

1.2



Foundational Technology Layers

COMPONENTS, MODULES AND SYSTEMS INTEGRATION

1.2 Components, Modules and Systems Integration

1.2.1 Scope

Development and production of smart electronic components and systems (ECS) requires physical and functional integration (PFI) of several functionalities into a new physical entity at component, module and system levels (CMS). 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. 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, interoperable and reconfigurable where possible. 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 on-chip integrated systems (SoC) covered in Chapter 1.1.

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 this chapter and in Chapter 1.1, from their specific points of view. Particularly, alternative technologies (such as additive manufacturing), complementary materials (both at the functional and structural/substrate level) and heterogeneous approaches to assembly, integration and advanced packaging are considered in this chapter. The term heterogeneous integration is used in its widest meaning: a component should be taken to mean any unit, whether individual chiplet/die, MEMS device, passive or active component or assembled package, that is integrated into higher order single components, modules or systems. Developments of heterogeneous integration technologies and platforms include also flexible electronics and photonics solutions. On the other hand, advanced packaging represents the suite of novel technologies, processes and competences that – in a cost-efficient, environmental sound way – allows for the physical, electrical and functional integration of any set of technological diverse components required to build an advanced system in a way that can safely interact with its application environment.

Smart CMS 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 functionalities such as 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**.

The methods, processes and schemes required for the design, production, assembly and testing of the various components, modules and systems and their integration need to be devised with appropriate quality, reliability, repeatability as well as scalability and sustainability (circular economy, CO₂ footprint, life cycle considerations, efficient use of resources).

Considering the new requirements imposed by modern and future smart systems, mastering the integration technologies at CMS levels is a significant capability of European industries. Such a strength needs to be sustained and reinforced to ensure Europe's leading position in smart systems engineering, as well as to bring innovations into real-life reliable and sustainable products, services and markets.

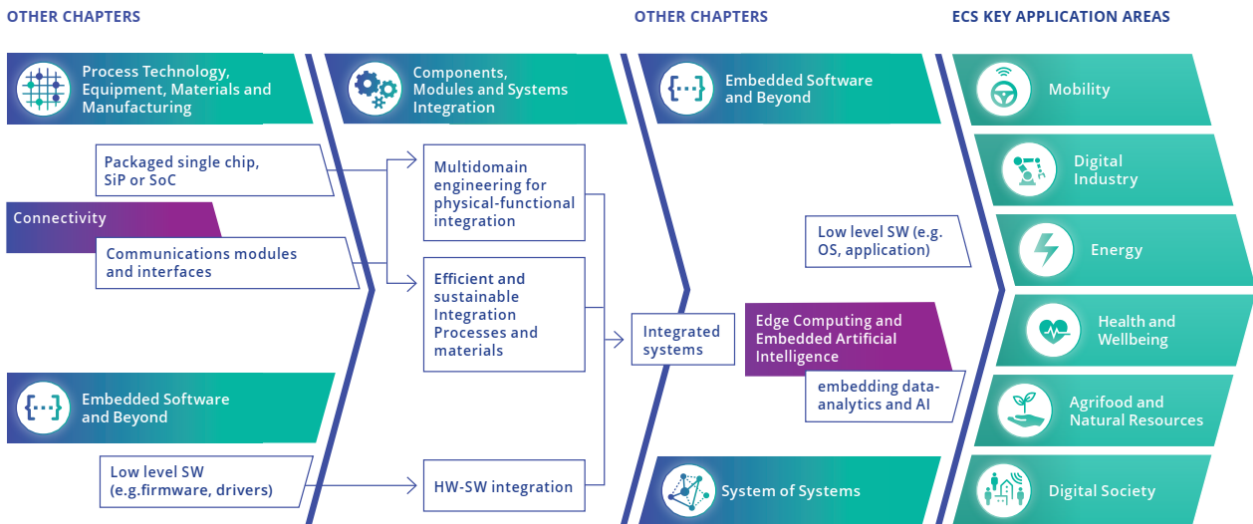


Figure 1.2.1 The Components, Modules and Systems Integration Chapter focuses on physical-functional integration of devices and components into subsystems and systems, using sustainable and efficient materials and integration processes.

1.2.2 Application breakthroughs

Technology advances at CMS level will have a key impact on applications. Future smart CMS will show a strong increase in functional and structural complexity and higher integration levels. They will show more diverse features and material integration in even smaller form factors.

With the ongoing, consistent societal digitization trend in all areas (edge-IOT applications, mobility, telecommunications, medical...), cyber-resilient, long-term available and digital storage of data, OS, firmware and boot media, long operational lifetime and adaptability to variable conditions for ordinary or critical application and infrastructure are coming to the fore.

Applications are the drivers for such approaches:

- Communication landscape with 5G, 6G and increasing data rates, including non-terrestrial networks (NTN), time-sensitive networks (TSN) as well as navigation and localization, including optical integration, components and systems for fiber networks.
- Autonomous systems in mobility, transport, logistics, manufacturing or control of buildings and micro-grids, etc., ensuring faster time response and decreasing the impact of human error.
- Monitoring at remote or difficult to access locations, e.g. structural health monitoring of infrastructure (bridges, tunnels, civil structures) or harsh environments supported by unattended systems, able to operate reliably with power autonomy and decision-making enabled at the edge.
- Healthcare landscape with applications moving towards prevention, diagnostics, therapy and rehabilitation, and life science and pharma domains is moving towards personalized medicine and regenerative medicine smart multifunctional systems, deployable in the body, on the body or around the body.

- The transition in mobility towards zero-emission power trains, with their significant cost and energy efficiency challenges, including 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 down to lot-size-1.
- Progression to scalable, fault tolerant and ultimately self-monitoring and repairable/re-configurable networks particularly for long life span applications such as environmental and structural health monitoring.
- Sensing of environmental parameters in smart agriculture, livestock or aquaculture, in manufacturing and working places, at home and in urban areas, e.g. for higher yield, energy efficiency and well-being.
- Imaging and audio applications including VR/MR/AR applications for security, healthcare, digital industry, (precision) agriculture, food industry, digital society (television, social media) and perception, requiring deployability, portability and functionality of electronics, photonics and information systems.
- Enabling repair as business, including repair index and set-up of repair processes. This also includes self-monitoring for condition evaluation.

1.2.3 Major Challenges

The following Major Challenges are identified:

- **Major Challenge 1: Functionality.** Developing new features for power, sensors, actuators and smart systems via new materials and methods enabling miniaturization and optimized performance.
- **Major Challenge 2: Advanced integration solutions.** Leading edge and advanced packaging technologies, design, materials, testing, including chiplets and integration on system level.
- **Major Challenge 3: Heterogeneous integration.** System-technology co-optimization for integration technologies, processes and manufacturing enabling cost-competitive smart systems supporting strategical autonomy.
- **Major Challenge 4: Sustainability.** Sustainable components, modules and systems and their integration processes to minimize their environmental impact over the entire lifecycle.

