of the previous challenges, but require fundamental changes to core aspects of our society, including how we think about our identity, security and rights. Concerns about technology are justified by recent events, such as security breaches in prominent companies, data theft and information misuse. In addition, AI provides more powerful examples of potential risks. Its full potential can be utilised only if we fully rely on it for decision-making, allowing it to process data beyond the human ability to cross-check and verify. This depends a high level of trust, raising questions about and requiring new technical solutions that take into account explainability, accountability, trustworthiness and ethics.

In 2020, we have experienced the necessity of a connected smart home and an adequate home office during the pandemic. However, the availability of high bandwidth connectivity is not yet evenly distributed geographically across Europe.

Machine learning is essential for a resilient future. AI will have a far greater chance of successful implementation if there is a focus on four key areas: augmented intelligence; intelligent automation; assessed intelligence; and adaptive intelligence. Augmented intelligence concerns augmenting and thus improving the productivity of humans. Intelligent automation is essentially about building systems that integrate humans and machines in productive ways (instead of just replacing humans entirely with machines). Assessed intelligence is all about making models robust by evaluating them rigorously and continuously. Finally, adaptive intelligence involves developing more resilient systems that can adapt to changing circumstances by shifting to a causal inference paradigm.

187 McKinsey Global Institute: "Tech for Good: Smoothing disruption, improving well- being", May 2019, p 42 and p 43.

188 McKinsey Global Institute: "Tech for Good: Smoothing disruption, improving well- being", May 2019, p 58.



F.83 *A consortium of three European SMEs[189] is developing a desktop Covid-19 testing device that will include a highly innovative photonic integrated circuit. The biosensing device will be able to yield reliable test results within 5 minutes.*

3.6.4.2.2 Key focus areas

High-priority R&D&I areas:

- Reliable and ubiquitous digital infrastructures.
- Access control/intrusion detection/surveillance.
- Provide protective environment and tools against virus infections.
- Off-grid living and emergency survival.

In the coming years, more people will work from home as the Covid-19 pandemic forced large groups of high-skill workers to do in 2020. To further enable working from home, or wherever and whenever one wants, wireless and wired infrastructures will have to be further improved (through increased reliable bandwidth, lower cost, better geographical coverage and finer granularity), security of connections will have to improve to protect the worker at home (as will the company using a distributed workforce with many internet connections) against cyber-attacks, and the theft of personal and/or company information. New functionality running in the private/public cloud will be needed to support real-time actions that may suffer from latency issues over the internet, as well as to support the worker in decision-making. Examples here are control of robotic surgical devices, remote control of robots in industrial processes, remote control of cameras in security applications and live television productions, and so on. Other professions, such as translation services, voice recognition and all kind of analytical algorithms for data analysis, also come to mind.

1.4 2.2 2.4

To create equal opportunities, innovative research should include: speech-generating devices (SGD) to help people with speech disorders; exoskeletons that empower disabled people in their everyday life; semi-autonomous vehicles that increase mobility for people with deafness and blindness; smart objects linked to geospatial information to improve women's security (e.g. invisible SOS buttons); augmentative and alternative communication tablets that help paralysed patients; VR solutions that provide realistic experiences for people with physical disabilities; and smart glasses that can be used to help people with autism on cognitive, social and emotional skills.

189 LioniX, Surfix and Qurin Diagnostics (supported by PhotonDelta).

1.2 1.3 3.4

In 2020 we learned that Europe will need better technologies: (i) to fight and contain the rapid spread of diseases such as Covid-19; and (ii) to ensure that public health institutions can maintain their capacity to meet the ever-increasing needs caused by such a pandemic[190]. The in-depth analysis provided by the European Parliamentary Research Service's "Ten Technologies to Fight Coronavirus" identifies the importance of AI, blockchain, open source-, telehealth- and gene-editing technologies, 3D printing, nanotechnology, synthetic biology, and drones and robots for fighting pandemics. As an example, *Figure F.83* depicts a photonic Covid-19 biosensor that demonstrates agile innovation by European SMEs.

Intrinsically, technology is neither good nor bad – it is the use to which it is put that makes the difference. Malicious uses of technology include mass disinformation campaigns and cyber-attacks that seek to jeopardise national security, and cyber-fraud that targets consumers. This duality has always existed. Over the coming years, technologies such as the IoT, smart robotics, automation and AI are likely to follow the same pattern. It is up to European technology specialists to ensure that the technologies developed not only support diversity and inclusion, but also protect both the individual and groups against cyber-attacks, theft of personal information and unwanted intrusion into the personal environment.

Required R&D&I developments within ECS

To facilitate empowerment and resilience, specific R&D developments are necessary within ECS technology, as shown in *Figure F.84*.

3.6.4.3 Major Challenge 3: facilitate inclusion and collective safety

3.6.4.3.1 Status, vision and expected outcome

Ambition: safeguard collective society and wellbeing for all.

- Societal and digital inclusion.
- Provide societal access for all.
- Ensure collective resilience against setbacks.

Although European countries have different types of welfare models, they also share a history of robust social protection and a focus on inclusive growth, which has been under stress in recent years[191]. There could be cracks in the sustainability of the EU social contract over the next decade caused by six trends: ageing; digital technology, automation and AI; increased global competition; migration; climate change and pollution; and shifting geopolitics. Based on these trends, inequality may rise again, and divergence within Europe could increase.

Inequality at work may emerge through a combination of: (i) automation and the substitution of labour; and (ii) corporate diffusion dynamics, leading to a competitive disadvantage among non-adopting firms. To prevent reduced employment and secure real wage growth, automation through the use of AI, robotics and other new technologies should lead to significant productivity gains. In general, occupations based on more repetitive and non-digital tasks will be taken by workers with low education and skills, who will therefore be the first to experience pressure on wages.

190 https://www.europarl.europa.eu/ RegData/etudes/IDAN/2020/641543/ EPRS_IDA(2020)641543_EN.pdf

191 Testing the resilience of Europe's inclusive growth model, McKinsey Global Institute, December 2018, p4.

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major Challenge 2: Facilitate empowerment and resilience	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING	COMPONENTS, MODULES AND SYSTEMS INTEGRATION	EMBEDDED SOFTWARE AND BEYOND	SYSTEM OF SYSTEMS	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL	CONNECTIVITY	ARCHITECTURE AND DESIGN: METHODS AND TOOLS	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Reliable, dependable and secure SW and HW	X		X			X	X	X
Trustable AI/ML algorithms					X			X
Advanced cybersecurity and privacy methods and tools						X	X	X
Ensuring of safety and resilience based on ECS technologies		X	X	X	X	X	X	X
Energy-efficient and dependable HW and SW solutions (e.g. for IoT devices, wearables)	X		X	X	X		X	X
Seamlessly operating SW (e.g. for IoT devices, wearables)		X	X	X		X		
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband connectivity based on 5G systems and beyond	X	X	X			X		X
Distributed (production) systems		X		X	X	X	X	X

F.84 *Required R&D&I developments within ECS – Major Challenge 2*

Collective growth and wellbeing is not only determined by equality at work, but also by individual development supported by collective interactions. Studies have shown that active social relationships increase health and longevity by improving key biomarkers of physical health. A lack of interaction causes a subtle decline in mental health by reducing attention, learning, memory and decision-making skills. In short, our bodies reward us for social interaction and punish us for isolation by negatively impacting mental and physical health. Direct interactions with family and friends, participating in team sports and, for instance, visiting an event with friends are very important. No technology can fully replace direct contact. However, the spread of

the Covid-19 virus has shown that direct social interactions may not always be as possible as we have been used to. Thus, we will have to rethink our social interactions, and find out how we can adapt existing and new technologies to increase and improve social interactions – not just between individuals but also between individuals and groups, as well as between different groups. How can improved technologies support existing social interactions, and secure healthy digital social interactions in cases of setbacks?

In addition, collective safety can be enhanced by solutions that directly address specific communities or groups of people the individual is a member of, such as family, friends, neighbourhood, region, (sports) club or association. These solutions can either have a warning or alerting function (e.g. contamination, local fire, local air pollution, incident of violence), but can also be of a supporting nature – for instance, alerts or instructions in combination with collective supporting devices (e.g. automated external defibrillator (AED), diagnostics, measurement).

3.6.4.3.2 Key focus areas

High-priority R&D&I areas:

- Digital inclusion: tools, infrastructure, training, connectivity.
- Collective safety: secure access control, surveillance, pandemic control, prevention of misinformation without limiting freedom of expression.
- Safe environment for living, working and transport: buildings and bridges resilient against earthquakes through continuous monitoring (e.g. fibre-based stress sensors).
- Emergency/crisis response solutions and services.
- Dynamics of society: systemic change.

As Europe wants to play a major role in digital inclusiveness, it is important to ensure availability and accessibility of solutions to enable remote education, learning, training and assessment of professionals, students and consumers in all regions (both cities and rural areas). Also, solutions to support social inclusiveness for people of all age should become available.

1.4 2.2

The EU has stated, in their document on orientations towards the first strategic plan for implementing Horizon Europe[192], that the interaction of science, technology, social sciences and humanities will be crucial in this respect, as will be the input of the creative sector and artists to sustainable inclusive innovation and human- oriented technologies.

To facilitate inclusion, more research will be needed on education, simple human–machine interfaces and digital technology interfaces that avoid the digital split between high- and low-educated citizens. In addition, remote presence and remote connectivity to keep people connected even if they are not in the same location, trustworthy social media, serious gaming, media consumption and AR/VR will be key.

2.4

To safeguard digital inclusion, education is one of the most important research areas. Examples here are the use of AI to build personalised journeys and enhance learning outcomes, to adapt curriculum to individual student needs, digital support and nudging systems to reduce the administrative burden on teachers, tablet-based learning to improve results and decrease distress for students with dyslexia, automation of administrative tasks to free up time and resources for educational professionals, wearable devices that provide real-time support to pupils, eye-tracking solutions to adapt students' learning experiences, and use of AR/VR to provide immersive experiences to civilians in less well-served areas.

192 https://ec.europa.eu/research/pdf/horizon- europe/ec_rtd_orientations-towards-the- strategic-planning.pdf

AR may improve connectedness for remote places, reducing the need for commuting or business travel. It could also enable consumers to enjoy an event together even if they are not physically at the event.

There are still several challenges to effectively take full advantage of AI in video creation and consumption. One is the size of video data. Results are only accurate when algorithms are fed with millions of observations. Technologies therefore have to be deployed and strategies have to be implemented to gather data at scale to harness the full power of AI techniques. However, size creates another challenge: datasets need to be manually labelled by humans to train the model, making the process expensive and cumbersome. New techniques that are becoming available to overcome the challenge of (expensive) data categorisation are reinforcement learning, generative adversarial networks, transfer learning and "one- shot learning". In consumer-facing applications, such as marketing and recommendation algorithms, AI models may need to be refreshed continuously due to changes in the environment that drives them. Continuous updates to AI models are expensive. Other challenges relate to data management and data gathering: to create accurate results with AI, and thus value, different types of data have to be managed in a unified manner. This includes audience data, operational data and content data (metadata). Also, "selection bias" (i.e. the data gathered is not representative of the population studied) has to be prevented to exclude wrong conclusions in a perfectly working model.

2.1

2.4

To facilitate collective safety, further research is required on secure access control, intrusion detection, (video) surveillance of security sensitive areas, and individual and collective activity tracking.

Secure access control as a service (ACaaS) is growing in relevance. This combines biometric readers and identity access management, and can be integrated with other physical security systems (e.g. video surveillance) and building automation systems. Combined with building occupancy management systems, it can deliver valuable information on the location of staff and visitors, and in the event of an emergency to rapidly clear the building.

Covid-19 has brought new physical security requirements. In addition to regular cameras, thermal cameras could be added at the entrance of buildings and venues to measure people's temperature as they enter premises. Physical access control, enriched with video security evidence, can provide important insights on where an infected individual has been, which doors they have used and who else may have come into contact with those doors and that individual. It can also provide these insights for more general security purposes.

More research on AI security solutions will ease the work of security operators. AI software can analyse images and audio from video surveillance live streams and recordings, and use image recognition algorithms to recognise faces, objects and events, more than a hundred times faster than human operators. AI algorithms can also be used to carry out event detection, scene reconstruction, video tracking, object recognition, and (re)-identification, 3D pose estimation, motion estimation and image restoration. Video surveillance may be extended with freely moving cameras mounted under drones to recognise unusual behaviour in crowds from a high altitude, to monitor hazards such as fires, floods or erupting volcanoes, and to recognise criminal faces and follow targets. Since drones are airborne, they need fast mobile and wireless communications. Low-latency broadband technologies such as 5G can improve the precision and speed of their response times, and enable high-speed communication to a nearby edge computing device.

1.2 1.3

1.4 2.1

2.4

Video quality should be further improved to support deep-learning algorithms, and to improve the video experience in media consumption: the spectral range and colour gamut can be extended, sensitivity has to increase for low light use and dynamic range for better performance under all (and changing) lighting conditions.

AI video and audio algorithms will have to be transparent and explainable. Dedicated video and audio technologies will be required to prevent and trace fake video and audio used to create misinformation in (social) media.

Required R&D&I developments within ECS

To facilitate inclusion and collective safety, specific R&D developments within ECS technology are necessary, as shown in *Figure F.85*.

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major Challenge 3: Facilitate inclusion and collective safety	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING	COMPONENTS, MODULES AND SYSTEMS INTEGRATION	EMBEDDED SOFTWARE AND BEYOND	SYSTEM OF SYSTEMS	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTRO	CONNECTIVITY	ARCHITECTURE AND DESIGN: METHODS AND TOOLS	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
ECS technologies for AR/VR and high-quality video/videoconferencing	X	X	X		X	X	X	
Tools, methods, SW and HW technologies for extensive and ubiquitous use of AI/ML	X		X		X	X	X	
Advanced cybersecurity and privacy methods and tools						X	X	X
Intelligent connected IoT devices using new sensors for safety and resilience of EU societies	X	X	X	X	X	X	X	X
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband connectivity based on 5G systems and beyond	X	X	X			X		X

Required R&D&I developments within ECS – Major Challenge 3

F.85

3.6.4.4 Major Challenge 4: facilitate supportive infrastructure and a sustainable environments

3.6.4.4.1 Status, vision and expected outcome

Ambition: contribute to a collective supportive infrastructure and environment.

- Provide reliable and resilient infrastructure.
- Protect society against destabilising forces.
- Establish a sustainable environment.
- Secure controlled climate change.

To fully benefit from the power of digitisation, Europe must enable a supportive infrastructure and environment. Given the rapid pace of change, this requires companies to get their technology, people and culture ready to join the digital transformation. This should be achieved by providing a reliable and resilient digital infrastructure (with ubiquitous and continuous connectivity), protecting society against destabilising forces and establishing a sustainable environment. The former includes preventing harmful use of the internet (e.g. manipulation of elections, misinformation such as "deepfakes" and "cheapfakes", but also identity theft and phishing), which are covered by Major Challenge 3. The latter includes securing controlled climate change (as stipulated in the Green Deal). Furthermore, monitoring and intelligent control of infrastructures and essential resources (especially in the urban environment) will contribute to a sustainable environment.

1.4 2.2 2.4

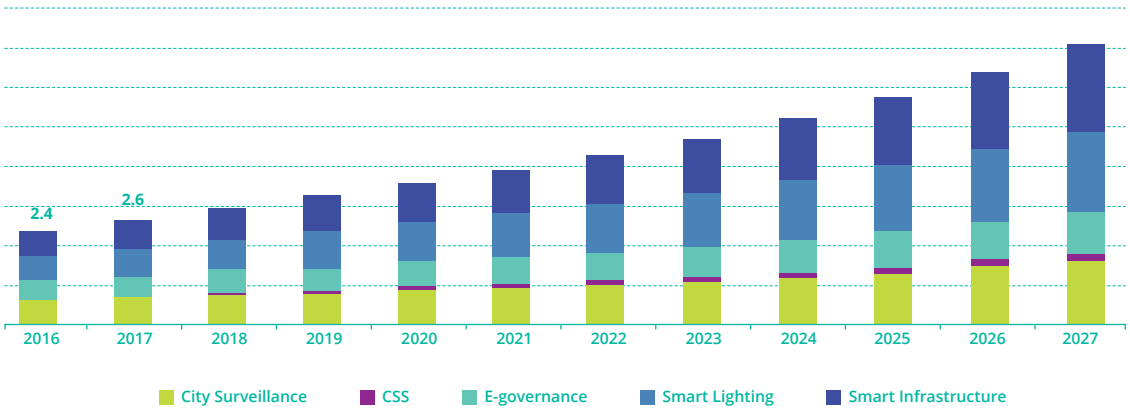
The vision is to introduce new digital products and services that contribute to a sustainable lifestyle in all areas of human life, including cradle-to-cradle and circular economy aspects. We are addressing the following aspects.

- Comprehensive assessment of resource usage to identify largest areas of consumption. As well as air quality monitoring systems, they need to offer solutions for lighting, heating, computing with reduced usage of energy, and other resources. In addition, solar panels and batteries, home-grown vegetables and city farming systems are key.
- Providing IoT/smart systems that support the digital business life with the minimum amount of resources (energy, water, paper, travelling, etc), ensuring a highly efficient, productive and sustainable working environment. Reduction of (food) waste in supermarkets and restaurants, as well as resource recycling.
- Smart water management to protect resources. Intelligent management of energy in public spaces such as football stadiums and railway stations, including smart street lighting. Promoting green areas in cities and enabling citizens to provide their own sustainable solutions.
- Sustainability and dealing with climate change.

2.1

3.5

U.S. SMART CITIES MARKET SIZE, BY SMART GOVERNANCE, 2016–2027 (US $ BILLION)



Growth of US smart cities market (Source: www.grandviewresearch.com)[193]

F.86

The European approach to working with regard to digitalisation will be focused on the preservation of our democratic system, and on values such as trust and cooperation. Ethical requirements will include fairness, accuracy, confidentiality, transparency, accountability, explainability, trustworthiness and absence of bias. This involves offering AI capability maturity programs to companies that use AI in their designs, to coach them in the best ethical points of view. In this way products will become more resilient, accessible, reliable and trustworthy, and hence ready to take part in the new European digital society.

3.6.4.4.2 Key focus areas

High-priority R&D&I areas:

- Physical infrastructure management/physical resilience.
- Intelligent infrastructure management (intelligent buildings, city-owned infrastructure, synergies with industry, etc.).
- Digital infrastructure management/digital resilience.
- Smart cities: e-government/citizen support.
- Resource monitoring (air, water, etc.) and feedback to enable more effective management.

To further improve digital infrastructures, investments should be aimed at enhancing infrastructure coverage and quality – for example, with broadband rollout and public Wi-Fi. Also, outcomes have to be influenced through legal frameworks and by setting standards.

2.2

Intelligent buildings will require security, eco-friendship and building management. Security systems such as access control and cybersecurity were covered under Major Challenge 3, but the further development of smart lighting, air quality monitoring and control, and IoT-based real-time monitoring of electric, water

193 *Source: Grand view Research: "Smart Cities Market Size, Share & Trends Analysis" Report by Application (Governance, Environmental Solutions, Utilities, Transportation, Healthcare), By Region, And Segment Forecasts, 2020 – 2027. See https://www.grandviewresearch.com/industry-analysis/smart-cities-market*

and gas meters to increase the energy efficiency of buildings with the help of distributed energy systems will improve the wellbeing of occupants and reduce the carbon footprint of buildings. Smart technology (e.g. sensors placed around radiators, boilers, pumps and other machinery to detect critical levels of noise, vibration or heat) will enable facility managers to save maintenance costs by switching from a reactive to a predictive maintenance model.

1.1 1.2 2.1

Cities are very complex organisms. They combine a variety of means allowing for mobility, city infrastructure providing different types of media (gas, water, energy, etc), and citizen-oriented services that increase their quality of life. It is predicted that by 2050 between 68% and 90% of the global population might live in cities, from small municipalities right up to megacities[194]. This means that, in the near future, technical means will be required to enable digital solutions for more sustainable development in cities of all size and wealth. Available technologies from tech giants such as IBM, Microsoft, Amazon, Google and Cisco raise concerns from city managers about data privacy policies, and the very high maintenance costs caused by licence fees and the potential for vendor lock-ins[195]. Available open source solutions – such as the Red Hat integration platform, which could be used in smart city applications – can also easily be acquired by large companies such as IBM[196] to be integrated with their company product portfolio offered commercially. This means that, in such a dynamically changing world, open source solutions that are widely available, promoted and deployed within EU (such as FiWare[197]) have to be developed to protect European sovereignty and values. Additionally, due to the rich industrial heritage in many EU countries, opportunities for re-using or integrating available well- developed open source industry platforms, such as the Eclipse Arrowhead Framework[198], have to be thoroughly investigated. This is especially the case since industry sites are often integrated within city areas, and therefore naturally create synergies that can influence each other. These smart city applications create natural synergies with the System of Systems, Mobility and Digital Industry sections.