1.2.5.1 *Major Challenge 1: Functionality*

1.2.3.1.1 State of the art

Physical and functional integration (PFI) considers the development of new elements and methods enabling more functionalities to be integrated physically on CMS, in the most effective form factor. This requires interdisciplinary technology innovations as smart CMS may utilize a combination of features based on nano-electronics, micro-electro-mechanic, thermoelectric, magnetic, photonic, micro-fluidic, optical, acoustic, radiation, radio frequency, biological, chemical and quantum principles. Furthermore, many types of devices are to be integrated together, such as sensors, actuators, energy generators, energy storage devices, data processing devices, transceivers and antennae. Different technological approaches such as mainstream silicon technologies, MEMS/NEMS, MOEMS and LAE can be combined for the synergistic assembly of electronic and photonic devices.

PFI goes beyond the compact monolithic SoC approaches supported by the semiconductor technologies covered in the **Process Technology, Equipment, Materials and Manufacturing** Chapter. It addresses System

in Package (SiP) realizations involving different integration methods of components with a higher degree of technological heterogeneity into different platforms, including Integrated Circuit carriers, PCB boards, additive manufacturing on flexible or hybrid substrates, and co-packaging of optics and electronics.

PFI requires not only the integration of physical components together, but also the co-design and integration of software, especially embedded software and embedded AI accelerators, to create reliable and sustainable functional systems. This also extends to the development of modular architectures that enable such systems to be configured dynamically and optimally for a given application. However, this chapter concentrates on the physical integration of hardware, including computational devices into systems, while leaving the software edge to the **Embedded Software** Chapter.

1.2.3.1.2 Vision and expected outcome

Given the broad range of physical scenarios they face, smart CMS need to interact with many environments, ranging from lab to industrial and harsh environments to in vivo.

There is a multitude of operational issues affecting CMS regarding energy, performance and size. With respect to energy, for portable IoT devices, there is a need for low-power operation and provision of energy autonomy (self-powered devices or devices providing autonomy adequate to meet the application need (lifetime, service intervals, etc.), 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. Heterogeneous integration and advanced packaging and interconnection technologies need to be utilized to achieve the best performance in the smallest system-level form factor with the lowest power consumption, or at least take energy availability into account. In high-end consumer electronics, high-performance and ultra-dense compact interfaces at all integration levels are needed, from chiplets and chip assembly and packaging to component and module level connectors and connections with an increasingly widespread photonics communication approach.

MEMS/NEMS/MOEMS development focuses on sensors and actuators that benefit from the free surfaces and volumes that MEMS/NEMS/MOEMS processing is able to produce in a semiconductor substrate. The former relies 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 piezoelectrically, electrostatically or electromagnetically driven 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) enable new applications and improved performance for MEMS devices, e.g. in acoustic RF filters, in optical systems such as lidars and in ultrasonic sensing. MOEMS sensors such as microbolometer thermal imagers which are MEMS above IC components also rely on the thermal resistance change of thin pixel membranes induced by the absorption of infrared radiation. For hydrogen detection applications, existing MEMS technologies for pressure sensing are used and optimized. Additionally, new MEMS concepts for hydrogen detection are assessed to enable the future hydrogen economy.

The technical challenges for new and future integrated photonic CMS initially lie in a suitable co-design strategy (including associated methods/tools) of the various technologies to be combined as well as in their common processability and hardware integration (compatibility). The high level of integration also requires a special focus on thermal management, optimized thermal design, and suitable cooling concepts. This aspect, as well as other requirements, will determine the design and technology of future packages of photonic components. A particular focus is on those cases in which photonics and electronics have to work together at high bandwidths, such as very high-capacity transceivers, interfaces to electronic switching circuits in communications and data systems, high pixel-count active sensors, 3D imaging and displays.

Another technical challenge is the lack of standard solutions for hybrid integration. Additionally, we face a lack of standards for development (e.g. qualification testing) or even legal framework conditions (e.g. for the regular use of smart glasses and similar applications).

Heterogeneous integration technologies are strongly driven by consumer applications, such as the various types of portable and handheld devices. The manufacturers and associated supply chain for these high-volume applications are primarily based in Asia, and so for PFI Europe needs to reinforce its supply chain of integration and packaging solutions. The convergence between sensing and imaging domains for consumer applications, for example face recognition and augmented reality (AR) based on consumer lidar solutions, requires co-integration of (high-speed) electronics and Integrated Photonics into compact systems. Further, portable consumer electronics utilize flexible structures and technologies, which aim at even thinner and more flexible electronic components and systems 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 moulding, 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 from touch panels to RF antennas, control electronics, embedded lighting and sensors/actuators.

One of the key application drivers for the PFI of smart CMS is the IoT and its sensor nodes, which require a wide range of sensor and actuator functionalities, combined with data processing and wireless communication, and with power autonomy provided by energy storage and harvesting devices. Without an adequate alternative to primary batteries, IoT will not meet in full its deployment expectations. This also requires the development of low-power solutions for sensors and actuators, as well as radio communication components and processing. Thermal management challenges introduced by increased functionality in a minimum form factor need to be solved. New and improved energy storage, especially low-leakage rechargeable storage devices, in many cases capable of operating in harsh environments (temperature, ingress, in-vivo) needs to be developed as well as universally deployable and scalable harvesting solutions to improve the case-specific devices used today. In addition to this, it is important to improve in low-power techniques at the system level with co-design of hardware and software and overall system architecture, e.g. in wireless sensor networks, to ensure reliable, sustainable and energy efficient data collection and processing systems attending to the energy available and the possible processing capabilities split at the edge, gateway and cloud. Reliable and fault-tolerant wireless networks are required for applications where long-term continued sensing is critical (e.g. structural health monitoring of civil infrastructure).

Another domain strongly reliant on PFI are Electronic Control Units (ECUs). Due to their complexity and high degree of integration, these systems benefit from advances in generative design, miniaturization, scalability, increased processing power, cybersecurity, AI and machine learning integration, prognostics and health management as well as sensor fusion.

Components to provide power efficient computational resources, i.e. low-power microprocessors and devices with novel computational architectures such as neuromorphic devices, are needed, as are low-power computational methods, including distributed and low-power AI solutions in hardware, software, and in-sensor and data fusion data processing. In addition, reliable, energy-efficient, scalable, low-loss interconnection and packaging solutions are a necessity.

Smart CMS 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 of substrates and materials (e.g. Si, ceramic, polymer, glass, metallic glass), in packages and in systems, extending the coverage of the usual materials in semiconductor-based technologies. Many of the new features required by future smart systems can only be achieved by

introducing novel materials into the devices and systems, from back-end of the line processing of the microchips, or by post-processing on CMOS, to novel IC carrier technologies, including fan-out wafer level packaging and other SiP technologies as well as PCBs or in printing, additive manufacturing or other means. The development of new materials and the compatibility of those (with regard to e.g. process compatibility, environmental compatibility) is critical to the future development of PFI.

Quantum technology provides a new modality for More-than-Moore technologies not industrially considered earlier due to technology limitations in field-deployability, extreme cooling requirements etc. Recent years have seen rapid technological developments in the technological readiness of many quantum technologies: Quantum sensors, especially those based on gas cells, are being industrialized and miniaturized, promising better stability and accuracy of measurements, e.g. in magnetometry and inertial measurements. Quantum computers are developing into larger and more powerful machines year after year. Quantum communications, or quantum key distribution (QKD), enable secure encryption based on quantum states of photons. The rise in the applicability of quantum technology is based on successes in materials, fabrication processes and quantum science itself, but also in major part in the successful development of enabling technologies, such as control and low-noise readout electronics, packaging and heterogeneous integration and cryogenic cooling solutions, many of which are based on the successes and processes of electronics and semiconductor industry. Hence, the further development of these enabling technologies should be considered in detail.

The following key focus areas address the multimodality of ECS, which goes beyond semiconductor technology, requiring advanced packaging and heterogeneous integration of diverse materials, components and platforms. Full coverage of the physical-functional integration requires considering both the physical integration technology platforms and the functionalities of the integrated systems.

1.2.3.1.3 Key focus areas

- Sensing, imaging and actuation:
 - Sensors and actuators leveraging the integration of MEMS/NEMS, MOEMS and micro-optics elements.
 - Sensors and actuators for biological, medical and diagnostic applications, and for sensing of human vital signs and biomarkers, as well as for selective detection of gas and volatiles, allergens, residues/pollution in food/water, atmospheric particles, hazardous substances and radiation.
 - Sensors and systems enabling integration behind OLED and sensing through the OLED display.
 - Smart surfaces for HMI including integrated sensors for micro-LED and mini-LED displays.
 - Sensors and systems for sensing and imaging in the short wavelength infrared range, based on Ge on Si Integration or Pb-free quantum dots, enabling a broad range of new applications in the areas of lighting, biotechnology and life sciences, photovoltaics and information processing.
 - Advanced global shutter and rolling shutter CMOS Image Sensors (CIS) based on novel pixel technology for VIS-NIR imaging applications, with the goal to improve the performance, sensitivity, and efficiency of VIS-NIR CIS pixels, enabling high-quality imaging across a broad spectral range, as well as infrared imaging.
 - Imaging systems: lidars and radars, including multi-modal and hyperspectral, i.e. spectrally resolved, sensors.
 - Sensors and systems utilizing quantum principles, e.g. single photon sensors, including required cryogenic and cooling components and systems.
 - Devices with new features and improved performance for sensing and actuation using novel materials (metal nanowires, carbon nanotubes (CNTs), graphene and other 2D materials,

- cellulose nanofibers, nitrogen vacancies in diamond, metamaterials, metallic glass etc.), in combination with, or integrated on, CMOS.
 - Sensor fusion and virtual sensors including appropriate data and communication infrastructure, e.g. for condition monitoring, prognostics and health management for ECUs.
 - Ultra-low power event-based sensors, e.g. inertial motion & image detection for asset tracking, incident/anomaly detection, etc.
 - Dedicated LED and laser light sources from UV to visible to IR for sensing applications by avoidance/replacement of hazardous material (e.g. Cd/Pb-free QDs for color conversion, UV-C LEDs instead of Hg-lamps).
 - Materials that ensure the hermetic sealing of sensors, actuators and systems and at the same time contribute to the miniaturization of components.
- MEMS technology
 - CMOS or GaN-compatible thin film piezoelectric materials, such as ScAlN for piezo-actuated MEMS sensors and actuators.
 - Acoustic piezo-MEMS devices, pMUTs, and Acoustica RF filters for high frequencies above 6 GHz.
 - Audio MEMS systems such as micro speakers with more advanced integrated functionality, such as amplifier and integrated noise canceling (ANC).
- Integrated Photonics
 - New materials for active photonic devices, such as 2D materials, Lithium Niobate, Indium Phosphide; for improved performance, such as higher bandwidth in modulators, and detectors.
 - Light sources (e.g. μ LEDs, lasers and laser modules) with higher power and better performance and with tunable wavelength, using external cavity on photonic integrated circuits (PIC). Due to the high level of integration, electronic and photonic components must not be treated independently. Development of such components goes beyond the scope of the ECS-SRIA and is handled by Core Technologies Working Group of Photonics²¹.
 - Microbolometer thermal imagers with integrated optics and edge AI recognition for safety and mobility applications such as Automated Emergency Braking (AEB) and sensing for autonomous vehicles. Pixelated light sources for illumination, visualization and communication purposes including vertical hetero-integration of III-V materials on Silicon.
 - New waveguide materials and components to expand the wavelength range from UV up to mid IR optical elements for beam shaping and manipulation (like ultra-thin curved waveguides, meta-lenses, tunable lenses and filters, next generation holograms, ultra-wide-angle holograms).
 - Display technologies (like OLED-on-silicon, micro-LEDs, MEMS-mirrors, Phase parrays) and sensors (e.g. for eye tracking).
 - New devices for Quantum PICs.
- Flexible electronics
 - Sensing devices and power sources compliant with hybrid integration in wearables, considering flexibility, durability (e.g. washability) and biocompatibility.
 - Flexible and stretchable sensors and modules, e.g. OLED displays, OPVs, touch surfaces and other sensors/actuators, conformal antennas.
 - Functional materials for flexible and stretchable devices; organic and inorganic semiconductor materials and inks, perovskites for OPV.

- Barrier materials, dielectrics, and transparent conductor materials and inks for flexible electronics and additive manufacturing.
- Communications
 - Module-level high-speed wireless communication features, including current and new frequency bands.
 - High-speed photonics communications modules beyond 1 Tb/s.
 - 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.
 - Energy and application context aware comms that can dynamically adapt the architecture (edge, gateway, cloud) to meet sensing, processing and actuation needs based on limited energy available, especially at the edge. Continuous delivery of new features and fixes through Over-The-Air (OTA) updates to ensure the security of the device over time and reduce the digital waste by increasing the life span of a device.
 - Strategies and components for Electromagnetic interference (EMI) mitigation and reliable operation in harsh environmental conditions.
- Energy and thermal management
 - Low-power/low-loss modules for low-power sensing, actuation, processing and communication.
 - Multi-source power architectures with digital interfaces driven by dynamic and context aware algorithms that can adapt based on energy available versus needed for sensing, actuation, processing and communication.
 - Energy-autonomous multi-sensor modules and systems including energy harvesting, sensing, actuation, processing and communication.
 - Power management components and modules compatible with harsh environments (high temperatures, vibrations, bio-compatibility, ingress, electromagnetic interference (EMI) conditions for industrial, automotive, med-tech and space technology).
 - Devices using 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 of energy storage devices or new lightweight energy harvesters for mobility and transportation applications.
 - Solutions for thermal management for integrated photonics and RF systems at different integration levels including advanced and active cooling systems.
 - Thermal management and smart cooling systems for industrial applications and harsh environments.
 - Efficient smart compact cooling solutions and approaches for quantum devices and cryogenic multiplexing with semiconductors or superconducting devices.
- Information processing
 - Component and system-level features for self-diagnosis and module-level signal processing and control features for self-diagnosis, self-monitoring, and self-learning and self-repair.
 - Sensor level hardware and software solutions for security and privacy and data reliability.
 - Machine learning and artificial intelligence and data analysis at the sensor, module and systems level, i.e. on the edge data analysis embedded at different levels for smarter devices, including AI at sensor level.
 - Integrated and scalable solutions, both Software and Hardware integration with increased processing power for more sophisticated features, especially for edge AI and ECUs.
 - Use of quantum computing and Integrating quantum computing for data-analysis.