1.4 3.1 3.3

The impact of technology on environmental sustainability is likely to be highly significant. In retail, where shifting customer habits will be key (for example, for new products such as plant- or insect-based food), IoT sensors and devices will also yield a positive impact – for example, by reducing waste through improved food temperature or expiry date management. In the manufacturing sector, smart building applications related to energy and wastewater management, as well as applications such as carbon capture and biofuel generation on industrial sites, will have a significant impact.

Required R&D&I developments within ECS

Development of supportive infrastructure and a sustainable environment within EU needs the following specific R&D developments within ECS technology:

194 *https://www.un.org/development/desa/en/ news/population/2018-revision-of-world- urbanization-prospects.html*

195 *https://www.smartcitiesworld.net/news/ news/city-governments-fear-vendor-lock-in- from-iot-platforms-3776*

196 *https://www.networkworld.com/ article/3429596/ibm-fuses-its-software- with-red-hats-to-launch-hybrid-cloud- juggernaut.html*

197 *https://www.fiware.org*

198 *https://www.arrowhead.eu/arrowheadframework*

SPECIFIC R&D DEVELOPMENTS NECESSARY	ECS TECHNOLOGIES							
Major Challenge 4: Facilitate supportive infrastructure and a sustainable environment	PROCESS TECHNOLOGIES, EQUIPMENT, MATERIALS AND MANUFACTURING	COMPONENTS, MODULES AND SYSTEMS INTEGRATION	EMBEDDED SOFTWARE AND BEYOND	SYSTEM OF SYSTEMS	ARTIFICIAL INTELLIGENCE, EDGE COMPUTING AND ADVANCED CONTROL	CONNECTIVITY	ARCHITECTURE AND DESIGN: METHODS AND TOOLS	QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Open systems and platforms for managing complex cross-connected physical infrastructure and associated processes		X	X	X			X	
Energy-efficiency oriented HW technologies and embedded SW	X		X		X	X	X	
Advanced cybersecurity and privacy methods and tools						X	X	X
Intelligent connected IoT devices using new sensors for safety and resilience of EU societies	X	X	X	X	X	X	X	X
Ubiquitous, reliable and energy-efficient connectivity and localisation	X	X	X			X	X	X
Secure broadband low-latency connectivity based on 5G systems and beyond	X	X	X			X		X
Distributed (production) systems		X		X	X	X	X	X

Required R&D&I developments within ECS – Major Challenge 4

F.87

3.6.5 TIMELINE

The following table illustrates the roadmaps for Digital Society.

MAJOR CHALLENGE	TOPIC	SHORT TERM (2022–2026)
Major Challenge 1: facilitate individual self-fulfilment	**Topic 1.1:** improved human–machine interaction solutions	• Intensive research on human–machine interaction solutions
	Topic 1.2: online education and examination	• Developments of methods and solutions for online education and examination
	Topic 1.3: VR/AR training and support	• VR/AR pilots, including remote training, support and work
	Topic 1.4: support devices (wearables, robots, cobots, chatbots, etc)	• Wearables and chatbots used for commonly used devices
	Topic 1.5: nudging, gamification (for development or health reasons)	• New nudging, gamification systems developed for education and health
Major Challenge 2: facilitate empowerment and resilience	**Topic 2.1:** access control/ intrusion detection/ surveillance	• Classic surveillance systems
	Topic 2.2: reliable and ubiquitous digital infrastructures	• Increased quality of service (QoS) and available bandwidth with 5G, less time-critical functions moving to the cloud
	Topic 2.3: social media/ serious gaming/AR/VR	• AR on social media moves from photos to video >80% on social media in video by 2022; in-game systems that self-adapt to guide human learning
Major Challenge 3: facilitate inclusion and collective safety	**Topic 3.1:** digital inclusion: tools, infrastructure, training, connectivity	• Development of technologies (AR/VR, hearables, haptics, etc) for digital inclusion
	Topic 3.2: resilient society against setbacks	• Emergency/crisis response solutions and services with ubiquitous localisation
	Topic 3.3: societal acceptance of novel technologies	• Technologies (serious gaming, nudging, etc) for societal acceptance and adaptation
Major Challenge 4: Facilitate supportive infrastructure and environment	**Topic 4.1:** physical infrastructure management/ physical resilience	• Development of IoT and dedicated robot-based inspection systems supported by AI algorithms
	Topic 4.2: intelligent infrastructure management	• Development of systems for intelligent management of infrastructure (water, street lighting, heat, etc)
	Topic 4.3: digital infrastructure management/ digital resilience and cybersecurity	• Acceleration of initiatives to create open, secure privacy-oriented systems; development of AI-based algorithms for increased cybersecurity
	Topic 4.4: surveillance, homeland security and emergency response systems	• Edge/cloud solutions, IoT systems and robot-based inspection platforms, increased multimodal situational awareness, ubiquitous localisation

MEDIUM TERM (2027–2031)	LONG TERM (2032–2037)
• Improved human–machine interaction solutions in pilot phase	• Improved human–machine interaction solutions in the commercial phase
• Online education and examination used in most EU universities, also for education of adults	• Online education and examination widely used across the EU
• VR/AR training, support, and remote work is mature	• VR/AR training widely used across the EU
• Support devices (wearables, robots, cobots, chatbots, etc) gain more intelligence and interaction	• Support devices (wearables, robots, cobots, chatbots, etc) used in daily life
• Nudging, gamification pilots in education and health	• Nudging, gamification (for development or health reasons) is widely used across the EU
• Smart surveillance with rudimentary intrusion detection	• Smart surveillance with AI-based intrusion detection
• Bandwidth and QoS increase especially for video-based applications • Time-critical functions moved to cloud	• Bandwidth and QoS no longer an issue for video applications. • AI algorithms support supervision
• Apart from, AR also VR for videos on social media • Multimodal and multi-sensory interfaces in serious gaming • Application beyond single game. • Personal learning	• Real-time emotion state sensing • Cognitive learning
• Pilot deployments of hybrid systems for collective interactions	• Technologies for immersive collective interactions
• Trustable solutions for collective activity tracking, access control and intrusion detection	• Trustable AI-supported hybrid solutions for resilient society
• Human-oriented trustable AI systems and technologies	• Trustable AI for collective growth and wellbeing
• Pilot deployments of trustable AI-based systems relying on dependable edge/cloud IoT	• Intelligent, affordable and trustable IoT and robot-based systems are available
• Pilot deployments of trustable AI-based orchestration systems to create synergies in infrastructure management	• Smart systems for multi-domain infrastructure orchestration and management available
• Adaptation and pilot deployments of available interoperable open and reliable systems supported by trustable AI algorithms for increased cybersecurity	• Open, secure, interoperable and reliable privacy-oriented systems empowered by trustable AI-based IoT solutions available
• Deployment of trustable AI-based edge-cloud solutions, IoT systems and robot-based inspection platforms for surveillance and emergency response support	• Trustable and dependable AI-based IoT systems and robot-based inspection platforms for increased situational awareness widely available

3.6.6
SYNERGY WITH OTHER THEMES

There is synergy with several other ECS key application areas, which has been delineated as follows:

- **Mobility:** where the Mobility Chapter mainly addresses infrastructure-related aspects, Digital Society implies "being on the move" from time to time. The aspects addressed by the Major challenges for Digital Society in general therefore also apply when being on the move.
- **Digital Industry:** while sustainability is an important aspect of life in the digital society, this is also addressed in the Chapter on Digital Industry.
- **Energy:** electrical energy is a prerequisite of a digital society, as smart devices are based on it. Although in general energy generation and distribution is a different area, energy scavenging of IoT sensors and actuators, energy storage and wireless charging of smartphones and other wearables can be essential elements of a digital society.
- **Health and Wellbeing:** where healthcare aims to cure people of diseases, wellbeing implies measures to keep healthy people healthy. The Major Challenge "Ensuring individual empowerment and wellbeing" will contribute to the aim of keeping healthy people healthy by supportive products and services in the Digital Society.
- **Agrifood and Natural Resources:** the protection of natural resources can be considered part of ensuring environmental sustainability; for the rural, this is addressed in the Chapter on Agrifood and Natural Resources, while the urban lies more in the scope of Digital Society.

There is also synergy with some other ECS technology Chapters:

- **Quality, Reliability, Safety and Cybersecurity:** there are relevant Major challenges in that Chapter that link to this Chapter on Digital Society: quality and reliability, ensuring dependability in connected SW, privacy and cybersecurity, safety and resilience, and human–systems integration.
- **Connectivity:** homeland security and cybersecurity of the digital society needs reliable connectivity infrastructure.
- **System of Systems**: smart city topics require reliable digital solutions that can handle a variety of many interconnected systems within cities.

4

Strategic Research and Innovation Agenda 2022

LONG-TERM VISION

4.1 INTRODUCTION

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

The long-term vision is shaped by three main factors: technology, application domains and policies. Clearly, all factors are drivers of innovation, because (i) anticipated technological advances lead to innovative applications of these advances and (ii) user needs lead to technological innovations that enable these needs. At the same time, policies and politically established goals and processes lead technologies and applications towards common goals and targets such as the goals of the Green Deal and the European industrial competitiveness. It is apparent that, each of these factors motivates, shapes and initiates innovation efforts at many levels.

In regard to policies, which lead many technologies and applications in a pan-European scale, the ECS community has specified its common objectives that influence and shape innovation in the long term and that should be considered in the future research directions. As anticipated in the Introduction, these four high-level common objectives are to:

- boost industrial competitiveness through interdisciplinary technology innovations;
- ensure EU digital autonomy through secure, safe and reliable ECS supporting key European application domains;
- establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal, and
- unleash the full potential of intelligent and autonomous ECS-based systems for the European digital era.

These objectives, which are aligned with policies and European political priorities, address the need to establish unrestricted access to goods and services, free exchange of know-how and information, under trusted, protected and regulated multilateral agreements in the emerging international political and economic landscape. The European Union's policies to protect its strategic autonomy, and sustain its competitiveness are shaping and continuously advancing, especially for the ECS industry, which constitutes the backbone of the digital society. European digital sovereignty – European Union's ability to maintain control and security of its products, overcoming disruptions and vulnerabilities – is one of the major challenges when considering that its major economic drivers, i.e. digitization and connectivity, are strongly dependent on the supply of hardware and software from countries outside Europe. This challenge needs to be addressed immediately, for the short term as well as for the long term, by research programmes in the following topics:

- Safety and security: development of rigorous methodologies, supported by evidence, that a system is secure and safe; safety and security are requirements for trustworthiness. These methodologies should enable certification through ap-propriate certification methods, such as testing and/or formal methods to prove trustworthiness guarantees.

- Artificial intelligence and machine learning (AI/ML): AI/ML-based techniques will contribute significantly to the development of robust ECS components, systems and applications, with short development cycles. AI/ML will influence all major technologies in ECS development, e.g., model-based engineering, and will constitute a major link between quality, reliability, safety and security.
- Trustworthiness: development of methodologies that integrate traditional ECS technologies with AI/ML, from device level up to applications and human interface. Trustworthiness is key to the acceptance of such emerging systems. Advances in explainable AI models for human/system interaction, safety, security, risk analysis and management, liability and certification are necessary for the necessary trustworthiness that will lead to the acceptance of the new generation of innovative products.

The European Green Deal is another policy that combines wide civilian acceptance with high political priority and shapes innovation strongly. As climate change and environmental degradation pose an existential threat to Europe and the world, the European Green Deal is the European strategy to make the economy of the European Union sustainable in the long term[199]. By 2050, a modern resource-efficient and competitive economy has to be in place, characterized by:

- Zero net emissions of greenhouse gases;
- Economic growth decoupled form resource use;
- No person and no place is left behind.

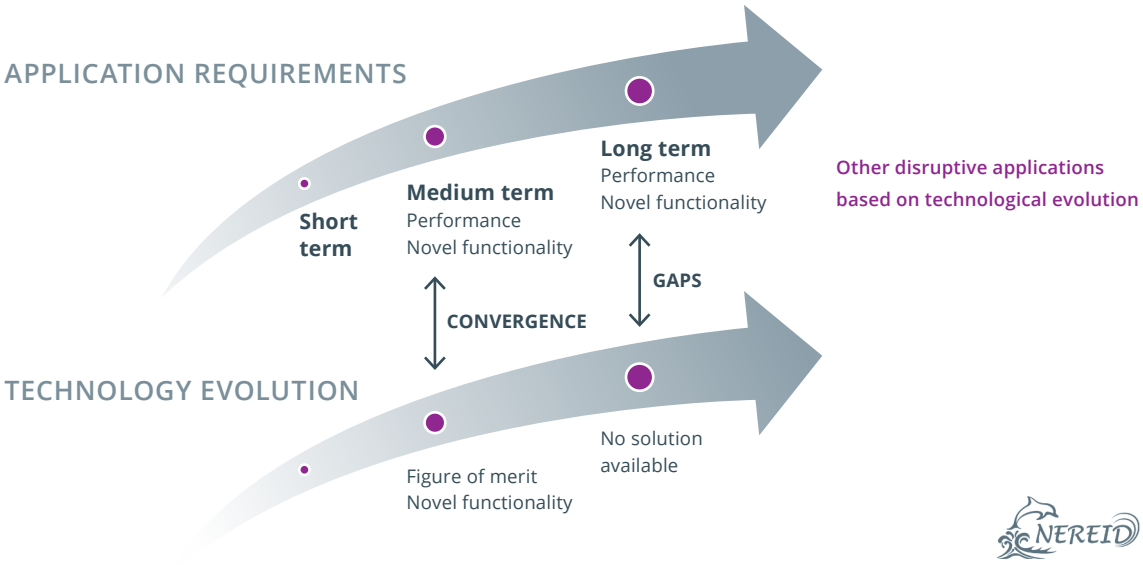
The ECS community is instrumental to the realization of the European Green Deal; the many challenges associated with energy management can be tackled only with ECS-based solutions, leading to energy-efficient ECS devices as well.

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

Additionally, and independently of policies, long-term vision is shaped by technological and application evolution and revolution. Many future applications will be enabled by enhanced functional and non-

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

functional properties provided by new technologies (both hardware and software), as projected in technology-application roadmaps such as the one shown in *Figure F.88*. Typically, the advances that are foreseen through roadmaps are considered evolutionary. However, there have been several occurrences of, so called, revolutionary or disruptive developments in technology. These are not projected in roadmaps, they exploit and establish innovative technological models and have tremendous technological and societal impact. Often, they lead to paradigm shifts with significant impact to business and society. The World Wide Web is a typical example of disruptive technology.

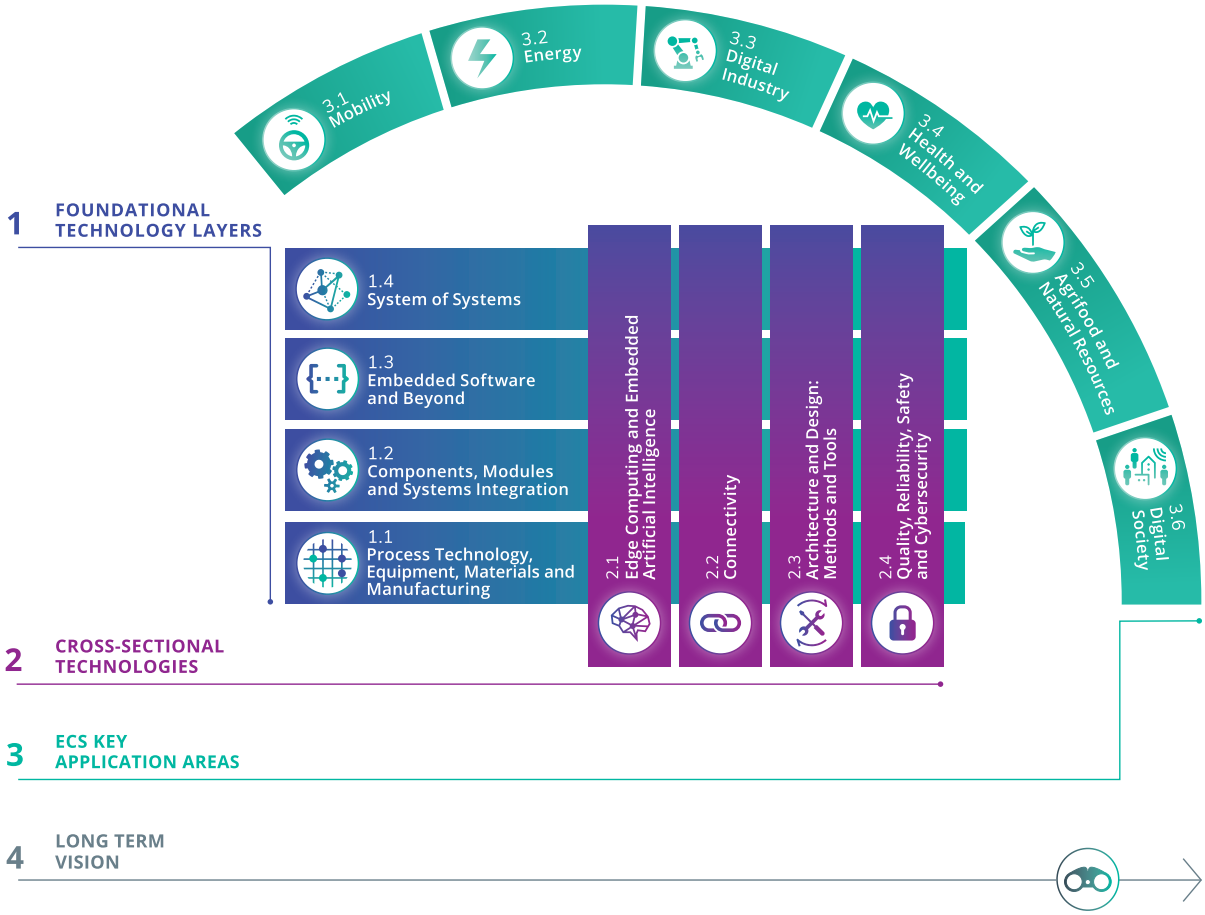


Technology evolution and application requirements F.88

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. Clearly, maintaining and extending these competences is fundamental to the continuous offering of disruptive technologies that will preserve the European competitive position.

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

4.2 MODEL



F.89 *Technology domains evolution and application requirements*

We consider a layered model for the technological and application challenges for ECS, as shown in *Figure F.89*. The foundational technology areas enable the description of components and systems in a hierarchical fashion at different levels of abstraction. For example, components and modules are described in Layer 1.2, are built exploiting technologies at Layer 1.1 and provide basic components to build systems of systems (SoS) at Layer 1.4.

Cross-sectional are the technologies that can be included in any and all foundational technology areas; they can be considered as properties that are implemented with different technological methods in the various foundational technology layers. For example, AI/ML or reliability are technologies that can be integrated at the device level as well as at the component and system level; apparently, at each level, they are implemented with different methodologies and address different problems.

Importantly, the circular layer around the technological layers indicates that the systems that are built with the foundational and cross-sectional technologies are used to implement applications in various domains;

the circular layer enumerates the bulk of application domains where European ECS constitute an effective, successful international competitor.

In the remaining sections of this Chapter, we present challenges in technologies, fundamental and cross-sectional, as well as in the application domains that are enumerated in *Figure F.89*, with the understanding that our presentation addresses anticipated evolutionary and revolutionary technologies based on conventional technological and societal understanding. Independently, our expectation is that disruptive innovations will be readily integrated in our long-term view, since they will affect part or parts of the layered model we exploit for abstraction, understanding, presentation and openness.

4.3 TECHNOLOGY LONG-TERM CHALLENGES/VISION

4.3.1 Process technology, equipment, materials and manufacturing

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

In the More Moore field, there are strong interests in Europe for specific activities that involve very low power devices, leading to possible disruptive applications – for instance, for future IoT systems, embedded memories, 3D sequential integration or application-driven performance (e.g. high temperature operations in the automotive industry).

New materials, including 1D and 2D structures, ultimate processing technologies and novel nanodevice structures for logic and memories are mandatory for different applications, as well as new circuit architectures, design techniques and embedded software. Some of these nanostructures are also very interesting for advanced sensors energy harvesters and photonics. All of these are key for future high performance/ultra-low power terascale integration and autonomous nanosystems.

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

- Nanowires and nanosheet, for high performance and very low-power nanoscale devices, the best material and geometry options for logic (high speed as well as low power) need to be identified.
- Millimetre-wave front-ends with III-V MOSFETs have to be developed (with applications in communications, radar, etc.), including 3D aspects of processing.

- Non-conventional switching devices, like negative capacitance field-effect transistors (NCFETs), tunnel effect transistors (TFET), 1D (CNT) or 2D (graphene and others), which could be suitable for very low power devices, need development in basic material, extended characterization of optimal architectures and design strategies.
- For nano-electro-mechanical FETs (NEMS-FET), low voltage reliable devices have to be developed.
- Spin-based devices also for switching and sensing.