- Integration of electronic components in electronic control units:
Another domain strongly reliant on PFI are Electronic Control Units (ECUs). Due to their complexity and high degree of integration, these systems benefit from advances in generative design, miniaturization, scalability, increased processing power, cybersecurity, AI and machine learning integration, prognostics and health management as well as sensor fusion.
 - Sensing, imaging and actuation
Sensor fusion and virtual sensors including appropriate data and communication infrastructure, e.g. for condition monitoring, prognostics and health management for ECUs.
 - Information processing
Integrated and scalable solutions, both Software and Hardware integration with increased processing power for more sophisticated features, especially for edge AI and ECUs
 - Advanced packaging and SiP technologies
Robust heterogeneous 3D integration of sensors, actuators, electronics, processing units, communication, RF front-end components and energy supply into miniaturized systems.

1.2.5.2 Major Challenge 2: Advanced integration solutions

The major challenge Advanced integration solutions aims to address the growing demand for smaller, more efficient, and reliable electronic components. This challenge will focus on developing advanced packaging technologies that enable the integration of multiple functions and components into a single package, while also improving thermal management and reliability. Key areas of research will include advanced materials and manufacturing processes, as well as the development of new design and simulation tools to optimize the performance of integrated electronic packages. By fostering collaboration between industry, academia, and research institutions, this agenda seeks to position Europe as a global leader in advanced electronic packaging solutions.

1.2.3.1.4 State of the art

The state of the art in electronic packaging worldwide is characterized by a strong emphasis on miniaturization, integration, and reliability. Globally, there is a significant focus on developing advanced packaging technologies that enable the integration of multiple functions and components into smaller and more efficient packages. This includes the use of advanced materials, such as organic, silicon or glass substrates and advanced interconnect technologies, as well as the development of innovative manufacturing processes, such as 3D integration and wafer-level packaging. Main research focus worldwide is on chiplets technology. Additionally, there is a growing emphasis on improving thermal management and reliability through the use of advanced simulation and testing methods.

The European industry is actively involved in revitalizing electronic packaging technologies and is a key player in the global landscape, especially in the field of electronic packaging for harsh environments. European companies and research institutions are at the forefront of developing innovative packaging solutions for power electronics, contributing to the overall state of the art in electronic packaging worldwide. Further collaborative efforts and research initiatives are required, to keep the European industry in leadership position.

1.2.3.1.5 Vision and expected outcome

The Advanced integration solutions challenge envisions a future where electronic devices are smaller, more efficient, and reliable. The expected outcome is to establish Europe as a global leader in advanced packaging technologies, with a focus on miniaturization, integration, and reliability. Through initiatives like the Pack4EU project, the vision is to develop innovative packaging solutions that enable the seamless integration of multiple functions and components into smaller and more efficient packages. This will be achieved through 9 recommendations (source Pack4EU):

- Implementation of an **Industrial Transfer Instrument** dedicated to semiconductor packaging bridging the gap between prototyping and production.
- Establishment of a **High-Level Packaging Board** composed of industry leaders to guide strategic directions driven by market needs, ensuring innovation in packaging standards and practices.
- Implementation of a **Technical Expert Group** for developing and updating a **Roadmap for Advanced Packaging** in Europe.
- Creation of **Open Piloting Facilities** for small and medium volume production as a seed for growing European Advanced Packaging capabilities.
- Development of tools and methodologies for a **Design-to-X** approach & Standardization for an OPEN European Co-Design Ecosystem.
- Consolidation of international relationships through open calls on **Sustainable Packaging Materials and Substrates**, for example in liaison with IAM4EU and ERMA.
- **A strategy for training and skills development** including: Bridging research and education and facilitating international exchange on training through an EU Education Hub and Building a framework for access to EU-funded research pilot lines for students.
- Support for **Small and Medium Enterprises** through dedicated open calls applying, for example, cascade funding schemes or other funding instruments dedicated/adapted to SMEs.
- Creation of a **Pan-European Network** for Advanced Packaging to federate and strengthen the European ecosystem.

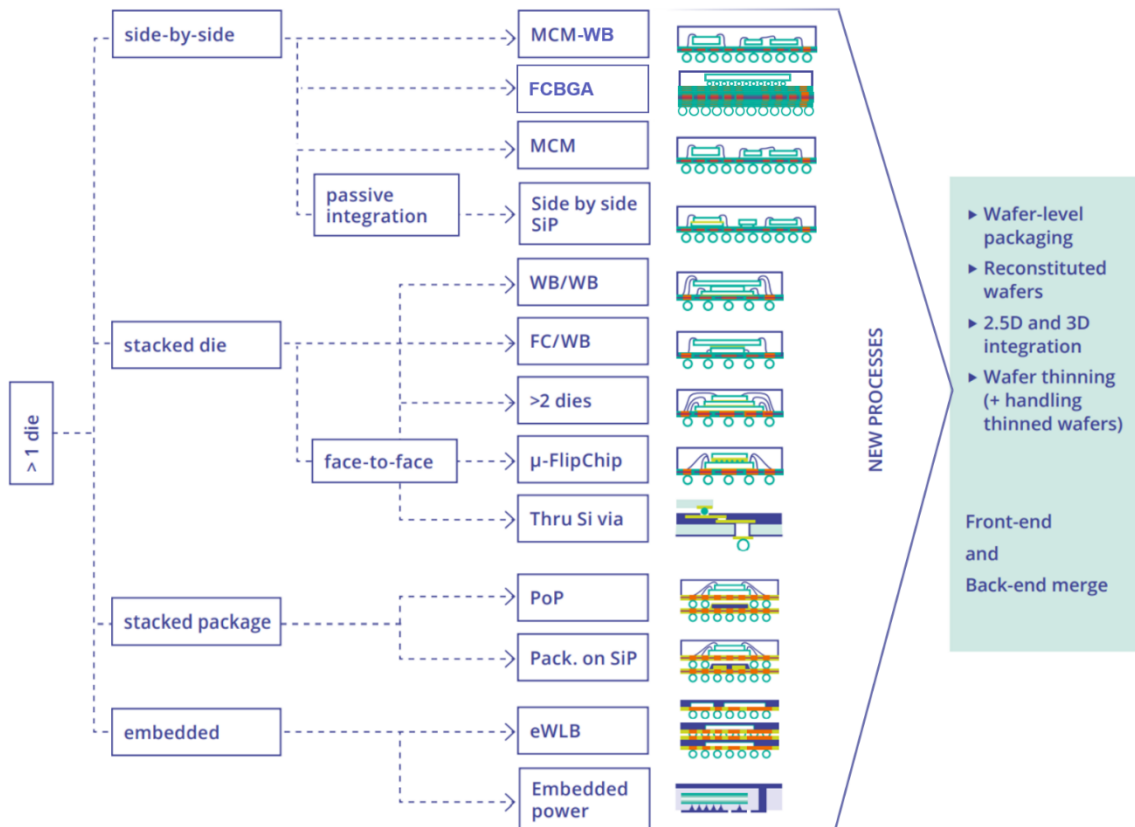


Figure 4 System in a package (SiP) examples. With merging of front-end and back-end, almost unlimited possibilities enabled (Source: Andreas Grassmann – Infineon – 3D Systems Summit)