In the field of alternative memories, resistive RAM, magnetic RAM and ferroelectric RAM/FeFET will be key for driving the limits of integration and performance beyond that afforded by existing non-volatile, DRAM and SRAM memories. Research should address:

- Widening the material screening and programming schemes.
- Variability and reliability, especially data retention.
- Trade-off between programming speed and programming power/data retention,
- Compatibility with standard logic process.
- Architectures for memory embedding in logic, for novel computing schemes.

In the long term Beyond-CMOS domain, the challenges to be addressed are in the field of beyond-conventional CMOS technologies, non-Boolean logic, and beyond-von Neumann architectures, including novel state variables, new materials and device, and innovative device-architecture interaction.

Silicon photonics is required to interface conventional electronics with photonic-based communications and sensors, and in a longer perspective with photonics-based quantum computing and communications.

The emerging field of Quantum computing poses its own challenges in process technology, equipment and materials:

- As there are still several candidates for becoming the standard quantum computing technology (such as quantum dots, spintronics, photonics, etc.), a wide range of materials is relevant, together with innovations in process technology.
- New metrology capabilities are required, especially the measurement of electrical properties, such as local mobility, is needed.
- To achieve practical applications, reliable fabrication, connection and read-out of qubits need to be developed. The low temperatures at which most quantum systems are operated requires the development of cryogenic devices, to interface conventional electronics.

To cope with the Green Deal sustainability objectives, the main European semiconductor manufacturing plants should be close to zero CO_2- and GHG-emission and should use 100% of renewable energy sources in 2030. Since the water consumption constitutes the largest fraction of material consumption in the wafer fabrication process, the semiconductor industry must investigate the way for using more recycled or reclaimed water for the various cleaning steps. Moreover, in order to secure their whole supply chain and for not wasting mineral resources in view of the limited extractable quantities of metals in the earth's crust, chipmakers will be more and more concerned with the potential scarcity of some ores that are compulsory for producing ultra-pure metals for the high-volume manufacturing of devices. One way should be to use recycled metals instead of premium metals. Another approach for preventing the use of natural resources consists in recovering the metals for the electronic wastes (e-wastes). The recovery of scarce metals from microelectronic devices opens a wide research domain for material scientists, as well as to ensure sustainable metal sources for chipmakers.

4.3.2 Components, modules and systems integration

The interaction among people and other information agents and their environment usually features a trade of data, which is curated into information that either results in a gain of knowledge and/or the enabling of purposeful action or reaction to a given situation.

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

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

- new sensitive and structural materials (hard & soft),
- physical-to-digital (and vice versa) transducers architectures,
- local (on-system) intelligence, and
- communication/interaction interfaces with users or higher instances of the decision chain.

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

From non-CMOS materials and device processing on top of CMOS wafers to System-in-Package (SiP) and customized application platforms, heterogeneous and hybrid integration of different technologies beyond semiconductor ones will continue as a key trend in the future, e.g. integration of semiconductor electronics with flexible and stretchable substrates and components, or closer integration of electronics and photonics with PICs and fast semiconductor driving/control/sensor components.

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

Moreover, ECS are pivotal elements of the digital transition that supports the current and future quest for making our civilization sustainable maximizing performance and minimizing e-waste, and particularly to slow down, revert or make human environments resilient to climate change. Multifunctional smart information systems will be in demand to react faster to such upcoming challenges and risks. For instance, globalization of human activity and large-scale weather changing patterns will ease the spread of known diseases beyond their usual geographical boundaries as well as spur the appearance of new ones. Swinging weather conditions will affect application fields directly exposed to climate conditions such as mobility, energy, or agrifood/ environmental applications. ECS helping these applications to react to those abrupt changes need to be integrated and packaged themselves in a way that can cope with these harsher environmental conditions.

Integration, as the art of recursively combining physical devices, components and systems together to form a new entity with increased functionality in the minimum volume possible, will be key to leverage the different positive aspects of diverse technologies and their reference materials. It has been already appraised that a combination of nanoelectronics, photonics (optoelectronics), electronic smart systems and flexible, organic and printed electronics is setting the path for future enabling functional electronics[200], which will be characterized by aspects such as:

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

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

4.3.3 Embedded software and beyond

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

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

200 https://5e-project.eu

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

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

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

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

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

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

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

4.3.4 System of Systems

System of Systems (SoS) is projected to become an area of exceptional economic growth, both short term and over the coming decades[201] This will create a strong market pull for the complete ECS value network upstream of the SoS area.

Strategic investments addressing open platforms, engineering and deployment efficiency, SoS management and control represent key factors to propel Europe towards very large scale of digitalisation and automation solutions across integrated and optimised operations of engineering, production, logistics, infrastructures, etc.

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

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

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

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

4.3.5 Edge Computing and embedded artificial intelligence

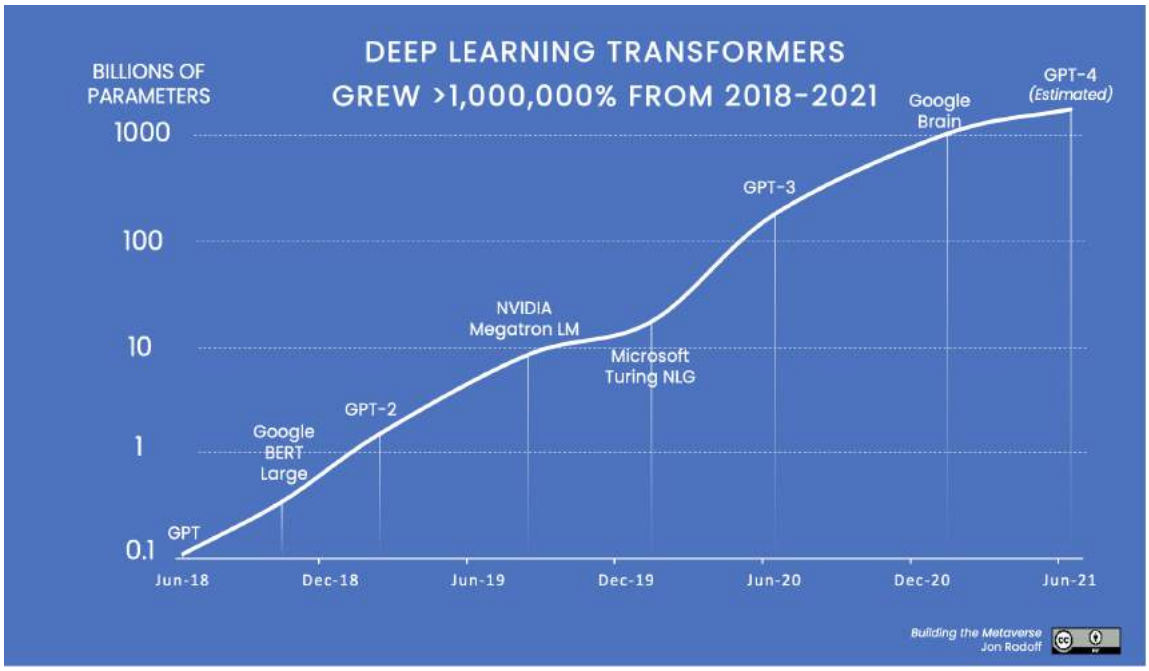
Artificial intelligence will be the enabling foundation for the digital society, ensuring that the systems that make up its framework function in an effective, efficient, secure and safe manner. Most of the ambitions that are to be realized in the digital society, such as a zero emission economy, affordable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

201 Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Available online at: https://artemis-ia.eu/publication/download/advancy-report.pdf.

autonomous cyber-physical systems, embedded systems) and the analogue real world. In this direction, there are several issues that need to be addressed, as presented below.

4.3.5.1 Exponential increase of the need of computing power for deep learning,

AI technology is becoming increasingly demanding for computational power, especially for the learning phase. As *Figure F.90* shows, the need for increased accuracy in AI techniques leads to methods that employ increasing numbers of parameters (for deep learning techniques, specifically, in *Figure F.90*), which, in turn, lead to dramatic increase of need for computational power to implement these techniques. This will imply new progress in energy efficiency in order to keep the Cost of Ownership affordable. Mainly the GAFAM and BAITX will be able to afford the computing infrastructure that will require a large number of servers.



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

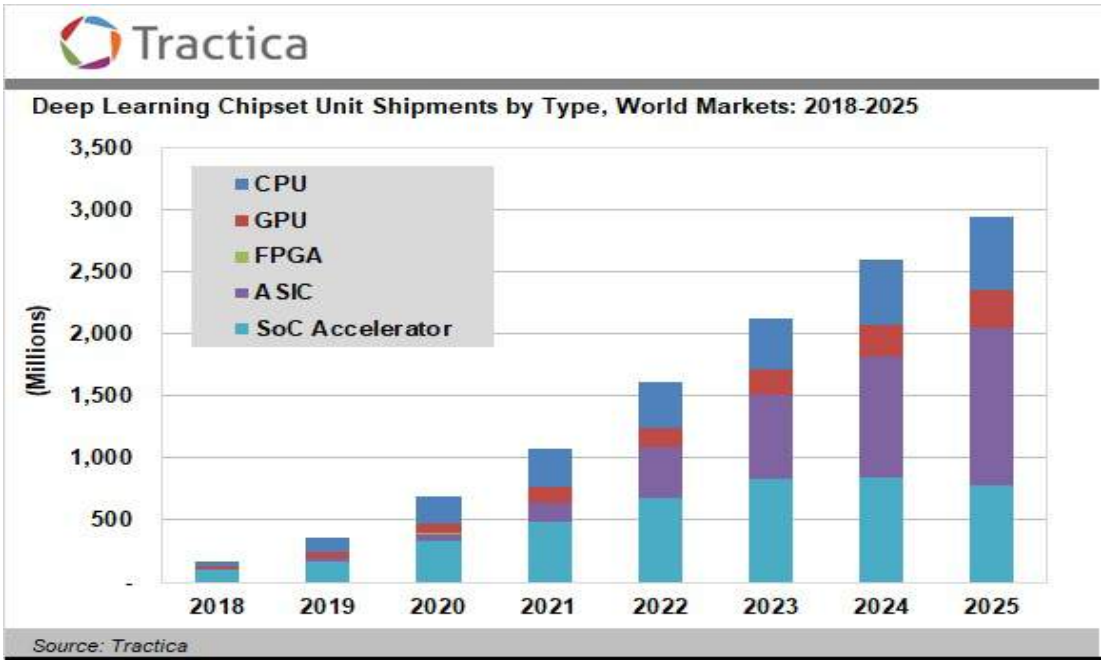
F.90

4.3.5.2 Explosion of usage and variety of chips for IA at the edge

IA accelerators will appear in many devices from the deep edge to home servers, allowing to process all kind of data and changing the way we interact with computers. *Figure F.91* demonstrates this, showing the dramatic increase of deep learning chiplets that have been shipped worldwide in the last years. Computing systems will disappear in the environments and will allow natural interactions.

To be able to cope with the diversity of requirements and the Cambrian explosion of designs, AI techniques will be used to select the best architecture (automatic design space exploration) and to generate the code from high-level specifications (No-code) with guarantees of correctness.

New AI paradigms will emerge (such as self-supervised approaches) that can be highly efficient at the edge, and decreasing the need for a large database and computing power like for deep learning.



F.91 *The growth of deep learning chip shipments (2018-2025)*

4.3.5.3 New paradigms will be used for computing with physical phenomenon, with high efficiency

Novel physical characteristics will be used to compute, the equations of the physical phenomenon being similar to the ones of the problem to be solved (e.g. minimization of a function). This can use electrons, but also photons (cf. LightOn), spins (spintronics) or the characteristics of new materials (e.g. ReRAMs or MRAMs, used in neuromorphic architectures for example). Quantum computing enters in this category. Most of these technologies will be used first in servers for very specialized acceleration but will slowly improve to be integrated in edge devices. Other modes of coding information besides bits will be used, e.g. using qbits or encoding in time like for neuromorphic architectures where information is coded in a succession of spikes, or their coincidence in time.

Other massively parallel approach using biological technology (based on proteins, DNA construction, etc) can also emerge for niche applications, or for storage[202]. This can also lead to biocompatible electronics or better recyclable systems (circular economy).

4.3.5.4 Home factories to create custom computing systems/deep edge devices

The mass market will be still fulfilled by very advanced foundries, but "small" foundries will also appear (if they are cheap enough and efficient) to make the very diversified deep edge devices that most of the time don't need the latest technology. Some low cost applications could be done with non-silicon technologies, e.g. using printing or 3D printing technologies[203]. This will allow enterprise level organization to have their own "device manufacturing" that don't need high quality clean rooms, and that will be highly automatized (leveraging AI for the exploration of architectures and code generation).

202 https://www.microsoft.com/en-us/research/project/dna-storage/

203 https://www.nature.com/articles/s41586-021-03625-w

In addition to these major issues, emerging challenges include:

- Dynamic instantiation of multi-paradigm computing resources according to the specifications of the task to be performed. Automatic interfacing, discovery, and configuration of resources.
- Integration in the same package of multiple computing paradigms (classical, deep learning, neuromorphic, photonic, etc.).
- Complete 2.5D (interposers and chiplets) ecosystem, with tools increasing productivity and reuse of chiplets in different designs.
- Exploring potential use of quantum computing in Artificial Intelligence.
- Use of AI to design SoC more or less automatically.
- At all levels (from chips to systems), automatic interoperability, adaptation to the data structure and physical interface, considering the communication characteristics. (Mid-term? Automatic translator of data and data format).
- Global reconfiguration of the resources to satisfy the functional and non-functional requirements (latency, energy, etc.).
- Linear and/or functional scalability.
- Digital twin (functionalities simulation).
- Auto-configuration of a distributed set of resources to satisfy the application requirements (functional and non-functional).
- Standardize flow for HW/SW qualification of generic set of functions (including re-training) which are used in a downgraded application/use case.
- Integration and orchestration of multiple computing paradigms into AI-based embedded systems.
- Certifiable and explainable AI.
- Next generation computing (Heat death, dark silicon, dark data, etc.), new computing devices (photons, spins, etc.), using physics to make computation.

4.3.6 Connectivity

Connectivity is today a key enabler to support the development of innovative applications in several markets, such as consumer, automotive, digital manufacturing, network infrastructure (to name a few). This is also pushed by the need of being connected anywhere+anyhow+anytime. The availability of innovative connectivity technologies, both wireless (e.g., low-power wide area networks (LPWAN), cellular (5/6G)) and wired (e.g., new bus-oriented communication protocols), will enable and enhance a wide range of new business opportunities for the European industry in the context of Systems of Systems (SoS), Cyber-Physical Systems (CPS), and Internet of Things (IoT). Long-term roadmaps for connectivity and interoperability will guide a seamless integration of heterogeneous technologies (hardware and software) for the design and implementation of complex connected systems in effective ways.

Connectivity is a critical asset to any digitalisation and automation activity to strengthen Europe's position and enable European industry to capture new business opportunities associated with the connected world we live in. It is vital to support European technological leadership in connectivity, fostering digitization based on Internet of Things (IoT) and System of Systems (SoS) technologies; for example, this can be achieved by being at the forefront of new standard development for the current 5G initiative, the emerging SoS market, and the upcoming 6G initiative. Furthermore, in order to bring added value and differentiation with respect to US and Asian competitors, European industry has to secure access to any innovative software and hardware technology that enables the efficient engineering of large and complex SoS (which will help to

capture more value by targeting higher-end or more innovative applications, as highlighted by the Advancy report[204]). For instance, connectivity (e.g., in terms of wireless infrastructure market lead by Ericsson and Nokia) will be supported by the leading European leadership position in the traditional IT environments as well as the embedded segments, guaranteed by companies such as STMicroelectronics, Infineon and NXP. Connectivity from device, over the edge, and to the cloud will need to be virtualized, relying on run-time design, deployment, and management of integrated edge and cloud network architectures. This will enable the connectivity from cloud to far edge, shifting the perspective from point-to-point connectivity to application-to-application connectivity.

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

Connectivity will provide the basis for a data layer supporting instant and seamless data and information exchange between producers (supply below the data layer) and consumers (demand above the data layer) within and between domains. This layer will enable large-scale integration of SoS, CPS and IoT solutions. Targeting systems and applications, we should consider the interconnection between sub-systems and focus on individual component technology development, according to needs identified at system or application level. To support this system vision, the promotion of innovative technology enabling heterogeneous integration is key. In order to fully leverage this heterogeneous integration at hardware level, software interoperability is a parallel challenge to provide connectivity that will allow for SoS integration. Thus, an alternative major challenge is to enable SoS integration through nearly lossless interoperability across protocols, encodings and semantics. To do so, dedicated software tools, reference architecture and standardisation are key to supporting SoS integration, thus enabling the provision of a scalable and evolvable SoS. As it remains very difficult to assume that highly customised embedded systems will be built based on a single, unified, high-level modelling principle and toolset, there is a quest for consolidation, or even the standardisation of basic runtime frameworks, component libraries and subsystem interfaces that will ease the deployment of interoperable components into generic, domain-specific solutions and architectural frameworks in a bottom-up fashion. Such an approach is also expected to provide for better traceability of requirement validation, and formal verification of distributed system compositions and their emerging functional and non-functional properties.

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

204 Advancy, 2019: Embedded Intelligence: Trends and Challenges, A study by Advancy, commissioned by ARTEMIS Industry Association. March 2019. Available online at: https://artemis-ia.eu/publication/download/advancy-report.pdf.

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

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

4.3.7 Architecture and design: methods and tools

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

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

To realize this vision and associated goals, the European effort needs to extend existing and develop new processes and methods that cover the whole lifecycle of products, from initial requirements elicitation through design, integration, verification, validation, test, certification, production to commissioning, operation, maintenance, and decommissioning. These processes and methods need to support data collection from production as well as from operation and maintenance in order to be analyzed and used for continued development and integration, updates in the field, validation, verification and test at the development phase as well as in the field at run-time.

Novel architectures and development and analysis tools need to be developed which will enable:

- Seamless design, development, integration, verification, validation and test across all layers of the technology stack, from semiconductor up to systems of systems. These methods need to address individual ECS-based systems, (groups of systems that form and dissolve statically or dynamically as well as systems that cooperate with other systems and with humans, at the cloud or at the edge. Furthermore, methods and tools need to support open platforms and integration of open systems.
- Verification, validation and test of highly automated and autonomous systems, especially coping with open-world assumption and uncertainty.
- System development that includes AI methods, such as explainable and trusted AI.
- The use of AI based methods in the design and development process, for example design space exploration and analysis, including certified products.

- Managing the increasing functionality, connectivity, and complexity of systems.
- Managing the increased diversity of tools, such as modeling and description languages and simulation and testing tools, in emerging components, modules, and systems.

4.3.8 Quality, reliability, safety and cybersecurity

Quality, reliability, safety and cybersecurity are fundamental components of any innovation in the digital economy. Especially in Europe these characteristics are particularly important since European products are well known to be of high quality in almost every aspect. They are driven by high expectation of the European society demanding these features. Continuous evolution of our European society is driven by the development of electronic components and systems (ECS). By having now a mobile phone in our hands we can buy a flight ticket, make a money transfer or keep social contacts. Even more services are available. ECS simply promises to make our lives more comfortable, safe and efficient but this promise relies on user trust and acceptance concerning the perception of sufficient privacy, security, understandability, and usefulness in their daily lives. In the near future, highly automated and autonomous systems supported by AI will have a constant growing trend. We expect that in the next ten years such systems will be increasingly deployed not only in controlled environments, such as in manufacturing industries, but massively spread in our personal, professional, and social spheres.

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

In order to keep European leadership in electronic devices and systems we have to keep our effort to provide to our customers innovative products of the well-known high quality, reliability, safety and cybersecurity. From this perspective we expected the following challenges to be considered in a long term:

- Development and integration of new materials for advanced packaging and interfaces, new characterization techniques, and new failure modes caused by new use-case scenarios.
- AI/ML methods incl. digital twin to be a cornerstone of keep leadership regarding quality and reliability of ECS made in Europe and be an enabler for new data-driven business models.
- Model based engineering (incl. standardization of data management and processing) to be a key instrument for virtual release of ECS through the supply chain and shortening time to market.
- Assuring user trust and acceptance of ECS through early inclusion of user requirements, explainability-by-design, and user education and training.
- Model based engineering (incl. standardization of data management and processing) to be a key instrument for virtual pre-qualification of ECS and shortening time to market.
- Data transmission methods and protocols that are so reliable that they can be used to transmit life-sustaining information over long distances (e.g. for robotic surgery).
- Reliable and certified software that can be kept even if the underlying hardware or hardware architecture is changed incl. potential influence of SW updates on HW reliability.
- Software that can adapt to a degrading underlying hardware to achieve a long-lasting and reliable HW/SW combination.
- Liability of trusted AI-driven systems (it is based on trustworthiness of (AI-driven) systems, included safety and certification of AI-driven CPS, which is a main challenge in 2021).
- Safely manage /design for human interactions in complex systems, SoS and application scenarios

- Ensuring sustainability, cybersecurity, safety and privacy, for AI-driven and quantum-based systems (based on “ensuring safety, security and privacy and sustainability of (AI-driven) systems”).
- The attention to the environment and privacy have increased significantly in the population. This implies that conceive any safety solutions is not enough. Our vision in 2030 is an integration between disciplines, which have nothing to do with safety or computer science in scricto sensu, such as privacy, social trust, liability and sustainability.

4.4 APPLICATION EVOLUTION AND LONG-TERM CHALLENGES

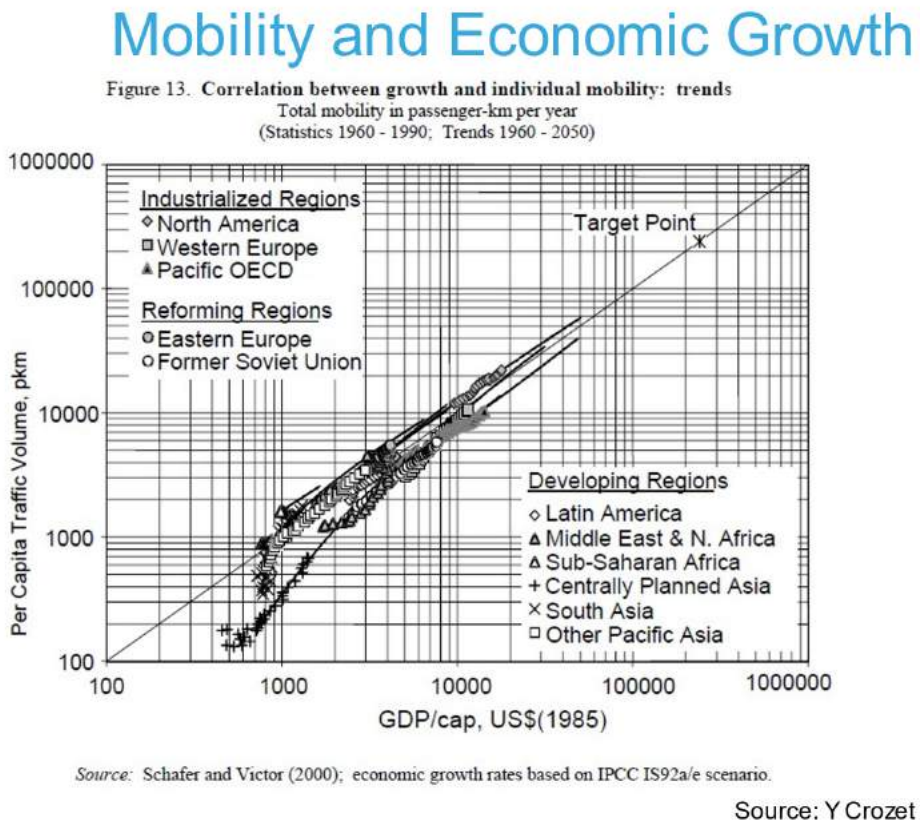
4.4.1 Mobility

The European Union has issued ambitious policy statements regarding transport and smart mobility:

- Emissions from transport could be reduced to more than 60% below 1990 levels by 2050.
- The EU has adopted the Vision Zero and Safe System approach, to eliminate deaths and serious injuries on European roads.
- Sustainable Mobility for Europe: safe, connected, and clean.

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

Until now, the rule was simple: more income equals more travel distance as *Figure F.92* indicates. Will this very simple equation still work in the future?



The correlation between growth and individual mobility

F.92

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

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

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

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

Today's vehicles contain more software than any other embedded system and most compute applications. Tomorrow's vehicles will multiply the software lines of code by a factor 6. Semiconductor value in the car more than doubles through the next 10 years (from 100$ to 1200$). Some already talk about "software-enabled vehicles" or "data-centers on wheels". Besides the electronics and software to get the car rolling, there will also be a lot of complexity added in terms of performing safety & security checks and to monitor the health or lifetime of electronic components and batteries. Overall, the evolution of the car and mobility in general results in the rise of complexity in electronics and software that has almost become uncontrollable.

Additionally, the growing global population as well as the aging society will be supported by more and more automated transport means at all mobility variants taking the best advantage of the available resources as roads, parking space, airspace, waterspace and serving best the needs for mobility of the society. This will be supported by sensors combining different sensor principles in one sensor with significantly less power consumption as well as new AI optimized edge computers in the transport vehicles. These systems will be part of completely new HW/SW systems spanning from sensors via embedded edge computers via predictable, fast, clean (also for the user), safe, secure and failsafe communication to globally interconnected cloud systems.

4.4.2 Energy

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

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

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

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

- New, highly efficient power devices based on wide band gap semiconductor mate-rials such as SiC and GaN-on-silicon, and possibly Ga2O3, AlN, diamond, diamond-on-silicon or nanowire-based materials.
- New, cost-efficient, Si-based power devices to enable high efficiencies for mass-market applications such as super-junction MOSFETs.
- Power management for very low power applications as required for IoT, including the development of energy harvesting technologies, covering the full range from GW to µW levels.
- High temperature-capable packages serving new materials and 3D technologies that offer the highest requirements and integration capabilities.

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

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

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

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

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

4.4.3 Digital industry

Digital Industry is a must of European productive and commercial evolution on the next decade, following and empowering the EU policy related to Digitalisation. Digital Capabilities and functions will be the enabler

for safer, greener, sustainable, lower cost and more productive, autonomous and competitive EU industrial ecosystem.

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

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

The manufacturing industry can essentially be classified into two main categories: process industry and discrete product manufacturing. The process industry transforms material resources (raw materials, feedstock) during a (typical) (semi)continuous conversion into a new material that has significantly different physical and chemical 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, lifecycle engineering, human-system integration etc. ECS technologies are essential parts of most of the advances in these domains.

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

- The SPIRE[205] Roadmap 2030 and the SPIRE Vision 2050, which lists the following targets.
- Replacement of fossil-based materials by bio-based materials requiring completely new processes.
- Re-use of waste streams that require complete redesign of materials, products and related production processes.
- New resource efficient applications that require completely new designed processes.
- Complete redesign of industrial parks to realise industrial symbiosis.
- The Factories of the Future (EFFRA[206]) roadmap summarises its vision as follows:
  - Agile value networks: lot-size one – distributed manufacturing.
  - Excellence in manufacturing: advanced manufacturing processes and services for zero-defect and innovative processes and products.
  - The human factor: developing human competences in synergy with technological progress.
  - Sustainable value networks: manufacturing driving the circular economy.
  - Interoperable digital manufacturing platforms: supporting an eco-system of manufacturing services.

205 *https://www.spire2030.eu/what/walking-the-spire-roadmap/spire-Roadmap*

206 *https://www.effra.eu/factories-future-roadmap*

- The Connected Factories[207] project forecasts the emergence of new manufacturing concepts, such as:
  - Hyperconnected factories.
  - Autonomous factories.
  - Collaborative product-service factories.

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

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

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

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

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

207 https://www.effra.eu/connectedfactories

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

4.4.4 Health and wellbeing

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

ECS will keep on being key enablers to 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 aging population.

Going beyond 2028, personalised and patient tailored healthcare will be at the forefront of technology advancement. Further miniaturisation of biomedical devices and integration of smart integrated systems (e.g. smart catheters, electroceuticals) will have significant impact on point of care diagnosis and treatment. Real time localised detection of disease and minimally invasive targeted drug delivery will be a key priority. Achieving enhanced reliability and building stakeholder confidence in these technology advancements will be key to successful implementation. Data integrity and security around the use and storage of personal information will require new methods of application development and a robust system of operation, especially if moving towards a more connected healthcare approach with more focus on tailored patient diagnosis and treatment.

Beyond those technological challenges including aspects such as reliability, safety and privacy issues in terms of regulation and uptake by practitioners, especially when dealing with procurement policies, have to be tackled. A priority will be in bringing these stakeholders closer in the involvement phase of developing key enabling technologies (KETs) for healthcare applications with a customer pull and technology push approach.

Improvements in medicine over the ages greatly benefited from advancements in other disciplines. Medicine evolved over time from a "mechanical" medicine (surgery) toward "chemistry" medicine and more recently biotech medicine. Nowadays, the development in ICT and digitization has an important impact 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 include, for instance, human models also known as the "digital twin". Here, ECS will have a crucial role in ensuring the necessary link between the digital and the real twins. Real time acquisition and processing of data and vital parameters collected from on-body IoT sensors, is a key technology that will advance existing wearables and will enable identification and prediction of a person's condition. The use of AI technologies, based on extended measurement data, will enable significant advances in this area.

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

Some additional developments are presented described in the following:

- Fully personalised medicine will be enabled by smart monitoring of health parameters, including factors from the molecular to the environmental levels. Developments in healthcare will benefit from the concept of "digital twins" and so that prediction of health evolution and preventive treatment will become reality and standard procedures. Fully personalised and accurate health data will be available anywhere, anytime.
- Drug development will be assisted by emerging methodologies such as 'organ-on-chip'.
- 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.

These innovations in the medical domain can be accelerated by the creation of an ECS-based technology platform for medical applications. A list of emerging medical domains where further technical developments are required has been compiled by the Health.E Lighthouse[208] initiative:

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

Despite this urgent need and the enormous resources that are being invested in research, true innovation in terms of products reaching the market has been slow. One of the root causes identified is the lack of open technology platforms. This will release the power of Moore's Law that has been the driving force in electronics for more than fifty years, to the healthcare domain: "Moore for Medical". It is the vision of

208 https://www.health-lighthouse.eu/emerging-medical-domains

the Health.E Lighthouse that innovation can be accelerated by stimulating the development of truly open technology platforms.

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

4.4.5 Agrifood and natural resources

Over the following decades the global population will increase, rising to an estimated peak of 9.78 billion by 2064. By the middle of the century, about two-thirds of the population will live in urban areas. This will require new digital approaches to supply the growing number of people with food, which will involve a great threat to food security for certain countries and especially for large cities. Digitalisation has already helped initiate open field farming through precision agriculture, but there are other ways of targeting this issue, especially by the emerging areas of "digital farming" and "vertical farming". In this form of farming, plants are grown in vertical arrays, inside buildings, where growing conditions can be optimised. Crops are supplied with nutrients via a monitored system under artificial lighting and can thus be grown year-round. This method makes it possible to grow plants without soil and natural sunlight, with optimal growth conditions being created artificially. The full potential of this approach can only be achieved with the help of information technology (IT) and IoT components and paradigms such as AI and Industry 4.0, which all still need to be adopted for this purpose. With these digital farming approaches, it will be possible to secure food supply autonomy and food safety for large parts of the EU. Furthermore, investigation into the provision of corresponding technologies and approaches will enhance the strategic autonomy of Europe.

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

4.4.5.4.1 From Farm to Fork

European food is already a global standard for food that is safe, plentiful, nutritious and of high quality. Now European food should also become the global standard for sustainability. EU agriculture, the manufacturing, processing, retailing, packaging and transportation of food make a major contribution to air, soil and water pollution and GHG emissions, and has a profound impact on biodiversity. As such, food systems remain one of the key drivers of climate change and environmental degradation. For this reason, the From Farm to Fork action targets to reduce dependency on pesticides and antimicrobials, reduce excess fertilisation, increase organic farming, improve animal welfare, and reverse biodiversity loss.

4.4.5.4.2 Biodiversity Strategy for 2030

Biodiversity is also crucial for safeguarding EU and global food security. Biodiversity loss threatens our food systems[209], putting our food security and nutrition at risk. Biodiversity also underpins healthy and nutritious

209 World Economic Forum (2020), The Global Risks Report 2020.

diets and improves rural livelihoods and agricultural productivity[210]. For instance, more than 75% of global food crop types rely on animal pollination.

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

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

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

210 Food and Agriculture Organization (2019), State of the World's Biodiversity for Food and Agriculture (http://www.fao.org/state-of-biodiversity-for-food-agriculture/en/)

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

4.4.6 Digital society

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

Furthermore, the trend of combining of working at the office and from home (or other remote locations), which has been triggered by the Covid-19 pandemic, will continue, and people will endeavour to combine work and private life in other ways.

Digital infrastructures with increased quality of service (QoS) and available bandwidth, will support these trends and will be ubiquitous, both in rural areas as well as in cities. These networks will be open and secure, and also support intelligent control management of critical infrastructures (e.g. water supply, street lighting, traffic). Edge/cloud solutions will arise which will enable increased multimodal situational awareness and ubiquitous localization

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

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

4.5 CONCLUSIONS

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

In this Chapter, we have presented research and innovation directions for ECS in the long-term, considering the European priorities, such as the Green Deal, and the main objectives of the European ECS community. Considering the interdependence of emerging technologies, application domains and policies that drive innovation, and taking into account the corresponding trends of European industry in the next few years, we identified long-term challenges for technologies and applications, to provide direction for the community to meet the expected needs of the future. Clearly, the list of challenges and directions that we provide is neither complete or restricting. Innovation is a continuous process that adapts to new technological capabilities - as they progress - application needs and, even, new application domains that are not foreseen. However, the current review indicates a clear path to establishing European leadership considering current trends and constraints.

Strategic Research and Innovation Agenda 2022

APPENDIX

GLOSSARY

INTRODUCTION

The scope of the ECS SRIA is very broad and spans many disciplines, each of which has developed a specific understanding of some of the terms used in this report. As a result, the same term can have different meanings for specialists in different ECS domains. This glossary defines some of those terms in an exclusive way to ensure there are no inconsistencies across the various chapters. Although there may be readers that feel uncomfortable with a few of the definitions provided here if they differ from what they commonly mean in their own areas, we feel that developing a common language is important in building a strong and integrated ECS community.

SRIA DEFINITIONS

3D integration: a vertical stack of circuitry or integrated circuits (ICs) for meeting electronic device requirements such as higher performance, increased functionality, lower power consumption, and a smaller footprint. In general, 3D integration is a broad term that includes technologies such as: 3D wafer-level packaging; 2.5D and 3D interposer-based integration; 3D stacked ICs (3D-SICs), monolithic 3D ICs; 3D heterogeneous integration; and 3D systems integration.

3D printing: also known as additive manufacturing, this is the construction of a three-dimensional object from a computer-aided design (CAD) model or digital 3D model. The term "3D printing" can refer to a variety of processes in which materials are deposited, joined or solidified under computer control to create a three-dimensional object, with typically the materials (such as liquid molecules or powder grains being fused together) being added on a layer-by-layer basis.

5G: fifth-generation wireless (5G) is the latest iteration of cellular technology, engineered to greatly increase the speed and responsiveness of wireless networks. With 5G, data transmitted over wireless broadband connections can travel at multi-gigabit speeds, with potential peak speeds as high as 20 gigabits per second (Gbps) by some estimates. These speeds exceed wireline network speeds and offer latency of 1 millisecond (ms) or lower, which is useful for applications that require real-time feedback. 5G will enable a sharp increase in the amount of data transmitted over wireless systems due to more available bandwidth and advanced antenna technology. 5G networks and services will be deployed in stages over the next few years to accommodate the increasing reliance on mobile and internet-enabled devices. Overall, 5G is expected to generate a variety of new applications, uses and business cases as the technology is rolled out.

Ambient Assisted Living (AAL): information and communication-based products and services that integrate modern technologies (sensors, microcontrollers, connectivity, secure elements, Artificial Intelligence, etc) into the homes and lives of disabled persons, and vulnerable or older adults. These technologies aim to improve the lives of those facing some of the challenges of ageing, and those who care for older people if they need help. An impact of AAL is also in reducing the costs of health and social care.

Artificial Intelligence (AI): the theory and development of information processing systems able to perform tasks usually requiring human intelligence (such as visual perception, speech recognition, decision-making, and translation between languages) with a certain degree of autonomy.

Augmented reality (AR): an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.

Autonomous system (AS): performs desired tasks in unstructured environments without continuous human guidance.

Biologic drugs: products that are produced from living organisms or contain components of living organisms. Biologic drugs include a wide variety of products derived from human, animal or microorganisms by using biotechnology. Types of biologic drugs include vaccines, blood, blood components, cells, allergens, genes, tissues and recombinant proteins.

Blockchain: decentralised, chronologically updated database with a consensus mechanism created from a network for the permanent digital securitisation of property rights.

Brain–computer interface (BCI): a direct communication interface between a (biological) brain and a technical (IT- and/or ECS-based) system. A BCI can transfer information in both directions – e.g. enabling the brain to control the technical system or enhancing human perception (such as hearing) with additional information from the technical system (e.g. hearing aid).

Care pathway: the sequence of health and care services a patient receives after entering the care system during an episode of care.

Cath lab: examination room in a hospital or clinic with diagnostic imaging equipment used to visualise the arteries of the heart and the chambers of the heart.

Cloud: the on-demand availability of computer system resources, especially data storage (cloud storage) and computing power, without direct active management by the user. The term is generally used to describe data centres available to many users over the internet (from Wikipedia).

Component: a combination of devices and other elements (such as passives) that fulfil a specific need, such as transduction of a single physical parameter within a well-specified case. A component is not self-contained in all its functions, as it requires the close support of other components for operation (e.g. in data processing, power handling, embedded software).

Computer-aided design (CAD): the use of computers (or workstations) to aid in the creation, modification, analysis or optimisation of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

Contract-based design: a design methodology where the system, itself as well as its constituents (subsystems, components, modules, etc), are described by contracts that are formalised by specifications of their functional behaviour and properties. This is often given in a "assume-guarantee" format (e.g. for a certain software module a contract could be: "If the other components of the system guarantee the availability of input data at certain, well-defined times and if the hardware platform on which this module is running guarantees the availability of certain processing and memory resources (assumptions), then (guarantee) this module will produce its output within a certain, guaranteed time interval"). In this methodology, a designed system is

"correct" if (informally): (i) all assumptions of all constituents are met by guarantees of other constituents; and (ii) the contracts of all constituents together imply the contract of the complete system.

Coopetition: a neologism for the act of cooperating and competing at the same time. Companies that compete in the market with their products might still cooperate on topics that are either pre-competitive or non-product differentiating. Typical examples here are interoperability, standards and development processes.

Cyber-physical system (CPS): an ECS in which a physical artefact is controlled or monitored by algorithms. A CPS is the result of tight intertwined hardware and software components capable of creating a link between the physical world and the digital world, to operate on different spatial and temporal scales, exhibit multiple and distinct behavioural modalities, and interact with each other in ways that depend on the context. Examples of CPS include smart grid, autonomous automobile systems, medical monitoring, industrial control systems, robotics systems and automatic pilot avionics.

Cybersecurity: the protection of information against unauthorised disclosure, transfer, modification or destruction, whether accidental or intentional (IEC 62351-2).

Deep edge: the farthest extreme node where subsystems (sensors, actuators, data loggers) interface with the real world. This node is connected to the cloud, but the connection can be intermittent or absent for long periods of time. The emergence of "tiny machine learning" is based on this premise to enable AI in performance-constrained environments (ultra-low power, limited memory size and calculation power), but always very close to the subsystem.

Deep learning (DL): a special form of machine learning based on artificial neural networks, DL is where the system is able to automatically discover the representations needed for feature detection or classification from raw data. The adjective "deep" in deep learning comes from the use of multiple layers in the network (from Wikipedia).

Deeply embedded software: software that runs on dedicated hardware and not on standard microprocessors. In its simplest form, it is called "firmware".

Dependability: according to IEC 60050-192:2015, dependability (192-01-22) is the ability of an item to perform as and when required. An item here can be a device, component, module or system. Dependability includes availability (192-01-23), reliability (192-01-24), recoverability (192-01-25), maintainability (192-01-27) and maintenance support performance (192-01-29), and in some cases other characteristics, such as durability (192-01-21), safety and security. A more extensive description of dependability is available from the IEC technical committee on dependability (IEC TC 56).

Development or design tools, development or design frameworks, design flow: design tools are software tools supporting engineers with different tasks during system designs. Ideally, these tools are integrated into frameworks that: (i) provide a uniform user interface to all tools; (ii) "sort" the tools according to the different steps in the design process; and (iii) ensure interoperability between the integrated tools. Regardless of whether the tools used are integrated into a framework or not, the order in which the tools are used is called the "design flow".

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

Digital infrastructure: foundational services necessary to the IT capabilities of a nation, region, city or organisation.

Digital twin: a digital replica of a living or non-living physical entity. Digital twin refers to a digital replica of potential and actual physical assets, processes, people, places, systems and devices that can be used for various purposes. The digital representation provides both the elements and the dynamics of how the physical entity operates and "lives" throughout its lifecycle. To be useful in systems engineering, digital twins need to be executable (i.e. engineers must be able to use them in simulations as representatives of the actual physical entity) and/or amendable to formal analysis methods. The more aspects of the physical entity are represented in a digital twin, the more useful it becomes.

Divide and conquer strategy: a strategy in systems engineering where a large problem (i.e. designing and building a complex system or even System of Systems) is iteratively broken down ("divided") into smaller problems (i.e. designing subsystems, modules and components), which are then divided further or solved ("conquered"). The results of each step are then integrated into a solution for the next-level larger problem. Divide and conquer typically leads to hierarchical designs; it is also a strategy well suited for distributed developments within supply chains and platform economies.