1.2.3.1.6 Key focus areas

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

Advanced packaging and SiP technologies

- Robust heterogeneous 3D integration of light sources, sensors, actuators, electronics, processing units, communication devices, RF front-end components and energy supply into miniaturized systems, often working in harsh environments.
- Embedding of power sources (energy harvesting transducers, batteries, supercaps, etc.) into a package (PwrSiP).
 - Increasing functionality in IC Substrates for high-efficiency power delivery including voltage regulator circuitry and integrated capacitances and other passives. The solutions can entail specific passives dice as part of a SiP. Additionally, fine structuring capability achieving high bandwidth interconnections has to be reached either sequentially (2.1D) or recombining separated manufactured carriers (2.3D and 2.5D).
- IC carriers with integrated voltage regulator and capacitance increasing the power delivery efficiency, as well as finer structuring in IC carriers: below 5/5 μ m line width and spacing and finer micro-vias (below 15 μ m diam.).
- Chiplet integration concepts
 - Multi-node chiplets for compute applications involving high speed chip-chip interconnections with high resolution electrical and optical routing in substrate or redistribution.

- Heterogeneous Integration of MEMS, Quantum Computing, Power, etc. into Chiplet-based systems.
 - High density (HD) substrates, incl. HD routing components as bridges as enabler for successful chiplet-based systems.
 - Low stress assembly using low temperature assembly/interconnections processes, for example nanowires.
 - Virtual prototyping methods to ensure low warpage design of the chiplets with stress-minimization.
- Integration with biological and molecular systems, including fluidics and surface coatings and functionalization materials and methods for multi-functionality on the same base structures, e.g. biosensor arrays on Silicon.
- New functional materials for packaging that enable integration of sensing or other functionality or enhanced functionality into the packaging itself, e.g. packaging as a part of the antenna or sensor functionality, e.g. embedded heatsinking/spreading to increase the thermoelectric energy harvested.
- Customized materials and methods for housings and coating features and new substrate materials for specific requirements: high-efficiency and high-power density, high frequencies, disposable, bio-compatible, non-fossil, harsh environments.
- Rapid prototyping and manufacturing technologies (additive manufacturing, 2D and 3D additive technologies, etc.).
- High-performance materials for passives enabling close coupled passives for high-density heterogeneous integration such as magnetic cores, high-k dielectrics.
- Ultra-dense and small interfaces in all integration levels, from chip assembly and packaging to component and module level connectors and connections.
- Integration of different sensors and sensor hubs for sensor fusion (e.g. combination of acceleration sensor, microphone, micro speaker for enhanced noise cancellation).
- Manufacturing and characterization processes for hermetic sealing of components or subsystems with low leakage level.
- New failure analysis tools and methodologies including digitalization methods such as digital twin, AI/ML to improve efficiency and robustness for leading edge and advanced packaging and shorten development time.
- Innovative equipment and methodologies supported by digitalization methods for pre-assembly of thin silicon dies to improve production quality.
- Interconnect technologies that allow 3D stacking as well as horizontal interconnecting of dice and chiplets. This also includes interconnects through optical interfaces, most notably off-chip, but also within a package.
- Packaging for RF application technologies:
 - Solutions for high-frequency miniaturisation, such as for mm-wave applications (> 60 GHz) and for > 100 GHz, including antennae integration THz applications for which no package solutions currently exist.
- Packaging for photonic application technologies:
 - Solutions for advanced optical functionalities in the packages, either for sensors (visible, NIR, infrared), or for PIC.
 - Specific solutions for the signal conditioning of other sensors (mechanical, physical, chemical...).
- Packaging for power discrete packages and power modules:
 - High-Tg and high-thermally-stable polymer materials for packaging and high-performance TIMs that will enable more efficient operation of WBG devices.
 - Integration of power devices with logic and sensors in one package.
- Enhanced reliability, robustness, and sustainability technologies:

- Solutions for high reliability, robustness and high quality taking into account packaging materials and related interfaces. 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 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.

1.2.5.3 Major Challenge 3: Heterogeneous integration

1.2.5.3.1 State of the art

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

Heterogeneous integration, from components up to the system level, requires engineering on many technology domains, such as power, signal integrity, EMC, thermal and mechanical. All such domains and their hardware and software interplay (power and communications) must be designed together to ensure a high device- and system-level performance and the necessary integration. The challenge here is to combine all these domains in the design and simulation of integrated systems, often with inadequate information of all the properties of the included materials, components and processes. Where possible historical data and related algorithms should be used to predict and optimize system level performance. This may involve changing sensing intervals and/or how and where data is processed and routed. Furthermore, standardized and interoperable design and simulation methods that enable and support such multi-physics and multimodal design and manufacturing must be addressed, with the possibility to parameterize not only the material parameters, but also the system parameters, e.g. variability in the quality of the contact (e.g. thermal, mechanical) between the transducer and the ambient energy sources in the case of power harvesting. Modelling and design tools for thermal, mechanical and electrical characteristics in small 3D packages, including moulded and additive manufacturing methods are needed, linking to the **Architecture and Design; Methods and Tools** Chapter.

Heterogeneous chiplet integration enables the creation of highly customized, optimized and advanced systems by leveraging specialized chiplets for different functions. It enables faster and cost-effective manufacturing, as smaller chiplets have higher yields and can be produced independently. Furthermore, the ability to integrate chiplets from different manufacturers cultivate a more competitive, flexible and dynamic ecosystem. Designing systems with multiple specialized chiplets requires advanced design tools and methods

to ensure the seamless functioning together. Each chiplet may have different power, performance and communication requirements, necessitating careful planning and integration (hardware and software). Developing cutting-edge interconnect solutions such as silicon, glass, and organic substrates-based interposers, through vias, and micro-bumping to enable high-density, high-bandwidth connections between chiplets. Thermal management is another key challenge, as densely packaged chiplets can generate substantial heat. Developing innovative cooling solutions and advanced materials is required to efficiently dissipate the generated heat to maintain performance and reliability.

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), 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, pilot lines and fabrication facilities and capacities need to be developed.

In integrated photonics, if it comes to monolithic integration, the optical waveguides and devices are fabricated as an integrated structure onto the surface of a substrate, typically a silicon wafer. As a result of integration, complex photonic integrated circuits (PICs) can process and transmit light in similar ways to how electronic integrated circuits process and transmit electronic signals. New waveguide and active materials are constantly developed, e.g. SiN waveguides on silicon or Ge detectors and 2D materials for active components, such as modulators or detectors. The fabrication of PICs consists of a multi-faceted integration problem, including monolithic integration, heterogeneous integration of active components (e.g. laser sources), and high-speed driving electronics for e.g. high-speed communications above 100 GHz bandwidth, thermal management and other functionalities, such as fluidic functions for bio and medical sensing. Further system development regarding integrated photonics includes an often 3D assembly of electronics and photonics with passive optical MEMS as well as optics components like lenses, mirrors and beam splitters.

Integration and packaging technologies for quantum systems are key enablers to make quantum sensors and other systems industrially applicable. The integration and packaging in quantum technology poses several non-typical requirements for preserving the quantum coherence. These requirements include use of non-typical materials, such as extremely-low loss dielectrics and superconductors. Further, the packaging must support extreme cooling or even cryogenic operation, either by integrating a cooler technology inside, or by being inserted in an external cryo-cooler, which also entails vacuum operation. Thermal conductivity and handling of thermal expansion of different materials at every level, from wafer and chip level integration methods, to packaging and connection to room temperature are critical. Especially quantum computing requires multi-channel high-fidelity control and read-out solutions, with accurate synchronization and timing, from low-frequency to GHz range to the optical range of frequencies, depending on quantum system modality. Cryogenic electronics, cryo-CMOS or similar, are developed for solving these requirements, at the same time increasing the integration level of the quantum system, by introducing the control and readout elements closer to the qubits or other quantum devices.

The critical requirements to enable new advanced applications are to ensure sustainable and cost-efficient manufacturing while providing optimal performance and reliability. Further important developments include integration of different silicon IC components into miniaturized multifunctional modules following different SiP approaches, combining technologies such as flip chip, bonding, lamination and substrate materials such as silicon, glass, ceramics and 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.

For many portable devices e.g. Wireless Sensors Network (WSN) edge nodes, the power source in itself becomes a more complex challenge to integrate materials and devices, moving from traditional batteries and capacitors. This requires a complex combination of energy harvesting transducers, primary and rechargeable storage devices that need to interact with PMICs, MCUs, sensors and transceivers. Collectively, they need to make decisions at a node and network (gateway, cloud) level on when to use versus store energy and where to take it from based on energy available. The physical mounting of transducers and electrically controlling their characteristics (e.g. impedance matching) will also be critical to maximize their performance.

1.2.5.3.2 Vision and expected outcome

The challenge of integration processes, technologies and the manufacturing of smart CMS 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, many industrial applications may require the availability of CMS in relatively small quantities over decades, which adds a new challenge to the scalability of manufacturing and implementation of the latest technologies.

The complexity and diversity of heterogeneous CMS substantially exceeds that of mere microelectronic components due to their multi-physics and multiple domain nature. In addition, the packages will include integrated functionalities, rather than being “passive” boards and frames. Integration and packaging methods should not compromise, but guarantee and even increase the performance of the interlayering components. Especially low-loss integration methods to enable integration of large RF systems or integrated photonics. These technologies would enable e.g. RF front-ends or active antennas for millimeter wave frequencies enabling novel beyond-5G telecom solutions, or in integrated photonic communication and sensing systems. Merging different PIC technologies to compensate for missing functionality in individual cases is based on a variety of technologies, such as die flip-chipping, wafer bonding, micro-transfer printing, edge coupling, and others. Amongst current examples, one that is particularly pronounced is the integration of III-V light sources with silicon photonics, which is missing from silicon technology on its own.

In this multifunctional and multimodal integration at CMS level, the development of manufacturing methods that meet the accuracy and repeatability criteria of high-quality and high-reliability products for a broad range of applications and constraints (physical, mechanical, thermal, environmental) is challenging and needs development. This method development shall be accompanied by process modelling leading to a digital twin for manufacturing allowing documentation, simulation and improvement of manufacturing challenges in a digital environment (see also Chapter 2.4).

Additive manufacturing can provide structural and functional solutions for smart CMS integration that are not feasible with traditional methods. These methods will enable zero-defect manufacturing starting at lot one. Although additive manufacturing also improves manufacturing flexibility, solutions for the cost-efficient scaling of these fabrication methods must be addressed. 3D CMS integration methods will need to be developed to provide greater functionality and miniaturization in a cost-effective, sustainable and scalable way.

With respect to this multi-modality of heterogeneous integration methods, the key focus areas are divided based on the main technologies: advanced packaging and SiP technologies, integrated photonics, flexible electronics, quantum systems and manufacturing methodology, as follows.

1.2.5.3.3 Key focus areas

- Advanced packaging and SiP technologies
 - Robust heterogeneous 3D integration of light sources, sensors, actuators, electronics, processing units, communication, RF front-end components and energy supply into miniaturized systems, often working in harsh environments.
 - Embedding of power sources (energy harvesting transducers, batteries, supercaps, etc.) into a package (PwrSiP) and on a chip (PwrSoC).
 - IC carriers with integrated voltage regulator and capacitance increasing the power delivery efficiency, as well as finer structuring in IC carriers: below 5/5 μ m line width and spacing and finer micro-vias (below 15 μ m diam.).
 - Multi-node chiplets for compute applications involving high-speed chip-chip interconnections with high-resolution electrical and optical routing in substrate or redistribution.
 - Embedding of power sources, ASIC drivers and audio MEMS sensor and actuators such as microphones and micro speakers into a heterogeneous SiP.
 - Integration with biological and molecular systems, including fluidics and surface coatings and functionalization materials and methods for multi-functionality on the same base structures, e.g. biosensor arrays on Silicon.
 - New functional materials for packaging that enable integration of sensing or other functionality or enhanced functionality into the packaging itself, e.g. packaging as a part of the antenna or sensor functionality, e.g. embedded heatsinking/spreading to increase the thermoelectric energy harvested.
 - New materials and methods for housings and coating features and new substrate materials for specific requirements: high power, high frequencies, disposable, bio-compatible, non-fossil, harsh environments.
 - Rapid prototyping and manufacturing technologies (additive manufacturing, 2D and 3D additive technologies, etc.).
 - High-performance materials for passives enabling close coupled passives for high-density heterogeneous integration such as magnetic cores, high-k dielectrics.
 - Ultra-dense and small interfaces in all integration levels, from chip assembly and packaging to component and module level connectors and connections.
 - Integration of different sensors and sensor hubs for sensor fusion (e.g. combination of acceleration sensor, microphone, microspeaker for enhanced noise cancellation).
 - Manufacturing and characterization processes for hermetic sealing of components or sub-systems with low leakage level.