Edge computing: a computing paradigm where computation and data storage are close to the location where they are needed, to improve response times, save bandwidth and increase independence. It can also include the gateway between deep edge devices and other edge devices (organised in a federation of devices, see fog computing), or with the cloud (modified from Wikipedia).

Embedded (or edge) high-performance computing: provides supercomputing processing performance in rugged, compact and easily deployable computing architectures optimised to work in harsh environments in the field. Bringing high-performance computing capabilities from data centres to field-deployable applications means reducing space, weight and power absorption, increasing resistance, robustness and reliability while maintaining the same advanced computational performance and energy efficiency. Embedded (or edge) high-performance computing is an enabling technology for many vertical domains, such as autonomous driving, UAV, and security and surveillance systems.

Embedded software: the software that runs on embedded and cyber-physical systems, providing the low-level functionalities required to use the available hardware resources, dedicated operating systems, run-time environments, virtualisation and containerisation platforms, application software, micro-services, etc. Embedded software is specifically conceived to optimally exploit the limited hardware resources of embedded and cyber-physical systems. For deeply embedded software, see the separate definition.

Embedded system: an ECS generated from the combination of a microprocessor(s), GPUs or system on a chip, memory, input/output peripheral devices and embedded software that have a dedicated function within a larger mechanical or electrical system.

Extended reality (XR): refers to all real and virtual combined environments and human–machine interactions generated by computer technology and wearables, where the "X" represents a variable for any current or future spatial computing technologies.

Fog computing: an architecture that uses edge devices to carry out a substantial amount of computation, storage and communication locally, and routed over the internet backbone (from Wikipedia).

Functional safety: the ability of a system or piece of equipment to control recognised hazards to achieve an acceptable level of risk – such as maintaining the required minimum of operation even in case of likely operator errors, hardware failures and environmental changes – to prevent physical injuries or damages to the health of people, either directly or indirectly.

Prosthetics: the branch of medicine or surgery that deals with the production and application of artificial body parts.

Healthcare: the preservation of mental and physical health by preventing or treating illness through services offered by the health profession.

Heterogeneous integration: refers to the integration of separately manufactured components into a higher-level assembly (system in a package) that, in the aggregate, provides enhanced functionality and improved operating characteristics. In this definition, components should be taken to mean any unit, whether individual die, MEMS device, passive component or assembled package or subsystem, that are integrated into a single package. The operating characteristics should also be taken in its broadest meaning to include characteristics such as system-level performance and cost of ownership (from ITRS Assembly & Packaging chapter).

Industry 4.0: the application of technology to digitally transform how industrial companies operate. These technologies include the industrial Internet of Things (IoT), automation and robotics, simulation, additive manufacturing, and analytics. Industry 4.0 is driven by a need to boost efficiency, become more agile to respond to market unpredictability, improve quality, and to enable new business models.

In silico clinical trials: in silico means performed on a computer or via computer simulation. The term characterises biological experiments carried out entirely on a computer. Although in silico studies represent a relatively new avenue of inquiry, they have begun to be used widely in studies that predict how drugs will interact with the body and with pathogens.

In vitro diagnostics: the technique of performing a given procedure in a controlled environment outside of a living organism. Many experiments in cellular biology are conducted outside of organisms or cells. One of the abiding weaknesses of in vitro experiments is that they fail to replicate the precise cellular conditions of an organism, particularly a microbe.

In vivo clinical trials: experimentation using a whole living organism as opposed to a partial or dead organism. Animal studies and clinical trials are two forms of in vivo research. In vivo testing is often employed over in vitro because it is better suited for observing the overall effects of an experiment on a living subject. Integrated practice unit: Involves a shift from the current siloed organisation by specialty department and discrete service to being organised around the patient's medical condition. Care is delivered by a dedicated multidisciplinary team of clinicians who take responsibility for the full cycle of care for the condition, encompassing outpatient, inpatient, and rehabilitative care, and supporting services (e.g. nutrition, social

work, behavioural health). The team measures processes and outcomes as a team not individually, and accepts joint accountability for outcomes and costs.

Integrated circuit: an electronic circuit formed on a small piece of semiconducting material, performing the same function as a larger circuit made from electronic building blocks.

Integration platform: an ECS allowing the integration of different systems, applications and services into a single system. They can be found on all layers of the design hierarchy, ranging from "communication backplanes" in hardware design to "reference architectures" and "middlewares" in system engineering, to distributed service platforms in System of Systems. Integration platforms are an important basis for: (i) standardisation; and (ii) platform-based economies.

Internet of Things (IoT): the set of technologies that bring intelligence to objects, enabling them to communicate with other objects or with other devices. IoT describes the network of physical objects – "things" – that perform functions. For example, with these technologies, billions of sensors embedded in everyday devices can be designed to record, process, store and transfer data, and to interact with other devices or systems that use the network's capabilities.

Interoperability: the capability of computing systems to exchange information that can be understood and used by the receiving system.

Key digital technologies: electronic and photonic components, and the software that defines how they work. These technologies underpin all digital systems, including Artificial Intelligence and the Internet of Things.

Lab-on-a-chip (LOC): a miniaturised device that integrates one or several biological or chemical analysis functions on a single chip (e.g. detecting specific proteins).

Large-area electronics (LAE): electronics fabricated utilising printing and roll-to-roll fabrication methods that, as opposed to integrated circuit technologies, can be used on significantly larger substrates. Inorganic and organic inks and pastes are used for printing conductors and active components such as transistors. Substrates in LAE are typically flexible, such as plastic films or paper, giving rise to the term "flexible electronics".

Machine learning: ability for a machine to learn by example without being explicitly programmed to perform the target function. This is one method for implementing Artificial Intelligence.

MEMS, MOEMS, NEMS, MNS, MNBS: micro-electromechanical systems (MEMS) originally referred to miniaturised devices that provided a precise mechanical output (typically a small vertical, horizontal, or rotary displacement) upon an electric excitation (e.g. a microrelay), or vice versa, or an electronic signal from a mechanical excitation (e.g. a microaccelerometer or gyroscope). When the objective of such displacement was to interact with light (e.g. a micromirror), the term "micro-opto-electromechanical systems (MOEMS) was used. Gradually, the transduction domain was extended beyond the mechanical one and chemical and biological mediation were also considered. The overall size of MEMS devices could be in the mm or cm range, the term "micro" referring to the dimension of the device's internal features to be mastered for the device to be functional. The term "nanoelectromechanical systems" (NEMS) is used when such critical dimension falls back into the nano domain. The terms "microsystem", "micro-nanosystem" (MNS), or "micro-nano-bio system" (MNBS) were alternatively introduced for those small devices amenable to such generalised

transduction principles. This kind of device could be fabricated in principle with different materials, but silicon technologies provided a micromachinable material and a miniaturised technology responsive to the integration of the electronic signal to be conveyed or transduced. MEMS, MOEMS, NEMS, MNS and MNBS are very successful means of interaction between the physical and digital worlds, providing information systems with the means to interact with their environment, sensing it, actuating on it or being powered by it.

Model-based design: where design artefacts (the system, subsystems, component, modules, as well as their connections and the environments in which they will be used), are represented by models that are abstract descriptions of certain aspects of such artefacts (typically, their functional behaviour, timing properties, etc). Ideally, these models are: (i) executable, thus usable in simulation and early verification and validation (V&V); and (ii) detailed enough to be usable in formal analysis and test methods.

Module: ensemble of properly integrated components so that their reunion embodies a definite functionality required for the proper working of a system (e.g. sensing and actuation module, control module, communication module, energy provision module). A module is self-contained in hardware and software, making it interchangeable between systems, and allowing higher abstraction level in systems design.

Molecular biology: study of phenomena in terms of biology molecular (or chemical) interactions. Molecular biology emphasises chemical interactions involved in the replication of DNA, its "transcription": into RNA, and its "translation" into or expression in protein – that is, in the chemical reactions connecting genotype and phenotype.

Open source hardware: the blueprint of hardware artefacts that is (partially) freely available and which anyone can use, modify or enhance (depending on different licences associated with the blueprint).

Open source software: software with source code that is (partially) freely available and which anyone can use, modify or enhance (depending on different open source licensing models existing).

Operational design domain (ODD): comprises the "operating conditions under which a given [...] system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain [environmental] characteristics" (Surface Vehicle Recommended Practice — Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE: J3016, 2018).

Optical coherence tomography (OCT): a non-invasive imaging test that uses light waves to take cross-section pictures of the retina to help with diagnosis. They also provide treatment guidance for glaucoma and diseases of the retina such as age-related macular degeneration (AMD) and diabetic eye disease.

P4 medicine: a shift in medicine from a reactive to a proactive discipline that is focused on predictive, personalised, preventive and participatory (P4). P4 medicine will be driven by system approaches to disease, emerging technologies and analytical tools.

Patient-generated health data (PGHD): health-related data created, recorded or gathered by or from patients (or family members or other caregivers) to help address a health concern.

Personalised medicine: tailoring of medical treatment for patient cohorts to be treated in a unique manner depending on their health status and previous course of a disease and analysis of personal characteristics.

Plug and play components: component with a specification that facilitates the discovery of a hardware component in a system without the need for physical device configuration or user intervention in resolving resource conflicts.

Point of care: the location at which patient services are delivered (excluding hospital, doctor's office, patient's home).

Point-of-care testing (POCT or bedside testing): performance of clinical laboratory testing at the site of patient care rather than in a laboratory, often by non-laboratorians.

Point of need: new model of having critical data and information when and where it is needed rather than at the point of care. These are diagnostics that can be done anytime, anywhere, for anyone – for instance, as a vital part of managing a chronic disease over time, resulting in improved treatment and patient outcomes.

Predictive maintenance: techniques designed to help determine the condition of in-service equipment to estimate when maintenance should be performed.

Product lifecycle management (PLM): process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products.

Prognostics (a.k.a. health management): a method that permits the assessment of the reliability of the product (or system) under its application conditions. It predicts the occurrence of an event based on current and future operational and environmental conditions to estimate the time at which a system no longer fulfils its function within desired specifications ("remaining useful life").

Prosthetics: the branch of medicine or surgery that deals with the production and application of artificial body parts.

Quality: in this SRIA, quality is defined as "the degree to which a product meets requirements in specifications that regulate how the product should be designed and manufactured, including environmental stress screening (burn-in) but no other type of testing". In this way, reliability, dependability and cybersecurity, which some readers may have expected to be included under quality, will be treated separately.

Quantum computing: an area of computing focused on developing computer technology based on the principles of quantum theory, which explains the behaviour of energy and material on the atomic and sub-atomic levels. A quantum computer utilises quantum entanglement between qubits to solve a set of computationally complex problems efficiently. The computational power of quantum computers is estimated to grow faster than classical computers in the future.

Quantum sensing: sensor technologies that make use of quantum technology.

Quantum technology: the creation, manipulation and detection of single particle quantum states accurately, enabling the use of quantum superposition and entanglement, where quantum states of several particles cannot be described independently, even when spatially separated. Currently, quantum effects typically require very low temperatures and the use of cryogenic technologies.

Recommender-based (methods and) tools: methods and tools in which the current status of a system under design is analysed and evaluated by design-supporting software, which then gives recommendations to the engineer as to possible further steps and/or options for completing the design, ideally together with an evaluation of the pros and cons for each option.

Reliability: the ability or probability, respectively, of a system or component to function as specified under stated conditions for a specified time (ISO 25010).

Safety (a.k.a. functional safety): freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or the environment (IEC 61508).

Security of ECS (a.k.a. IT security/cybersecurity): in this SRIA, security of ECS is defined as the prevention of illegal or unwanted penetration, intentional or unintentional interference with the proper and intended operation, or inappropriate access to confidential information. Security is considered to be composed of confidentiality, integrity and availability (ISO 21549-2).

Self-X: in self-X, X stands for adaptation, reconfiguration, etc. Usually in self-reorganising systems the major issue is how to self-reorganise while preserving the key parameters of a system, while being coherent with the initial requirements (e.g. performance, power consumption, real time constraints). Self-adaptation and self-reconfiguration has an enormous potential in many applications.

Smart city: an urban area that uses different types of electronic methods and sensors to collect data. Insights gained from that data are used to manage assets, resources and services efficiently; in return, that data is used improve the operations across the city (from Wikipedia).

Smart drug delivery system (SDDS): an advanced method of drug-targeted (DT) delivery. The smart drug delivered by this system must fulfill the following criteria: (i) increase the doses of delivered drug to the targeted body part of interest (tissue/cells/organs); (ii) not be degraded by any of the body fluids; (iii) diminish side effects by improving the efficacy of drug treatment; (iv) absorption of the delivered drug must cross a biological membrane; and (v) drug is released in appropriate dosages to the body part of interest. SDDS is highly complex and involves an integration of various disciplines, such as biology, chemistry and engineering.

Smart systems integration (SSI): (integrated) smart systems incorporate sensing, actuation and control up to cognitive functions to describe and analyse a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. The enabling principles of these functions include nanoelectronics, micro-electromechanics, magnetism, photonics, chemistry and radiation. SSI is an assembly of technologies that: build products from components; combine functions in products and systems; connect and network systems to other systems; and, importantly, enable systems to receive and store a “knowledge base” – the software that makes them “smart”.

System: for the purpose of this SRIA, a system is a set of electronic-based constituents (subsystems, modules and components, realised in hardware, software, or both) that are integrated in a way to together allow the system to perform a desired (set of) function(s).
Note that:

- Due to ECS typically being constructed hierarchically, a (e.g. camera or other sensor) "module" being part of the electronic "system" in an autonomous car might itself be referred to as a "system" when designing it (e.g. while integrating lower-level components to together achieve the "camera function") (see also: system in a package, system on a chip, and others).
- The difference between a "system" (comprising subsystems, modules and components) and a "System of Systems" (also comprising subsystems) is that the constituents of a system are chosen and integrated during design-time (i.e. completely under control of the engineers), while in a System of Systems the constituent (sub)systems are independent and dynamically form (and disband) a System of Systems at run-time.

System in a package (SiP): a number of integrated circuits and other electronics building blocks (e.g. MEMS, antennas) enclosed in one single package.

System on a chip (SoC): an integrated circuit that incorporates multiple building blocks of an electronic system, including processors, memory units, accelerators, and input/output ports, and which covers the complete functionality of an electronic system.

System of Systems (SoS): a collection of independent and distributed embedded and cyber-physical systems dynamically composed to generate a new and more complex system, provided with new functionalities and driven by new goals not present in the constituent embedded and cyber-physical systems individually. An SoS must satisfy five characteristics: operational independence of constituent systems; managerial independence of constituent systems; geographical distribution; emergent behaviour; and evolutionary development processes. A system that does not satisfy these characteristics (specifically the first two) is not considered an SoS.

Teleoperation: teleoperation (or remote operation) indicates operation of a system or machine at a distance. It is similar in meaning to the phrase "remote control" but is usually encountered in research, academia and technical environments. It is most commonly associated with robotics and mobile robots, but can be applied to a whole range of circumstances in which a device or machine is operated by a person from a distance.

Telepresence: the use of virtual reality technology, especially for remote control of machinery or for participation in distant events.

Tracking mode simulation: adapting simulation by respective measurements of the real counterpart.

(Technical) Trustworthiness: having some reasonably well thought-out assurance that the technical realisation of a system is worthy of being trusted to satisfy certain well-specified requirements (e.g. safety, security, reliability, robustness and resilience, ease of use and ease of system administration, and predictable behaviour in the face of adversities, such as high-probability real-time performance).

Value-based healthcare: a healthcare delivery model in which providers, including hospitals and physicians, are paid based on patient health outcomes. Under value-based care agreements, providers are rewarded for helping patients improve their health, reduce the effects and incidence of chronic disease, and live healthier lives in an evidence-based way.

Verification and validation (V&V): independent procedures that are used together for checking that a product, service or system meets requirements and specifications, and that it fulfills its intended purpose. Verification checks whether the development implemented the specified requirements of a product correctly ("are we building the product right"), while validation is a system test checking whether a product can fulfil its intended purpose in a real environment ("are we building the right product?").

Virtual commissioning: the practice of using "virtual" simulation technology to "commission" – design, install or test – control software with a virtual machine model before it is connected to a real system.

Virtual reality (VR): computer technology that makes a person feel like they are somewhere else. It uses software to produce images, sounds and other sensations to create a different place so that the user feels they are really part of this other place. Applications of virtual reality can include entertainment (e.g. video games) and educational purposes (e.g. medical or military training).

Wearables: wearable technology is a category of electronic devices that can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin.

X-in-the-loop: where "X" can be hardware-, software-, models-, systems-, etc. The term is used when testing ECS (or parts of an ECS). The system (e.g. component, module) to be tested is called "system-under-test" (SUT). This SUT is embedded into a testbed (or test environment) that provides the necessary input data (according to a specific test scenario), and which then monitors its outputs, comparing these actual outputs to the expected/specified ones. Within these testbeds, data flow therefore forms a "loop" (from the testbed through the SUT back to the testbed). Depending upon the realisation of the SUT (e.g. as a hardware component/module, software module, simulation model, complete system), different testbeds are needed and the resulting test process is called "hardware-in-the-loop", "software-in-the-loop", etc, or when referred to in a general way "X-in-the-loop".

ACRONYMS
USED IN THE DOCUMENT

5G	*Fifth-generation communication network*
6G	*Sixth-generation communication network*
A&P	*Assembly and packaging*
AAL	*Ambient Assisted Living*
ACA	*Anisotropic conductive adhesive*
ACES	*Autonomous, connected, electric and shared*
ACK	*Alexa Communication Kit*
ADAS	*Advanced driver-assistance system*
AF-EAF	*Air Force Enterprise Architecture Framework*
AFIoT	*Architecture Framework for the Internet of Things*
AFM	*Atomic force microscopy*
AI	*Artificial Intelligence*
AIN	*Aluminium nitride*
AIOTI	*Alliance for the Internet of Things Innovation*
AIoT	*Artificial Intelligence of things*
ALU	*Arithmetic logic unit*
AMD	*Age-related macular degeneration*
AMS	*Analogue/mixed signal*
API	*Application programming interface*
AR	*Augmented reality*
AS	*Autonomous system*
ASIC	*Application-specific integrated circuit*
AUTOSAR	*AUTomotive Open System Architecture*
B2B	*Business-to-business*
B2C	*Business-to-consumer*
BATX	*Baidu, Alibaba, Tencent and Xiaomi*
BCI	*Brain–computer interface*
BDVA	*Big Data Value Association*
BEOL	*Back end of line*
BEV	*Battery electric vehicle*
BGA	*Ball grid array*
BiCMOS	*Bipolar CMOS*
BIST	*Built-in self-test*
BOM	*Bill of materials*
BOX	*Buried oxide*
C&K	*Competence and knowledge*
CAD	*Computer-aided design*
CAFCR	*Customer Objectives, Application, Functional, Conceptual and Realisation Model*

CAGR	*Compound annual growth rate*
Cath lab	*Catheterisation laboratory*
CAV	*Connected autonomous vehicle*
CB	*Conductive-bridge*
CBRAM	*Conductive-bridging RAM*
CCAM	*Connected, Cooperative and Automated Mobility*
CDR	*Carbon dioxide removal*
CFD	*Computational fluid dynamics*
CMOS	*Complementary metal–oxide–semiconductor*
cMUT	*Capacitive micromachined ultrasound transducer*
CNN	*Convolutional neural network*
CNT	*Carbon nanotube*
CPS	*Cyber-physical system*
CPU	*Central processing unit*
CrMMC	*Carbon-reinforced metal matrix composites*
CT	*Computed tomography*
CVD	*Chemical vapour deposition*
D2D	*Device-to-device*
DCS	*Distributed control systems*
DfA	*Design for assembly*
DfM	*Design for manufacturing*
DfR	*Design for reliability*
DfX	*Design for excellence*
DL	*Deep learning*
DNN	*Deep neural network*
DRAM	*Dynamic random access memory*
DSA	*Directed self-assembly*
DSL	*Domain-specific language*
DSS	*Decision-support system*
DT	*Drug-targeted*
DUV	*Deep ultraviolet*
E/E	*Electrical/electronic*
EC-RAM	*Error correction RAM*
ECPS	*Embedded and cyber-physical system*
ECS	*Electronic components and systems*
ECSO	*European Cyber Security Organisation*
ECU	*Electronic control unit*
EDA	*Electronic design automation*