- Integrated Photonics and co-integration with electronics
 - Photonic-electronic system integration based on integrated photonics, including high-speed RF electronics, MEMS/NEMS/MOEMS sensors, etc.
 - Multi-domain electro-photonic integration and electro-optic co-packaging.
 - Wafer-level integration of photonic and electronic components for smart emitters and detectors.
 - Enabling electronic-photonic systems by heterogeneous integration of active components on PICs (III-V semiconductors, ferroelectrics, ultra-low-loss waveguide materials). Heterogeneous integration processes and equipment for integrated photonics, including high-precision component placement and bonding, integration of active components on PICs (III-V semiconductors, ferroelectrics, ultra-low-loss waveguide materials) as well as low-loss fiber coupling to PICs.
 - Quantum PICs: Integration of single photon detectors and sources and quantum photonic systems in PICs.

- Flexible electronics
 - Integration towards low vertical form factor (<100 μm) and the miniaturization of external matching networks through 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 structural electronics (in glass, plastics, laminates, etc.).
 - New/alternative non-fossil, organic, biocompatible and compostable substrate materials, e.g. for implants, ingestibles, wearables, biosensors.
 - Adhesives, bonding materials and methods for integrating chips, light sources, drivers and sensors on flexible substrates.
 - Use of flexible Si-substrates for 3D form factors and for flexible electronics.
 - Integration and embedding of diverse materials and components such as antennae, PV panels, energy storage devices, magnetics, interconnect, heatsinks, displays, etc. in flexible or conformal electronics.

- Quantum systems
 - Materials and methods for integration and packaging of semiconductor electronics, Integrated Photonics and superconducting devices at cryogenic temperatures, including 3D technologies.
 - Integration and interfacing and cabling solutions for combining room temperature systems and cryogenic quantum components, sensors and systems.
 - Integration methods that enable scaling quantum systems efficiently, from wafer level 3D integration to module and system level.
 - Cryogenic electronics, cryo-CMOS and similar for increasing the integration level of quantum systems and enabling scaling up of quantum systems.
 - Development and miniaturization of cryogenic cooling systems, e.g. solid-state coolers.
 - Quantum PICs: Integration of single photon detectors and sources and quantum photonic systems in PICs.

- Manufacturing methodology, characterization and testing
 - Automation and customization in CMS integration for large-scale manufacturing, including Industry 4.0 techniques, design for manufacturing based on production data techniques, and lot-size-1 manufacturing, e.g. BIST (built in self-test) capability of components.
 - Manufacturing and testing tools (including tests, inspection) for CMS, enabling zero-defect integration.
 - Process modelling approaches with focus on productivity, yield, trustability and distributed manufacturing.
 - Material properties database for simulation and reliability based on a standardized ontology.
 - Design of new materials from properties requirements by the means of Materials by Design, materials genome and digital design approach.
 - Energy-effective joining methods, e.g. low-temperature soldering; selective heating processes (i.e. inductive or reactive) to limit overall temperature impact to the system while packaging.
 - Self-powered embedded sensors for ongoing performance and condition monitoring and tracking of devices, e.g. for provenance, life cycle assessments, field failure analysis and authentic validation.

1.2.5.4 Major Challenge 4: Sustainability

1.2.5.4.1 State of the art

In 2019, world-wide e-waste exceeded 50 million tons and is forecasted to grow to 70 million tons in 2030¹. The European Union is one of the most advanced actors in e-waste recirculation processes. Indeed, in this region 42.5% of e-waste is documented to be collected and recirculated as product or component or recycled as material, whereas this is the case for only 9.4% in Americas and 11.7% in Asia². This can be explained by the clearer European and national political support for such initiatives.

However, as increased integration will cause the borders between CMS 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 lifetimes extending to decades, thus the environmental regulations for recyclability cannot be known in detail by the time of product design. Nevertheless, early consciousness on the issue should preside the start of the product cycle. Based on identified challenges, regulatory measures under the Eco-design Directive are intended to establish design for energy efficiency and durability, repairability, upgradability, maintenance, reuse, repurposing and recycling. The European Commission presented its new **Circular Economy Action Plan** (CEAP) in 2020 to limit waste generation and encourage recycling, product repair and reuse. Part of this initiative is the digital product passport (DPP), which informs end-customers and businesses about products' sustainability. In general, the concept of the circular economy (CE) builds upon well-implemented strategies to prevent waste generation and includes eco-design rules during product design phase and measures for re-using products and components after a use phase.

The European Platform on Life Cycle Assessment (EPLCA) includes information on the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methods as a common way of measuring environmental performance ([EU Commission Recommendation 2021/2279](#)). The PEF and OEF are the EU's recommended LCA-based methods to quantify the environmental impacts of products (goods or services) and organizations.

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 the sustainability of the CMS production, including processes, materials and maintenance during the primary lifetime. The recyclability of the product must already be considered in the design and manufacturing phase to enable repairability, upgradeability, reconfigurability, extension of lifetime, and repurposing/re-use in a second life application, and finally the recovery of components and materials for recycling.

Given the increasing burden of improperly dealt with e-waste and considering that a significant part of CO₂ emissions arises from the fabrication of the ECS themselves, extending product lifetime is important for reducing ECS-related environmental load. This needs to be addressed by designs that enable repair or replacement of faulty components, avoiding the replacement of the full module or system. To fight obsolescence, hardware and software upgrades should be supported, even in field conditions. Reducing CO₂

¹ 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.

²NU/UNITAR SCYCLE – Nienke Haccoû

emissions during the lifetime of the system requires minimizing the power consumption at CMS levels while in operation by using low-power hardware and software technologies.

1.2.5.4.2 Vision and expected outcome

For increased sustainability of ECS, the circular economy, with its 9R framework (Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover) and eco-design, are the main tools to reduce the environmental footprint of ECS. Life cycle assessment as a framework will be used for identifying hotspots and checking results of the intended reduction. But ECS themselves can also be regarded as an enabler for a more circular economy.

Future ECS products must be environmentally friendly, covering all aspects from materials, manufacturing, operation and maintenance during their lifetime, considering recycling at their end-of-life. Activities must start by ensuring circularity (eco-design, environmentally friendly materials and manufacturing), employing a low CO₂ footprint over the whole life cycle, and facilitating the transition to a circular economy, wherever possible. Outcome activities will address:

- Non-fossil, recyclable, biodegradable and compostable materials, without releasing any dangerous materials or having other negative impact on the environment.
- Eco-design including eco-reliability of sustainable and more modular ECS.
- Sustainability and reducing energy consumption and environmental footprint of the manufacturing and integration processes.
- Increasing energy efficiency of ECS, during manufacturing and lifetime, and end-of-life.
- Upstream considerations and design for repair, upgradeability, dismantling, materials separation and recycling, lifetime extension and system health monitoring, self-monitoring and healing.
- Performance and condition monitoring, traceability, (predictive) maintenance, repair, upgrading, reconfiguring, recharging, retrofitting and re-use in second life, including ecosystems and tools to support these actions.
- Product indexes and digital product passports for ECS.
- Enablement of novel sustainable business models.