EFFRA	*European Factories of the Future Research Association*
eHPC	*Embedded high-performance computing*
EHR	*Electronic health record*
EIP-AGRI	*European Innovation Partnership "Agricultural Productivity and Sustainability"*
EMC	*Electromagnetic compatibility*
EMI	*Electromagnetic interference*
EMR	*Electronic medical record*
EMS	*Energy management systems*
eNVM	*Embedded non-volatile memory*
EOL	*End-of-life*
EP	*Engineering process*
EPI	*European Processor Initiative*
ERP	*Enterprise resource planning*
ERTRAC	*European Road Transport Research Advisory Council*
ESAAF	*European Space Agency Architecture Framework*
ESS	*Electronic smart system*
ETP	*European Technology Platform*
ETP4HPC	*European Technology Platform for High Performance Computing*
EU	*European Union*
EUV	*Extreme ultraviolet*
EV	*Electric vehicle*
FAIR	*Facebook AI Research*
FAIRness	*Findability, accessibility, interoperability and reuse*
FCC	*Federal Communications Commission*
FDSOI	*Fully depleted SOI*
Fe	*Ferroelectric*
FEM	*Finite element method*
FEOL	*Front end of line*
FET	*Future and emerging technologies*
FFT	*Fast Fourier transform*
FinFet	*Fin field-effect transistor*
FLOPS	*(flops or flop/s) Floating point operations per second*
FMEA	*Failure mode and effect analysis*
FMI	*Functional mock-up interface*
FMIS	*Farm management information system*
fMRI	*Functional magnetic resonance imaging*
FMU	*Functional mock-up unit*
FPGA	*Field-programmable gate array*

GAFAM	*Google, Apple, Facebook, Amazon and Microsoft*
GaN	*Gallium nitride*
GDPR	*General data protection regulation*
GHG	*Greenhouse gas*
GPS	*Global Positioning System*
GPU	*Graphics processing unit*
HAD	*Highly automated driving*
HCI	*Human–computer interaction*
HEMT	*High-electron-mobility transistor*
HEV	*Hybrid electric vehicle*
HF	*High-frequency*
HIL	*Hardware-in-the-loop*
HIR	*Heterogeneous Integration Roadmap*
HMI	*Human–machine interface*
HMLV	*High mix low volume*
HPC	*High-performance computing*
HTA	*Hexagon Tensor Accelerator*
HVAC	*Heating, ventilation and air conditioning*
HVDC	*High-voltage direct current*
HW	*Hardware*
I/O	*Input/output*
IC	*Integrated chip*
IC	*Integrated circuit*
ICT	*Information and communications technology*
IDM	*Integrated device manufacturer*
IEA	*International Energy Agency*
IGBT	*Insulated-gate bipolar transistor*
IIA	*Industrial Internet Architecture*
IIoT	*Industrial IoT*
IIRA	*Industrial Internet Reference Architecture*
INCOSE	*International Council on Systems Engineering*
iNEMI	*International Electronics Manufacturing Initiative*
IoMT	*Internet of Medical Things*
IoT	*Internet of Things*
IP	*Intellectual property*
IP	*Internet protocol*
IPCEI	*Important project of common European interest*
IPM	*Integrated pest management*

IPSR	*Integrated Photonic Systems Roadmap*
IR	*Infrared*
IRDS	*International Roadmap for Devices and Systems*
ISOC	*Internet Society*
IT	*information technology*
IVD	*in vitro diagnostic*
IXP	*Internet exchange point*
JU	*Joint undertaking*
KDT	*Key Digital Technologies*
KFI	*Key failure indicator*
KPI	*Key performance indicator*
LAE	*Large-area electronics*
LCA	*Lifecycle assessment*
LCP	*Liquid crystal polymers*
LCOE	*Levelised cost of electricity*
LoC	*Lab-on-a-chip*
LV	*Low voltage*
M2M	*Machine-to-machine*
MaaS	*Manufacturing as a service*
MaaS	*Mobility-as-a-service*
MCM	*Multi-chip module*
MCU	*Microcontroller unit*
MDM	*Multi-dimensional metrology*
MEC	*Multi-access edge computing*
MEC	*Mobile edge computing*
Medtech	*Medical technology*
MEMS	*Micro-electromechanical systems*
MES	*Manufacturing execution system*
MES	*Multi-energy system*
MIL	*Model-in-the-loop*
ML	*Machine learning*
MM-ENS	*Multimodal energy system*
MNBS	*Micro-nano-bio system*
MNS	*Micro-nanosystems*
MODAF	*Ministry of Defence Architecture Framework (UK)*
MOEMS	*Micro-opto-electro-mechanical system*
MOF	*Metal–organic framework*
MOOC	*Massive open online course*

MOSFET	*Metal–oxide–semiconductor field-effect transistor*
MPU	*Microprocessing unit*
MRAM	*Magnetic RAM*
MUT	*Micromachined ultrasonic transducer*
MV	*Medium voltage*
NB	*Narrowband*
NEMS	*Nano-electromechanical systems*
NFV	*Network functions virtualisation*
NFVI	*Network functions virtualisation infrastructure*
NLU	*Natural language understanding*
NPU	*Neuromorphic processing unit*
NVM	*Non-volatile memory*
OCT	*Optical coherence tomography*
ODD	*Operational design domain*
OECD	*Organisation for Economic Co-operation and Development*
OEM	*Original equipment manufacturer*
OOC	*Organ-on-a-chip*
OSI	*open systems interconnection*
OSS	*Operations support system*
OT	*Operational technology*
OTA	*Over-the-air*
OXRAM	*Oxide-based RAM*
P2P	*Peer-to-peer*
P4	*Predictive, preventive, personalised, participatory*
PAD	*Productivity-aware design*
PCB	*Printed circuit board*
PCM	*Phase-change memory*
PCRAM	*Phase-change RAM*
PDMS	*Polydimethylsiloxane*
PEALD	*Plasma-enhanced atomic layer deposition*
PFI	*Physical and functional integration*
PGHD	*Patient-generated health data*
PHM	*Prognostic health management*
PIII	*Plasma-immersion ion implantation*
PI	*Polyimide*
PLC	*Programmable logic controllers*
PLM	*Product lifestyle management*
PMIC	*Power management integrated circuit*

PMUT	*Piezoelectric micromachined ultrasound transducer*
PoC	*Point-of-care*
PoCT	*Point-of-care testing*
PoF	*Physics of failure*
PPAC	*Power, performance, area and cost*
PPE	*Personal protective equipment*
ppm	*Parts per million*
PPP	*Public/private partnership*
PSiP	*Power source in a package*
PTEMM	*Process technologies, equipment, materials and manufacturing*
PV	*Photovoltaics*
PVD	*Physical vapour deposition*
PwrSiP	*Power system in a package*
PwrSoC	*Power source on a chip*
PZT	*Lead zirconate titanate*
QIP	*Quantum information processing*
QoS	*Quality of service*
QRSC	*Quality, reliability, safety and cybersecurity*
Qubit	*Quantum bit*
qZSI	*Quasi-impedence source inverter*
R&D	*Research and development*
R&D&I	*Research and development and innovation*
RAM	*Random-access memory*
RAMI 4.0	*Reference Architecture Model for Industry 4.0*
ReRAM	*Resistive RAM*
RES	*Renewable energy system*
RF	*Radio frequency*
RFID	*Radio-frequency identification*
RL	*Reinforcement learning*
RNN	*Recursive neural network*
ROHS	*Restriction of Hazardous Substances Directive*
ROI	*Return on investment*
RPA	*Robotic process automation*
RRAM	*Resistive RAM*
RT-PCR	*Real-time reverse transcription polymerase chain reaction*
RTE	*Run-time environment*
RTO	*Research and technology organisation*
RUL	*Remaining useful life*

SaaS	*Software as a service*
SAC	*Conventional SnAgCu*
SAC	*Tin-silver-copper alloy (SnAgCu)*
SAE	*Society of Automotive Engineers*
SCADA	*Supervisory control and data acquisition*
ScAlN	*Scandium aluminium nitride*
SCM	*Storage class memory*
SCM	*Supply chain management*
SDDS	*Smart drug delivery system*
SDG	*Sustainable Development Goal*
SDK	*Software development kit*
SDN	*Software-defined networking*
SDR	*Software-defined radio*
SEAP	*Strategic Environmental Assessment Plan*
SECAP	*Sustainable Energy and Climate Action Plan*
SEES	*Self-powered electrochemical energy storage system*
SGD	*Speech-generating device*
SiC	*Silicon carbide*
SIL	*Software-in-the-loop*
SiP	*System in a package*
SKC	*Skills, knowledge and competence*
SME	*Small and medium-sized enterprise*
SoA	*Service-oriented architecture*
SoC	*System on a chip*
SoCPS	*System of cyber-physical systems*
SOI	*Silicon-on-insulator*
SoS	*System of Systems*
SOT	*Spin-orbit torque*
SOTIF	*Safety of Intended Functionality*
SPIRE	*Sustainable Process Industry through Resource and Energy Efficiency*
SRAM	*Static RAM*
SRGM	*Software reliability growth models*
SRIA	*Strategic Research and Innovation Agenda*
SSI	*Smart systems integration*
STDP	*Spike-timing-dependent plasticity*
STEM	*Science, technology, engineering and mathematics*
STS	*Socio-technical system*
STT	*Spin-transfer torque*

SUMP	*Sustainable Urban Mobility Plan*
SUT	*System-under-test*
SW	*Software*
SWM	*Smart Water Management*
TCP	*Transmission control protocol*
TEV	*Through-encapsulant via*
TOPS	*Tera operations per second*
TOU	*Time of use*
TPU	*Tensor processing unit*
TPU	*Thermoplastic Polyurethane*
TRL	*Technology readiness level*
TSMC	*Taiwan Semiconductor Manufacturing Company*
TSN	*Time-sensitive network*
TSO	*Transmission system operator*
TSV	*Through-silicon via*
TV&V	*Testing validation and verification*
UAV	*Unmanned aerial vehicle*
UAV	*Unmanned autonomous vessel*
ULP	*Ultra-low power*
UN	*United Nations*
UPS	*Uninterruptible power supply*
UXV	*Unmanned vehicle*
V&V	*Verification & validation*
V2G	*Vehicle to grid*
V2X	*Vehicle-to-everything*
VCMA	*Voltage-controlled magnetic anisotropy*
VIL	*Vehicle-in-the-loop*
VLSI	*Very large-scale integration*
VOC	*Volatile organic compound*
VR	*Virtual reality*
WBG	*Wide bandgap*
WHO	*World Health Organization*
WLP	*Wafer-level packaging*
WLTP	*Worldwide Harmonised Light Vehicle Test Procedure*
XR	*Extended reality*

LIST OF CONTRIBUTORS

CORE TEAM

Chairman

Paolo	Azzoni	*Eurotech, Inside-IA*	IT

SRIA Vice-Chairs

Patrick	Cogez	*AENEAS Office*	FR
Elisabeth	Steimetz	*EPoSS Office*	DE

Members

Christophe	Wyon	*CEA*	FR
Wolfgang	Dettmann	*Infineon*	DE
Jürgen	Niehaus	*SafeTRANS*	DE
Jerker	Delsing	*Lulea University of Technology*	SE
Sven	Rzepka	*Fraunhofer ENAS*	DE
Arco	Krijgsman	*ASML*	NL

INTRODUCTION AND OVERVIEW

Leaders

Paolo	Azzoni	*Eurotech, Inside-IA*	IT
Patrick	Cogez	*AENEAS Office*	FR
Jan	Lohstroh	*ARTEMIS-IA*	NL
Patrick	Pype	*NXP Semiconductors*	BE
Sven	Rzepka	*Fraunhofer ENAS*	DE
Elisabeth	Steimetz	*EPoSS Office*	DE

CHAPTER 1.1 – PROCESS TECHNOLOGY, EQUIPMENT, MATERIALS AND SEMICONDUCTOR MANUFACTURING

Leaders

Jo	De Boeck	*IMEC*	BE
Arco	Krijgsman	*ASML*	NL
Gerhard	Döll	*Carl Zeiss*	DE
Christophe	Wyon	*CEA*	FR
Dominique	Thomas	*STMicroelectronics*	FR
Christophe	Figuet	*Soitec*	FR
Christian	Meyne	*Infineon*	DE

Contributors

Mohand	Achouche	*III-V Lab*	FR
Ton	Backx	*Technical University of Eindhoven*	NL
Roel	Baets	*University of Gent*	BE
Livio	Baldi	*ENI2*	IT
Francis	Balestra	*IMEP*	FR
Markus	Bender	*Advanced Mask Technology Center*	DE
Jérôme	Bourderionnet	*Thales Research and Technology*	FR
François	Brunier	*SOITEC*	FR
Wolfgang	Buchholtz	*GlobalFoundries*	DE
Heinz	Cramer	*LAM Research - AU*	AU
Robin	de Bruijn	*Philips Innovation Services*	NL
Frank	de Jong	*FEI*	NL
Stefan	De Gendt	*IMEC*	BE
Wolfgang	Dettmann	*Infineon Technologies*	DE
Gerhard	Domann	*FhG ISC*	DE
Marc	Duranton	*CEA*	FR
Ilan	Englard	*Applied Materials*	NL
Thomas	Fleischmann	*Bosch*	DE
Luis	Fonseca	*IMB-CNM (CSIC)*	ES
Mart	Graef	*TU Delft*	NL
Soenke	Habenicht	*Nexperia*	DE
Paul	Heremans	*Imec*	BE
Michael	Heuken	*AIXTRON*	DE
Olaf	Kievit	*TNO*	NL
Jochen	Kinauer	*camLine*	DE
Anton	Koeck	*Materials Center Leoben*	AT
Herman	Leenders	*Technical University of Eindhoven*	NL
Arne	Leinse	*LioniX*	NL
Smuel	Mironi	*NOVA*	IL
Reinhard	Neul	*Robert Bosch*	DE
George	Nikolakopoulos	*Luleå University of Technology*	SE
Cian	O'Murchu	*Tyndall National Institute*	IRL
Lothar	Pfitzner	*Friedrich-Alexander-Universität*	DE
Anneliese	Poenninger	*EV Group*	AT
Klaus	Pressel	*Infineon Technologies*	DE
Pekka	Pursula	*VTT*	FI

Carlo	Reita	*CEA*	FR
Kari	Ronka	*Flexbright*	FI
Laurent	Roux	*Ion Beam Services*	FR
Martin	Schellenberger	*Fraunhofer-Gesellschaft*	DE
Michael	Scholles	*Fraunhofer-Gesellschaft*	DE
Robert	Schreutelkamp	*Applied Materials*	BE
Georg	Schwalb	*Siltronic*	DE
Pietro	Siciliano	*IMM-CNR*	IT
Hessel	Sprey	*ASM*	BE
Anne	Van den Bosch	*IMEC*	BE
Rogier	Verberk	*TNO*	NL
Andre	Verweij	*BESI*	NL
Philippe	Vialletelle	*STMicroelectronics*	FR

CHAPTER 1.2 – COMPONENTS, MODULES AND SYSTEMS INTEGRATION

Leaders

Pekka	Pursula	*VTT Technical Research Centre of Finland, Ltd.*	FI
Luis	Fonseca	*IMB-CNM (CSIC)*	ES
Sebastian	Schröck	*Robert Bosch GmbH*	DE

Contributors

Reinhard	Neul	*Robert Bosch GmbH*	DE
Matthias	Illing	*Robert Bosch GmbH*	DE
Christophe	Wyon	*CEA*	FR
Marco	Cavagnin	*AT&S AG*	AT
Stefan	Stegmeier	*Siemens*	DE
Kai	Kriegel	*Siemens*	DE
Michael	Hayes	*Tyndall*	IE
Valentina	Terzieva	*Imec*	BE
Jukka	Hast	*VTT Technical Research Centre of Finland, Ltd.*	FI
Arco	Krijgsman	*ASML*	NL
Blouet	Patrick	*ST Microelectronics*	FR
Paolo	Azzoni	*Eurotech*	IT
Wilson	Maia	*Thales*	FR
Tim	Kießling	*VDI / VDE*	DE

CHAPTER 1.3 – EMBEDDED SOFTWARE AND BEYOND

Leaders

Frank	van der Linden	*Philips*	NL
Ronald	Begeer	*TNO*	NL
Jasmin	Jahić	*University of Cambridge*	GB

Contributors

Paolo	Azzoni	*Eurotech*	IT
Frans	Beenker	*TNO*	NL
Gael	Blondelle	*Eclipse*	FR
Jerker	Delsing	*Lulea University of Technology*	SE
G	Demir	*Akimetal*	TR
Marc	Duranton	*CEA*	FR
Luis Lino	Ferreira	*ISEP*	PT
Joost	Gabriels	*Eindhoven University of Technology*	NL
Lenka	Koskova	*TUL*	CZ
Philippe	Krief	*Eclipse*	DE
Wouter	Leibbrandt	*TNO*	NL
Jan	Lohstroh	*INSIDE-IA*	NL
Harm	Munk	*TNO*	NL
Jurgen	Niehaus	*SafeTRANS*	DE
Antti	Niemela	*Lapimnamk*	FI
Olov	Schelen	*OPERAX*	SE
Michael	Siegel	*OFFIS*	DE
Ad	ten Berg	*NXP Semiconductors, INSIDE-IA*	NL
Peter	van Otterlo	*Eindhoven University of Technology*	NL
Marco	Jahn	*Eclipse*	DE
Daniela	Cancila	*CEA*	FR
Carlo	Cavazzoni	*Leonardo*	IT
Alberto	Bainchi	*Leonardo*	IT

CHAPTER 1.4 – SYSTEM OF SYSTEMS

Leaders

Paolo	Azzoni	*Eurotech*	IT
Jerker	Delsing	*Lulea University of Technology*	SE

Contributors

Ronald	Begeer	*TNO*	NL
Armando	Colombo	*University of Applied Sciences Emden/Leer*	DE
Harm	Munk	*TNO*	NL
Marina	Settembre	*Fondazione Ugo Bordoni*	IT
Leibbrandt	Wouter	*TNO*	NL
Stefan	Jakubek	*TU Wien*	AT
Christoph	Hametner	*TU Wien*	AT
Gianluigi	Ferrari	*University of Parma*	IT
Alberto	Bianchi	*Leonardo*	IT

CHAPTER 2.1 – EDGE COMPUTING AND EMBEDDED ARTIFICIAL INTELLIGENCE

Leaders

Marc	Duranton	*CEA*	FR
Ferdinand	Bell	*NXP*	DE
Pascal	Ribot	*STMicroeleectronics*	FR
Holger	Schmidt	*Infineon Technologies AG*	DE

Contributors

Paolo	Azzoni	*Eurotech*	IT
Martin	Cech	*University of West Bohemia*	CZ
Francesco	Conti	*Università di Bologna*	IT
Luca	Benini	*Università di Bologna*	IT
Bjorn	Debaillie	*IMEC*	BE
Mario	Diaz Nava	*STMicroelectronics*	FR
Christophe	Figuet	*Soitec*	FR
Stefan	Jakubek	*Tu Wien*	AT
Nicolas	Lehment	*NXP*	DE
Dirk	Mayer	*Fraunhofer*	DE
Francesco	Pessolano	*Xetal*	BE
Inessa	Seifert	*Vdi/Vde*	DE
Gerd	Teepe	*T3 Technologies*	DE

Massimo	Vecchio	*FBK*	IT
Ovidiu	Vermesan	*Sintef*	NO

CHAPTER 2.2 – CONNECTIVITY

Leaders

Jerker	Delsing	*Lulea University of Technology*	SE
Fred	Giansello	*ST*	FR
Didier	Belot	*CEA*	FR

Contributors

Alexandros	Kaloxylos	*5G Infrastructure Association*	GR
Christophe	Figuet	*SOITEC*	FR
Fredrik	Tillman	*Ericsson*	SE
Piet	Wambacq	*IMEC*	BE
Mohand	Achouche	*Nokia*	FI
Aamo	Pärsinen	*Oulu University*	FI
Yaning	Zou	*TU Dresden*	DE

CHAPTER 2.3 – ARCHITECTURE AND DESIGN: METHODS AND TOOLS

Leaders

Albrecht	Donat	*Siemens*	DE
Jürgen	Niehaus	*SafeTRANS*	DE
Horst	Pfluegl	*AVL*	AT
Ralf	Popp	*edacentrum*	DE

Contributors

Livio	Baldi	--	IT
Alberto	Bianchi	*Leonardo Group*	IT
Andre	Bolles	*OFFIS*	DE
Daniela	Cancilia	*CEA*	FR
Patrick	Cogez	*AENEAS*	FR
Manfred	Dietrich	*DiKuLi*	DE
Marc	Duranton	*CEA*	FR
Fahad	Golra	*Agileo Automation*	FR
Przemyslaw Jakub	Gromala	*Robert Bosch*	DE
Romano	Hoofman	*IMEC*	BE
Jasmin	Jahic	*Uni Cambridge*	GB

Sytze	Kalisvaart	*TNO*	NL
Philippe	Krief	*Ecplise Foundation*	--
Laura	Lezzerini	*MBDA*	IT
Nadja	Marko	*Virtual Vehicle*	AT
Frank	Oppenheimer	*OFFIS*	DE
Luigi	Pomante	*UNIVAQ*	IT
Peter	Priller	*AVL*	AT
Pablo	Sanchez	*TEISA UNICAN*	ES
Holger	Schmidt	*Infineon Technologies*	DE
Herbert	Taucher	*Siemens*	DE
Martin	Törngren	*KTH*	SE
Frank	Van den Linden	*Philips*	NL

CHAPTER 2.4 – QUALITY, RELIABILITY, SAFETY AND CYBERSECURITY

Leaders

Przemyslaw	Gromala	*Robert Bosch GmbH*	DE
Sven	Rzepka	*Fraunhofer ENAS*	DE
Joachim	Hillebrand	*Virtual Vehicle Research GmbH*	AT
Daniela	Cancila	*CEA*	FR
Peter	Moertl	*Virtual Vehicle Research GmbH*	AT

Contributors

Cristina	De Luca	*Infineon*	DE
Martin	Niessner	*Infineon*	DE
Christopf	Schmittner	*Austrian Institute of Technology*	AT
Marcello	Coppola	*ST Microelectronics*	FR
Haydn	Thompson	*THHINK Wireless Technologies Ltd*	UK
Markus	Tauber	*Research Studios Austria (RSA)*	AT
Martin	Törngren	*KTH*	SE
Dimitrios	Serpanos	*University of Patras*	GR
Paolo	Azzoni	*Eurotech*	IT
Fons	DeMey	*Uni. Antwerpen*	BE
Atefe	Dalirsani	*Robert Bosch GmbH*	DE
Olli	Venta	*VTT*	FI
Jerker	Delsing	*LTU*	SE
Claudio	Pastrone	*Links Foundation*	IT
Bentley	Oakes	*Uni Antwerpen*	BE

Marina	Settembre	*Fondazione Ugo Bordoni*	IT
Willem	van Driel	*Signify*	NL
Ovidiu	Vermesan	*Sintef*	NO
Marc	Duranton	*CEA*	FR
Lukasz	Kulas	*Politechnika Gdanska*	PL
Valentina	Palazzi	*Unipg*	IT
Bart	Vandevelde	*IMEC*	BE
Bo	Eriksson	*Ericsson*	SE
Elena	Tsiporkova	*Sirris*	BE
Daniel	Vanderstraeten	*OnSemi*	BE
Ugur	Yayan	*İnovasyon Mühendislik Ltd.*	TR
Kashi Vishwanath	Machani	*Globalfoundries*	DE
Dirk	Breuer	*Globalfoundries*	DE
Dag	Andersson	*RiSe*	SE
Klas	Brinkfeldt	*RiSe*	SE
Per-Erik	Tegehall	*RiSe*	SE
Wolfgang	Wondrak	*Daimler*	DE
Jonas	Arwindson	*Saab Group*	SE
Klaus	Pressel	*Infineon*	DE
Sylvie	Wuidart	*STMicroelectronics*	FR
Alberto	Bianchi	*Leonardo*	IT

CHAPTER 3.1 – MOBILITY

Leaders

Jochen	Langheim	*STMicroelectronics*	FR
Gereon	Meyer	*VDI / VDE*	DE
Michael	Paulweber	*AVL List GmbH*	AT
Patrick	Pype	*NXP Semiconductors*	BE
Daniel	Watzenig	*VIF*	AT

Contributors

Nicola	Amati	*POLITECNO DI TORINO*	IT
Remi	Bastien	*Renault*	FR
Kucie	Beaumel	*EGVIA*	BE
Thilo	Bein	*FRAUNHOFER*	DE
Andre	Blum	*Audi*	DE
Dominique	Bolignano	*Prove&Run*	DE
Jean-Luc	Brossard	*PFA*	FR

Alberto	Coen	*STMicroelectronics*	FR
Fredrik	Dahlgren	*Ericsson*	SE
Werner	Damm	*OFFIS*	DE
Wolfgang	Dettmann	*Infineon Technologies*	DE
Andreas	Eckel	*TTTech*	AT
Roch	Elkhoury	*Vedecom*	FR
Francois	Fischer	*ERTICO*	BE
Thomas	Fleischmann	*Robert Bosch*	DE
Carla	Gohin	*MPSA*	FR
Riccardo	Groppo	*IDEAS & MOTION*	IT
Manfred	Harrer	*ASFINAG*	AT
Berthold	Hellenthal	*Audi*	DE
Arnaud	Jaffuel	*Faurecia*	FR
Stefan	Jakubek	*TU Wien*	AT
Reiner	John	*Infineon Technologies*	DE
Dominique	Laousse	*SNCF*	FR
Herman	Leenders	*Eindhoven University of Technology*	NL
Dave	Marples	*Technolution*	UK
Chris	Merveille	*IKERLAN*	ES
Andreas	Middendorf	*Fraunhofer IZM*	DE
Herve	Mokrani	*Airbus DS SLC*	FR
Prasant	Narula	*APTIV*	DE
Patrick	Nebout	*Faurecia*	FR
Jurgen	Niehaus	*SafeTRANS e.V.*	DE
Markus	Pistauer	*CISC*	AT
Sven	Rzepka	*Fraunhofer*	DE
Patrick	Sega	*Valeo*	FR

CHAPTER 3.2 – ENERGY

Leaders

Wolfgang	Dettmann	*Infineon Technologies AG*	*DE*
Antonio	Imbruglia	*STMicroelectronics*	*IT*
Thomas	Hammer	*Siemens AG*	*DE*

Contributors

Michele	Albano	*Aalborg University*	*DK*
Angelo	Bonfitto	*Politecnico di Torino*	*It*
Thierry	Bouchet	*CEA LETI*	*FR*

Thomas	Ernst	*CEA LETI*	*FR*
Luis	Fonseca	*CNM CSIC*	*ES*
Albert	Frank	*Silicon Austria Labs*	*AT*
Francesco	Gennaro	*STMicroelectronics*	*IT*
Xavier	Jordà	*CNM CSIC*	*ES*
Hermann	Leenders	*TU Eindhoven*	*NL*
Sergio	Martinez-Navas	*LEITAT*	*ES*
Paul	Merkus	*TU Eindhoven*	*NL*
Chris	Merveille	*Ikerlan*	*ES*
Michael	Metzger	*Siemens*	*DE*
Michael	Ostling	*KTH*	*SE*
harald	Poetter	*FhG IZM*	*DE*
Pertti	Raatikainen	*VTT*	*FI*
Ville	Rauhala	*Lapinamk*	*FI*
Sven	Rzepka	*FhG ENAS*	*DE*
Michael	Salter	*RISE*	*SE*
Johannes	Stöckl	*AIT*	*AT*
Andrea	Tonoli	*Politecnico di Torino*	*IT*
Pavel	Vaclavek	*CEITEC*	*CZ*
Stefan	Wolf	*VDI VDE IT*	*DE*

CHAPTER 3.3 – DIGITAL INDUSTRY

Leaders

Alberto	Bianchi	*Leonardo S.p.A.*	IT
Olli	Venta	*Consultant*	FI
Antonio	Lionetto	*STM-IT*	IT
Mikka	Karaila	*Valmet Automation*	FI

Contributors

Delsing	Jerker	*LTU*	SE
Garcia	Carlos	*IMR*	ES
Yazici	Ahmet	*Eskisehir Osmangazi Univ.*	TR
Rogo	Francesco	*Leonardo SpA*	IT
Vallirinne	Jani	*Oulu University*	FI

CHAPTER 3.4 – HEALTH AND WELLBEING

Leaders

Olivier	Horbowy	*ST*	FR
Michael	Scholles	*FhG IPMS / MEOS*	DE
Peter	Zandbergen	*Philips*	NL

Contributors

Mario	Baum	*FhG ENAS*	DE
Ronald	Begeer	*TNO*	NL
Ronald	Dekker	*Philips*	NL
Marc	Desmulliez	*School of Engineering & Physical Sciences*	UK
Peter	Detemple	*FhG IMM*	DE
Wolfgang	Eberle	*IMEC*	BE
Helio	Fernandez Tellez	*IMEC*	BE
Cesar	Fernandez-Sanchez	*CSIC IMB-CNM*	ES
Ignacio	Garcia	*Soros Gabinete*	ES
Nicolas	Gouze	*VDI/ VDE-IT*	DE
Piotr	Grabiec	*Institute of Electron Technology*	PL
Radu	Grosu	*TU Wien*	AT
Rainer	Günzler	*Hahn-Schickard*	DE
Christian	Hedayat	*FhG ENAS*	DE
Stephan	Karmann	*Hahn-Schickard*	DE
Lenka	Lhotska	*CVUT*	CZ
Eila	Linna	*Lapin AMK*	FI
Marc	Masa	*LEITAT*	ES
Paul	Merkus	*TU Eindhoven*	NL
Carmen	Moldovan	*IMT*	RO
Eric	Moore	*Tyndall*	IE
Sotir	Ouzounov	*Philips*	NL
Peter	Ramm	*FhG EMFT*	DE
Pietro	Siciliano	*IMM-CNR*	IT
Philippe	Stoop	*ITK*	FR
Gerd	Teepe	*T3 Technologies*	NL
Tatiana	Trantidou	*ITML*	GR
Maurits	van der Heiden	*TNO*	NL
Frank	van der Linden	*Philips*	NL
Mark	van Helvoort	*Philips*	NL
Carmen	van Vilsteren	*TU Eindhoven*	NL
Andrea	Vitaletti	*Wsense*	IT

Andreas	Vogl	*SINTEF*	NO
Roberto	Zafalon	*ST*	IT
Silvia	Zinetti	*Inpeco*	IT

CHAPTER 3.5 – AGRIFOOD AND NATURAL RESOURCES

Leaders

Mario	Diaz Nava	*STMicroelectronics (Chair)*	FR
Giorgos	Fagas	*Tyndall (Co-Chair)*	IE

Contributors

Joaquin	Bastos	*Instituto de Telecomunicações*	PL
Thilo	Bein	*Fraunhofer*	DE
Jamila	Boudaden	*Fraunhofer*	DE
Sywert	Brongersma	*Imec-NL*	NL
Carles	Cane Ballart	*IMB-CNM (CSIC)*	ES
Ricardo	Coppel	*Hydrao*	FR
Rafael	Ferrer	*Hispatec*	ES
Laura	Lopéz	*Hispatec*	ES
Christian	Germain	*Agro-Bordeaux*	FR
Guillaume	Le Paud	*Teagasc*	IE
Herman	Leenders	*TUE*	NL
Suzanne	Lesecq	*CEA (leti)*	FR
Pierre	Lovera	*Tyndall*	IE
Mike	Morrissey	*Analog Devices*	IE
Luis	Munoz	*Universidad de Cantabria*	ES
Cian	O'Murhcu	*Tyndall*	IE
Alan	O'Riordan	*Tyndall*	IE
Luis	Perez-Freire	*Gradiant/AIOTI WG Smart framing*	ES
Peter	Ramm	*Fraunhofer*	DE
Olivier	Sommier	*Ertus*	FR
Philippe	Stoop	*Itk*	FR
Ricardo	Vazquez Perez	*Emalcsa*	ES
Ovidiu	Vermesan	*Sintef*	NO
Gwenaelle	Berthie	*IRT-Systemx*	FR
Lionel	Scremin	*IRT-Systemx*	FR

CHAPTER 3.6 – DIGITAL SOCIETY

Leaders

Paul	Merkus	*TU/e*	NL
Charly	Bastiaansen	*TiU*	NL
Francesco	Pessolano	*Xetal*	IT

Contributors

Klaas-Jan	Damstra	*Grass Valley*	NL
Nuria	De Lama Sanchez	*ATOS*	ES
Fabrizio	Fallarini	*MESAP*	IT
Helio	Fernandez Tellez	*IMEC*	BE
Lukasz	Kulas	*Politechnika Gdanska*	PL
Eila	Linna	*Lapinamk*	FI
Bruno	Rouchouze	*Thales*	FR
Herman	Leenders	*TU/e*	NL
Carina	Weijma	*Carweij*	NL

CHAPTER 4 – LONG-TERM VISION

Leaders

Dimitrios	Serpanos	*University of Patras*	GR
Enrico	Sangiorgi	*University of Bologna*	IT
Sven	Rzepka	*FhG ENAS*	DE

Contributors

Mart	Graef	*TU Delft*	NL
Jouni	Ahopelto	*VTT*	FI
Paolo	Azzoni	*Eurotech*	IT
Francis	Balestra	*IMEP*	FR
Sywert	Brongersma	*Imec*	NL
Daniela	Cancila	*CEA*	FR
Danilo	Demarchi	*Politecnico di Torino*	IT
Gianluigi	Ferrari	*University of Parma*	IT
Luis	Fonseca	*IBM-CNM (CSIC)*	ES
Péter	Fürjes	*MTA EK / MFA*	HU
Przemyslaw	Gromala	*Bosch*	DE
Said	Hamdioui	*TU Delft*	NL

Adrian	Ionescu	*EPFL*	CH
Ahmed	Jerraya	*CEA*	FR
Chris	Merveille	*IK4-IKERLAN*	ES
George	Nikolakopoulos	*Lulea University of Technology*	SE
Jon	Perez	*IK4-IKERLAN*	ES
Ralf	Popp	*Edacentrum*	DE
Michael	Salter	*RISE*	SE
Holger	Schmidt	*Infineon Technologies AG*	DE
Markus	Tauber	*FH Burgenland*	DE
Ad	ten Berg	*NXP Semiconductors, ARTEMIS-IA*	NL

MAIN OBJECTIVES:
AN ANALYSIS OF ALL MAJOR CHALLENGES

In this ECS-SRIA, for the first time, the **Major Challenges** identified by the different chapter teams were analysed and finally merged into **Main Common Objectives** for the ECS community as shown in the following tables.

In the table, Major Challenges numbering is composed by three digits X.Y.Z, where:

- X is the ECS-SRIA Part (1, 2 or 3);
- Y is the ECS-SRIA Chapter (1-4 for Part 1, 1-4 for Part 2 and 1-6 for Part 3);
- Z is the Major Challenge number in the specific Chapter.

EC STRAT. TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
ECS R&I OBJECTIVES	**Boost industrial competitiveness through interdisciplinary technology innovations** Interdisciplinary technology innovation	**Ensure EU sovereignty through secure, safe and reliable ECS supporting key European application domains** Secure, safe and reliable ECS	**Establish and strengthen sustainable and resilient ECS value chains supporting the Green Deal** Sustainable & resilient ECS	**Unleash the full potential of intelligent and autonomous ECS-based systems for the European Digital Era** Intelligent and autonomous ECS
Major Challenges in ECS Research and Innovation	**1.1.1** Advanced computing, memory and in-memory computing concepts	**1.3.5** Software reliability and trust	**1.1.4** World-leading and sustainable semiconductor manufacturing equipment and technologies	**1.1.1** Advanced computing, memory and in-memory computing concepts
	1.1.2 Novel devices and circuits that enable advanced functionality	**1.4.2** SoS interoperability	**1.2.4** Decarbonisation and Recyclability	**1.1.2** Novel devices and circuits that enable advanced functionality
	1.1.3 Advanced heterogeneous integration and packaging solutions	**1.4.3** Evolvability of SoS composed of embedded and cyber-physical systems	**1.3.5** Support for Sustainability by embedded software	**1.3.4** Embedding Data Analytics and Artificial Intelligence
	1.1.4 World-leading and sustainable semiconductor manufacturing equipment and technologies	**1.4.5** Control in SoS composed of embedded and cyber-physical systems	**1.4.2** SoS interoperability	**1.4.5** Control in SoS composed of embedded and cyber-physical systems
	1.2.2 Materials for integration	**2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain	**1.4.5** Control in SoS composed of embedded and cyber-physical systems	**2.1.1** Increasing the energy efficiency of computing systems
	1.2.3 Technologies, Manufacturing and Integration Processes	**2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	**2.1.1** Increasing the energy efficiency of computing systems	**2.1.3** Supporting the increasing lifespan of devices and systems
	1.4.1 SoS architecture and open integration platforms	**2.4.1** Ensuring HW quality and reliability	**2.1.3** Supporting the increasing lifespan of devices and systems	**2.1.4** Ensuring European sustainability in AI, edge computing and advanced control
	1.4.2 SoS interoperability	**2.4.2** Ensuring dependability in connected software	**2.1.4** Ensuring European sustainability in AI, edge computing and advanced control	**2.2.3** Autonomous interoperability translation for communication protocol, data encoding, compression, security and information semantics
	1.4.5 Open "system of embedded and cyber-physical systems" platforms	**3.1.1** Enable electrification & sustainable alternative fuels for CO_2 neutral mobility	**2.2.1** Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain	**2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity

EC STRAT. TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
Major Challenges in ECS Research and Innovation	**2.1.1** Increasing the energy efficiency of computing systems	**3.1.2** Enable affordable, safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, small drones, etc) and mobile machinery (for smart farming)	**2.2.4** Architectures and reference implementations of interoperable, secure, scalable, smart and evolvable IoT and SoS connectivity	**3.1.3** Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water
	2.2.1 Strengthening EU connectivity technology portfolio in order to maintain leadership, secure sovereignty and offer an independent supply chain	**3.1.5** Achieve real-time data handling for multimodal mobility and related services.	**2.4.4** Ensuring of safety and resilience	**3.1.5** Achieve real-time data handling for multimodal mobility and related services.
	2.2.2 Investigate innovative connectivity technology (new spectrum or medium) and new approaches to improving existing connectivity technology to maintain the EU's long-term leadership	**3.2.2** Energy Management from On-Site to Distribution Systems	**3.1.1** Enable electrification & sustainable alternative fuels for CO_2 neutral mobility	**3.2.1** Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems
	2.2.5 Network virtualisation enabling run-time engineering, deployment and management of edge and cloud network architectures	**3.2.4** Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply	**3.1.2** Enable affordable, safe and environmentally neutral light mobility (bicycles, tricycles, wheelchairs, small drones, etc) and mobile machinery (for smart farming)	**3.3.1** Responsive and smart production
	2.3.2 Managing new functionality in safe, secure and trustworthy systems	**3.4.1** Enable digital health platforms based upon P4 healthcare	**3.1.3** Enable affordable, automated and connected mobility for passengers and freight on road, rail, air and water	**3.3.3** Artificial Intelligence in Digital Industry
	2.3.4 Managing Diversity	**3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies	**3.2.1** Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems	**3.3.6** Autonomous systems, robotics
	3.1.5 Achieve real-time data handling for multimodal mobility and related services.	**3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system	**3.2.3** Future transmission grids	**3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies
	3.2.2 Energy Management from On-Site to Distribution Systems	**3.4.5** Ensure more healthy life years for an ageing population	**3.2.4** Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply	**3.4.4** Enhance access to personalized and participative treatments for chronic and lifestyle related diseases
	3.2.3 Future transmission grids	**3.5.1** Food Security	**3.3.1** Responsive and smart production	**3.4.5** Ensure more healthy life years for an ageing population
	3.2.5 Cross-Sectional Tasks for Energy System Monitoring & Control	**3.5.2** Food Safety	**3.3.2** Sustainable production	**3.5.1** Food Security

EC STRAT. TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
Major Challenges in ECS Research and Innovation	**3.4.1** Enable digital health platforms based upon P4 healthcare	**3.6.3** Facilitate inclusion and collective safety	**3.4.1** Enable digital health platforms based upon P4 healthcare	**3.5.3** Environmental protection and sustainable production
	3.4.2 Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies		**3.4.2** Enable the shift to value-based healthcare, enhancing access to 4Ps game changing technologies	**3.5.4** Water resource management
	3.4.3 Support the development of home as the central location of the patient, building a more integrated care delivery system		**3.4.3** Support the development of home as the central location of the patient, building a more integrated care delivery system	
	3.5.3 Environmental protection and sustainable production		**3.4.4** Enhance access to personalized and participative treatments for chronic and lifestyle related diseases	
	3.5.4 Water resource management		**3.4.5** Ensure more healthy life years for an ageing population	
	3.5.5 Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation		**3.5.3** Environmental protection and sustainable production	
	3.6.1 Facilitate individual self-fulfilment		**3.5.4** Water resource management	
	3.6.2 Facilitate empowerment and resilience		**3.5.5** Biodiversity restoration for Ecosystems Resilience, Conservation and Preservation	
	3.6.3 Facilitate inclusion and collective safety		**3.6.2** Facilitate empowerment and resilience	
	3.6.4 Facilitate supportive infrastructure and a sustainable environments		**3.6.4** Facilitate supportive infrastructure and a sustainable environments	

EC STRAT. TARGETS	INDUSTRIAL COMPETITIVENESS	EU SOVEREIGNITY	SUSTAINABILITY AND GREEN DEAL	DIGITAL AGE (AI, NGC)
	Ensure engineering support across the entire lifecycle of complex ECS-based systems Lifecycle engineering support			
Major Challenges in ECS Research and Innovation	**1.2.1** Physical and Functional Integration	**1.3.2** Continuous integration and deployment	**1.3.1** Efficient Engineering of Embedded Software	**2.1.2** Managing the increasing complexity of systems
	1.3.1 Efficient Engineering of Embedded Software	**1.3.3** Life cycle management	**1.3.2** Continuous integration and deployment	**2.3.1** Extending Development Processes and Frameworks (to handle connected, intelligent, autonomous, evolvable systems)
	1.3.2 Continuous integration and deployment	**1.4.1** SoS architecture and open integration platforms	**1.4.1** SoS architecture and open integration platforms	**2.3.3** Managing Complexity
	1.3.3 Life cycle management	**1.4.4** Systems of embedded and cyber-physical systems engineering	**1.4.6** SoS Monitoring and management	**3.1.4** Provide tools and methods for validation & certification of safety, security and comfort of embedded intelligence in mobility
	1.4.1 SoS architecture and open integration platforms	**1.4.1** SoS architecture and open integration platforms	**2.1.2** Managing the increasing complexity of systems	**3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation
	1.4.3 Evolvability of SoS composed of embedded and cyber-physical systems	**1.4.6** SoS Monitoring and management	**2.3.3** Managing Complexity	**3.3.5** Digital twins, mixed or augmented reality, telepresence
	1.4.4 Systems of embedded and cyber-physical systems engineering	**2.1.2** Managing the increasing complexity of systems	**2.3.4** Managing Diversity	
	2.1.2 Managing the increasing complexity of systems	**2.3.2** Managing new functionality in safe, secure and trustworthy systems	**2.4.5** Human Systems Integration	
	2.4.5 Human Systems Integration	**2.3.3** Managing Complexity	**3.3.4** Industrial service business, life-cycles, remote operations, and teleoperation	
	3.3.5 Digital twins, mixed or augmented reality, telepresence	**2.3.4** Managing Diversity		
		2.4.3 Ensuring cyber-security and privacy		
		3.1.4 Provide tools and methods for validation & certification of safety, security and comfort of embedded intelligence in mobility		
		3.3.4 Industrial service business, life-cycles, remote operations, and teleoperation		

Strategic Research and Innovation Agenda 2022

KEYWORDS INDEX

Symbols

2D materials 43
2nd life 177
2Zero 289, 290, 293, 306
3D printing 383
3D-stacked memories 42
17 Sustainable Development Goals 167
(bio)medical devices 48

A

abstraction 105
accelerators 465
access control as a service (ACaaS) 442
actuating 44
adapt 96
adaptable embedded software 100
adaptable systems 100
ADAS 215
ADAS functions 300
AD functions 300
advanced computing 41
Advanced Emergency Braking on Heavy Duty Vehicles 300
agriculture 399, 403, 406, 420, 423
agriculture ecosystem 415
agrifood 361
agrifood value chain 402
agro-ecology 407
AI 96, 238, 245, 301, 313, 399, 418, 419, 423, 477
AI capabilities 414
AI-enabled intelligence 297
AI/ML 458
airplanes 302
air pollution 410
air quality 400, 410
air quality monitoring 481
Alcohol Interlock Installation Facilitation 300
alternative energy 295
alternative fuels 295
Ambient Assisted Living 389
analysis 236, 238, 239, 243
Angstrom 53
animal welfare 408
ANN 168
antibiotics 399, 419
anti-patterns 108, 117
application-specific logic 45
aquaculture 399, 403, 420, 421
aquaculture ecosystem 416
architecting 100
architecture 235, 236, 237, 244, 314
Artificial Intelligence 161, 399, 464
Artificial Intelligence of Things (AIoT) 172
AR/VR 441
aspect-oriented languages 105
assembly and packaging 50
automated and connected multimodal mobility 291
Automated Design Space Exploration 187
automated engineering 146
automated mobility 302
automated testing validation and verification (TV&V) 146
automated transport 302
automated transportation systems 298
automated vehicles 302
automatic adaptation 113
automation 101, 304
automation function 302
automation requirements 146
Auto-ML 174
AUTomotive Open System ARchitecture 107
autonomous driving 292
autonomous embedded systems 463
autonomous operation 139
autonomous SoS connectivity 223
autonomous translation 224
autonomous vehicles 292
autonomous vessels 298
autonomy 96
AUTOSAR 107, 137
availability 297

B

ball grid arrays 49
BEVs 294
BiCMOS 45, 216
bi-directional 314

BIM *148*
biochemical *48*
biodegradable packaging *411*
biodiversity *399, 403, 415*
biodiversity restoration *415, 416, 420, 423*
Biodiversity Strategy 2030 *401, 403*
bio-waste management *400, 411*
Blind Spot Information System *300*
blockchain *408*
bluetooth *209*

C

carbon neutral *313*
carbon sequestration *412*
CCAM *289, 290, 293, 296, 298, 302, 306*
certification *96, 107, 303, 455*
charging infrastructures *296*
ChatOps *107*
circular economy *466, 476*
cities *446*
clean water *399, 412, 420*
climate *313*
climate change *444*
climate-neutral *36*
closed loop and digital control *139*
cloud *161*
CMOS *216, 460*
CNT *460*
CO_2 and emission neutral mobility *304*
CO_2 emission neutrality *291*
CO_2 emissions *314*
CO_2 neutral *473*
CO_2-neutral mobility *289, 290, 294*
CO_2-neutral vehicles *290, 293*
co-design *113, 177*
collective safety *439, 441*
comfort *302*
communication technologies *45*
compilers *106*
complexity *97, 236, 240, 243*
compliance *105*
compounds *410*
computer numerical controllers (CNC) *134*
connectability *297*
connected and automated mobile machinery *297*
connected cars *292*
Connected, Cooperative and Automated Mobility *289*
connected, cooperative and ultimately automated mobility *298*
connecting the virtual and physical world *249*
connectivity *304, 467*
contaminants *412*
continuously evolving lifecycle *142*
continuous system integration *105*
control *325*
control software *295*
control system *147*
conversion *332*
CPS *127, 161*
crisis response solutions *441*
cross-regional *315*
Cuda *111*
cyber physical SoS *134*
cybersecurity *96, 235, 262, 313*
cybersecurity test methods *301*
cyber-threats *301*

D

data analytics *101*
data integrity *100*
Data Movement challenge *180*
decarbonization *313*
decentralized *327*
deep-edge *163*
deep learning *165, 465*
dependability *96, 262, 267*
dependable communication *267*
deployment *101*
deposition *53*
design *235, 239, 245*
design patterns *117*
development *236, 248*
DevSecOps *107*
diagnostic imaging *383*
diagnostics *100, 295*
digital health platforms *381*
digital inclusion *427, 435*
digitalisation *95, 320*
Digital Society *361, 447*
digital tools *431*
digital twin *105, 265, 383, 419, 423, 463*
digitization *467*

diseases 399, 407
distributed 314
distributed control systems (DCS) 134
distributed edge computing 189
distributed intelligence 139
diversity 236, 240, 248
domain-specific languages 105
DPU 166
DRAM 460
drinking water 402, 409
drinking water distribution 412
Driver Availability Monitoring System 300
Driver Drowsiness and Attention Warning 300
drones 296, 405, 421
drug delivery systems 386
DSL 105
dynamically manage composability 143
dynamic reconfiguration 193

E

ECAS 185
Eclipse Arrowhead 135
Eclipse Basyx 135
ecological 114
economical 114
ECPS 95, 107
ECS 326
ECS industries 402
edge 161
edge AI 98
edge computing 104, 111, 162, 463
Edge Computing and Embedded Artificial Intelligence 269
effect transistors 460
efficiency 100, 314
efficient and flexible engineering processe 146
efficient engineering 106
e-health 479
electrical energy 313
electric vehicles 295
electrification 294, 295, 304, 306
electrification of vehicles 292
electronic control 320
Electronic Health Record 379
Embedded and Cyber-Physical Systems 95
embedded data analytics 100
embedded intelligence 95, 101, 297
embedded intelligence on the edge 98
Embedded (or Edge) High Performance Computers (eHPC) 176
embedded software 95, 101
Emergency Lane Keeping System 300
Emergency Stop Signal 300
emerging non-volatile memory 43
empowerment 437
emulation and forecasting 262
enable affordable, automated and connected mobility for passengers and freight 298
encapsulation 49
end-to-end traceability 408
energy 456
energy consumption 315
energy efficiency 36, 177, 465
energy harvesting 44, 48, 461
energy management 456
engineering and management frameworks 226
engineering efficiency 139
engineering methodologies 144
enterprise resource planning (ERP) 134
environmental pollution 400
environmental protection 404, 418, 419, 423
environmental protection and sustainable production 409, 418
environments 148
ERTRAC 306
etch 53
ethernet 209
EU4Health 379
EU leadership and sovereignty 141
European Green Deal 36, 130, 168, 289, 399
European organic and conventional agriculture 407
European Road Transport Research Advisory Council 306
European semiconductor 402
EU strategic open source platforms 139
Event Data Recorder 300
evolution 97
evolvability and composability 142
explainability of AI 178
explainable AI 467, 477
extendibility 96
extending lifecycle 100

F

failure mitigation *139*
FAIRness *430*
fan-out wafer-level packages *49*
farming systems *399, 405, 418, 421*
fast charging *295*
FDSOI CMOS *42*
federated intelligence *113*
federated knowledge *113*
federated learning *113, 183*
ferroelectric RAM/FeFET *460*
fertilisers *399, 409, 421*
field-effect transistors *460*
FinFET *42*
fisheries *399, 423*
fisheries ecosystem *416*
fishing methods *416*
fishing practices *416*
fishing techniques *416*
FiWare *135*
flexibility *325*
flexible electronics *47, 69*
flip chips *49*
fog *161*
food *423*
food chain *408, 418, 419*
food safety *404, 406, 408, 418, 480*
food security *414, 418, 480*
food supply chain *399, 407, 408*
food traceability *408, 419*
forest ecosystems *416*
forestry *399, 423*
forestry ecosystem *416*
framework *235, 237, 239*
freshwater resources *400, 412*
From Farm to Fork *402*
fuel cell-based vehicles *295*
functional safety *262*

G

GaAs *217*
GAFAM *168*
GaN *45, 217, 295, 322*
GDPR *171*
genomics *407*
GHG emissions *399, 403, 410*
GPU *111*
GPUs *164*
graphene *460*
Green Deal *95, 290, 293, 316, 456, 480*
greenhouse gas *314*
“green” manufacturing *54*
green mobility *295*
green vehicles *295*
grid *315*

H

H_2 *295*
H_2-based electrical vehicles *289*
HAD *305, 306*
haptic interfaces *461*
hardware-in-the-loop *303*
harvesting robotic systems *405*
Health and Wellbeing *361*
herbicides *409*
heterogeneous integration *41, 49, 69, 218*
heterogeneous systems *248*
HEVs *294*
High Level Architecture of the Alliance for Internet of Things Innovation *135*
highly automated driving *305*
high voltage *48*
HIL *303*
homecare *377*
horizontal interconnects *51*
hormones *416*
hybrid *324*

I

IEC 61512 (ISA 88) *144*
IEC 62264 (ISA95) *144*
IEC 62890 *144*
IEC81346 *144*
IGBT *45*
IIoT *163, 405*
image processing *383*
inclusion *439*
inclusive growth *439*
increasing complexity *177*
increasing lifespan *177*
individual self-fulfilment *433*
Industrial Internet Architecture *135*

Industrial Internet of Things 405
industry 4.0 171, 211, 477
inference 183
infrastructure 313, 328
infrastructure management 430
In-Memory-Computing 41, 178
In/Near Memory Computing 166
innovation 100
Innovative Health Initiative 378
InP 217
integrated pest management 407
integrated photonics 57
integration 96, 100, 101, 102, 105, 107, 108
intelligence at the edge 111, 178
intelligent buildings 445
intelligent embedded systems 163
intelligent food production systems 405
intelligent intra-row, herbicide-free weeding techniques 407
intelligent logistic systems 401, 408
Intelligent Speed Assistance 300
interconnect technologies 51
intermodality 290
Internet of Medical Things 380
Internet of Things 399
interoperability 96, 104, 177
interoperable 223
interposers 42
interposers and chiplets 186
inter-system communication 95
intramodality 297
IoT 127, 162, 399, 401, 418, 419, 423
IoT integration 107
IoT solutions 48
IPM 407
irrigation management 414
ISO 10303 144
ISO 15924 144
ISO 26262 302
IVD 384

K

key application area requirements 139

L

lab-on-a-chip 384
Lane Departure Warning System 300
laser 49
latency 105
leak localisation 413
LED 49
legacy 96, 105
lidar 48
lifecycle 96, 109, 236, 239, 244
lifecycle management 267
lithography 53
livestock 399
livestock health 408
livestock welfare 418
long-term governance 139
low-carbon economy 411

M

M2M 97
MaaS 306
Machine Learning 165, 301
machine-to-machine 97
machine-to-machine interaction 461
magnetic RAM 460
maintenance 96, 97, 236, 239, 463
manouver planning 302
manufacturing equipment 52
manufacturing execution system (MES) 134
manufacturing technologies 56
maritime industry 291
maximise circular resource usage 36
media consumption 441
MEMS 50, 69, 78
MEMS ultrasound technology 384
meta-edge 163
metamaterials 51
meta surfaces 219
metrology 53
micro-batteries 48
micro-bumps 49
micro-edge 163
microfluidics 386
micro-mobility 304
middleware 106
MIL 303
minimally invasive surgery 383
minimise waste 36
ML 162

mm-wave device *48*
Mobility *361*
mobility and transport as a service *296*
mobility-as-a-service *292*
model-based *106, 236, 241*
model-based design *96*
model-based embedded software engineering *100*
model-based engineering *146, 463*
model-based testing *106, 463*
model-predictive control *295*
modular, flexible and scalable platforms and electrical/electronic (E/E) architectures *297*
mold compounds *50*
monitor *105*
monitoring *99, 325*
Moore's law *53*
more than Moore *44*
MOSFET *459*
multicore *106*
multi-criticality *106*
multidisciplinary *100*
multimodality *304*
multimodal mobility *290*
multimodal mobility system *304*
multimodal transport *291*

N

nano- and microelectronics *35*
nanomaterials *51*
nanoribbons *43*
nanosheets *43*
nanosystem *459*
nanotechnologies *459*
nanowires *43*
naturalistic driving *303*
natural resources *399, 403, 423*
Natural Resources *361*
NCFET *460*
Near-Memory-Computing *178*
NEMS-FET *460*
neuromorphic *43, 44, 164, 178, 466*
neuromorphic computing *161*
neurorehabilitation *389*
NIST Big data Reference Architecture *135*
Non-Volatile Memories *185*
nudging *435*
NVM *180*

O

ODD *302, 303*
OEM *107*
off-road *302*
off-road vehicles *296*
online education *435*
ONNX *198*
on-road *302*
open-source *99, 223*
open-source hardware *168, 177*
operation *236, 239*
operational design domain *302*
optical coherence tomography *384*
optical communications *46*
optimisation *236, 240, 248*
optimisation methods *303*
organic *462*
organ-on-a-chip *388*
OSI *209*
OTA *292, 297, 299, 301, 302, 303*
overlay *53*

P

P4 healthcare *373*
packaged chip *35*
packaging *41, 219*
patient-generated health data *385*
patterns *108*
PCB *217*
Pedestrian and Cyclist Collision Warning *300*
perception system *302*
PERFoRM30 *135*
performance *105*
personalized medicine *373*
pests *399*
phenotyping *407*
photonics *69, 459*
photoplethysmography *387*
physical and functional integration *75*
physics of failure (PoF) *264*
piezoelectric ceramics *48*
platform *128, 235, 243, 254*
platooning *300*
plug and play integration *130*
point-of-care *380*
point-of-need *375*

portability 106
power 321
power electronics 295, 297
power grid 314
power semiconductor 318
power technologies 45
PPAC 52
precision aquaculture systems 416
precision farming systems 415
precision plant breeding 407
predictive control 295
predictive diagnosis 297
preventive maintenance 100
printed electronics 462
privacy 100, 299
proactive lifecycle management 54
processes 97
processing 53
process yield 53
production quality 261
prognostics and health management 261
programmable logic controllers (PLC) 134
programming languages 106
Protection of Vehicles against Cyber Attack 300

Q

QoS 139
quality 96, 105
quality by design 237
quantum 70
quantum computing 44, 57, 460
quantum dots 43

R

radar 48
real driving testing 297
real-time performance 139
reduction 314, 315
Reference Architecture Model for Industry 4.0 135
refurbishment 54
regulations 105
reliability 52, 96, 235, 237, 238, 245, 261, 301, 302, 325, 458
remediation 412, 418, 419, 423
remote sensing 387
renewable 313, 314, 316, 318, 322, 324, 327, 329, 331, 334, 338
Renewable Energy Carriers 306
renewables 316, 327
represent 127
resilience 297, 437
resilient infrastructure 444
resistive RAM 460
resource efficient 456, 476
re-use 99
Reversing Detection 300
RF 45
RF application 51
RISC-V 163
robot 419
robot controllers (RC) 134
robots 399, 405
robustness 52, 297
robust root of trust systems 262
RT-PCR 384

S

SAE levels 303
safe 456, 476
safe, secure, reliable 299
safety 96, 237, 238, 245, 254, 262, 297, 302
safety analyses 303
safety-critical 109
safety standards 291
satellite 405, 421
scalability 139
scaleable, smart and evolvable SoS connectivity 223
scenario-based verification and validation 303
scenario-based virtual validation 303
scheduling 106
secure 223, 456
secure communication 302
secure food supply 480
security 138, 237, 238, 254, 262, 297, 302, 315
security management 139
self-diagnostic 266
self-driving car 112
self-monitoring, self-assessment 266
self-organised multi-agent systems 298

self-X *177*
semantics interoperability *224*
semiconductor *315*
semiconductor chip *35*
sensing *44*
sensors *45, 320, 459*
sequestration *412*
serious gaming *441*
ships *302*
SiC *45, 295, 322*
SiGe *219*
SIL *303*
silicon photonic *46*
simulating *106*
simulation models *302, 303*
simulation models for environmental sensors *303*
SiP *69*
smart *456*
smart cities *445*
smart devices *401*
Smart drug delivery *479*
smart grids *474*
smart medicine *48*
smart metering *413*
smart minimally invasive devices *383*
smartphones *479*
smart systems *457, 477*
Smart waste management *482*
smart wound care *386*
SNN *168*
social protection *439*
society *96*
SoCs *111*
software architectures *297*
software reliability *267*
software upgrades *292*
softwarisation *268*
SOI *216*
soil analysis *409*
soil degradation *400*
soil nutrients *409, 420*
SOI photonics *46*
solar cells *48*
solid-state batteries *295*
SoS *95, 127*
SoS architecting *134*
SoS dimensions *148*
SoS flexibility *139*
SoS Monitoring and management *147*
SoS platforms *128*
SOTIF *302*
species diversity *415*
Speed Limitation Devices *300*
SRAM *460*
standardization *316*
STDP (Spike-timing- dependent plasticity *185*
storage *314*
sub-2 nm node logic and memory *52*
subTHz connectivity *220*
supervisory control and data acquisition (SCADA) *134*
sustainability *70, 95, 113, 177, 399, 430, 444*
sustainable alternative fuels *294*
Sustainable Development Goals *401*
sustainable production *404, 418, 419, 423*
synthetically created *303*
systemic change *441*
System-in-Package *69*
system of cyber-physical systems (SoCPS) *132*
System of Embedded and Cyber-Physical Systems *144*
System of Systems *16, 17, 28, 95, 127, 241, 268, 343, 436, 440, 443, 447, 440, 443, 447*
system on a chip *41*
systems to replace driver's control *300*

T

teleconferencing *212*
telehealth *212*
test *243*
test automation *108*
testing *100, 237*
test methods and tools *302*
TFET *460*
thermal cameras *442*
through-silicon via *42*
THz spectrum *219*
tool chains *144*
tools *95, 144, 235, 237, 244, 248*
tools and methods for validation and certification of safety, security and comfort *290*
training datasets *302*
transcriptomics *407*
transfer learning *183*
transmission grid *475*

transport systems 304
trustable 128
trustworthiness 235, 237, 297, 300
trustworthy 96
trustworthy social media 441

U

UL4600 302
ultra-low power 48, 246
unmanned air vehicles 296
updates 239, 245
upgradability 100
urban agriculture 406
uugmented reality 384

V

V2X 292, 299
validation 102, 302, 303
validation costs 302
validation of the safety and reliability of the automated mobility systems 289
validation toolchains 302
vehicle-in-the-loop 303
vehicles 302
verification 102, 302, 303
verification and validation 245
verification & validation 300
vertical indoor farms 406
vertical interconnects 51
VIL 303
virtual connectivity architecture 226
virtual design of experiment 265
virtual engineering 241
virtualisation 105, 219, 268
virtual release of ECS through referencing 266
virtual validation 303
virtual validation toolchains 302
vital signs 387
VLSI 114
von Neumann 42
VR/AR training 435
V&V 96, 238, 245, 248, 300, 301
V&V methods 300
V&V processes 108

W

wafer- level packaging 49
wastewater 399, 414, 420
wastewater treatment 412
waterborne transport 298
water distribution 420
water management 444
water quality 399, 412, 420
water resource management 404, 412, 420, 423
wearables 382
wide-bandgap materials 45, 48
WiFi 209
wire bonding 50
wireless communication technology 296
wireless sensor networks 406

Z

zero emissions 36, 296