The development of integration processes based on new design tools will allow the dismantling of components, as their recycling and recovery of materials (urban mining) is essential. Therefore, system design techniques move towards eco-design where we need to rethink the use of multifunctional components and modules. Design for component separation and recyclability is generally required in the selection of materials and the integration technologies. Recycling technologies, as well as new approaches to second life of ECS and re-use in new applications, 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. Finally, we should of course minimize the number of batteries we use and dispose and improve recycling of batteries and battery materials.

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.

1.2.5.4.3 Key focus areas

- Eco-Design of ECS to promote circularity:
 - Use of replacement materials to comply with Restriction of Hazardous Substances Directive (ROHS) regulations (such as lead, mercury and other metals, flame retardants and certain phthalates, PFAS) and minimization of critical raw materials (CRM) dependence, including rare earths replacement for magnetics, inductors and power integrity.
 - Use of recyclable, biodegradable, compostable, non-fossil materials from sustainable sources in combination with the development of efficient and environmentally benign recycling techniques in accordance with the legislative agenda.
 - Less materials for higher functionalization.
 - Assessment of the environmental impact of ECS at the design stage, as a tool for sustainable ECS, using life cycle assessment (LCA) or similar framework.
 - Certified up-to-date data for LCA, PEF, PCR and EDP.
 - Development of design, fabrication, integration, recovery, reconfiguration/reuse/repairability and disassembly strategies for products (module dismantling, component recycling, material recovery) and also short-lifetime devices (e.g. single-use medical devices, radio-frequency identification, RFID, tags and printed sensors) to meet the existing and emerging regulatory requirements.
 - Improvement of system reliability as a means to guarantee and extend the lifetime of electronic products with the final objective of responding to material efficiency requirements and providing an optimal balance on a life cycle scale.
 - Increasing power efficiency of ECS during lifetime by using low-power techniques with context awareness or energy harvesting.
 - Extensive use of software to increase the sustainability of ECS by extending product lifetime through continuous optimization and adaptation, by making existing ECS more intelligent through the use of AI, in particular at the Edge, and by optimizing the resource usage through hardware and software co-defined strategies. Ensure the trustworthiness and reliability of the ECS, including its software components, with a special attention to approaches involving AI that must be secure, reliable and automatically and autonomously adapted.
 - Promote methodologies allowing for the co-design of ECS hardware and software involving simulations and realistic models, including AI-aided development tools, to continuously estimate key metrics. This must be complemented by instrumentation of the ECS hardware and software to continuously assess the achievements of the key figures of merit over the entire ECS lifetime (including shelf and post-decommissioning).

- Sustainable manufacturing of ECS:
 - Explore the extension of materials efficient wet/dry processes such as additive manufacturing methods and laser/mechanical subtractive processes. E.g. printing, that consume less resources (energy, materials, water) and are compatible with renewable materials, such as bio-based substrates. At the same time, additive manufacturing offers new design capabilities for circular, thin and flexible devices, even for single use (e.g. wearable electrodes) with specified end-of-life management.
 - Optimization of resources and processes in production environments with potential in-situ re-use and regeneration of base materials and chemicals.
 - Reduce energy consumption (and greenhouse emissions) in clean rooms through the use of renewable energy sources and energy-efficient technologies or tools.
 - Increase water reusage in electronics manufacturing facilities.
 - Improved analytics for hazardous production remnants

- Inline sensors to research and mitigate environmental risks of GHGs, PFAS and hazardous materials and their integration to abatement systems and process equipment
 - Improve gas abatement systems.
 - Solutions to value scarce material use and to work on alternative technology integration strategies.
 - Breakthroughs and development in recycling processes and solutions for energy storage components, such as batteries.
 - Moving towards CO₂-neutrality and zero waste ECS economy.
- Sustainable products and business models:
 - Encouraging sustainable supply chains.
 - Introduction of product category rules and product indexes (including info such as energy and resource efficiency, durability, reusability, upgradability and repairability, presence of substances that inhibit circularity, recycled content, remanufacturing and recycling, carbon and environmental footprints, expected waste generation and information requirements) for components and systems to encourage the use of LCA based environmental product declarations.
 - Digital product passports should be promoted, tested and then widely established.
 - Encourage new business models to see value in eco-design and recyclability.
 - Value repairability: An EU-wide repair index inspired by the French repairability index.
 - Condition monitoring for usage as well as for health/performance and anomaly detection.
 - Improve efficiency of e-waste recyclability by robotics, thereby increasing new value streams and business through reuse.
 - Life cycle traceability of components and systems to capture condition, carbon footprint, authenticity and recyclability.

1.2.4 Timeline

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

Major Challenge	Topic	Short Term (2024-2028)	Mid-Term (2029-2033)	Long Term (2034 and beyond)
Major Challenge 1: Enabling new functionalities in components with More-than-Moore technologies.	Topic 1.1: Sensing, imaging and actuation	<ul style="list-style-type: none"> • Selective gas-sensing • Disease monitoring and diagnostics platforms (in vitro, wearables) • Lidar and radar systems • Functional materials (piezo, ceramics, polymers, metamaterials) • IR sensors integrated with CMOS • H2 low and mid pressure sensors; H2 detection in exhaust 	<ul style="list-style-type: none"> • Selective detection of allergens, residues • Fluidics • Drug delivery • Affordable IR imagers • Hyperspectral imaging • Materials and concepts for Quantum sensors • H2 detection in ambient surrounding 	<ul style="list-style-type: none"> • Convergence of sensing principles (e.g. thermal, optical cameras with lidar/radar) • Multifunctional healthcare support systems (wearables, implants) • Integrated Quantum sensors
	Topic 1.2: MEMS technology	<ul style="list-style-type: none"> • Novel piezo materials and piezo devices for MEMS/NEMS • Micro-optical (MOEMS) components • Compact audio MEMS • Self-monitoring and -calibration 	<ul style="list-style-type: none"> • Integration for multifunctional sensors and actuators based on MEMS/NEMS and MOEMS • Strong mechanical actuation mechanisms • Low-power audio MEMS systems for ANC 	<ul style="list-style-type: none"> • Self-monitoring, correcting and -adapting MEMS/NEMS • Highly integrated multifunctional, dynamically adaptive and context recognizing sensors
	Topic 1.3: Integrated photonics	<ul style="list-style-type: none"> • Novel devices operating at different wavelengths than used for telecom • Co-packaging and integration of Integrated photonics and high-speed electronics • Photonic health and medical sensors 	<ul style="list-style-type: none"> • Tunable laser sources for PICs • Materials and devices for Quantum PICs. • Optical elements for beam shaping and manipulation (like ultra-thin curved waveguides, metalenses, tunable lenses and filters, next generation holograms, ultra-wide-angle holograms) • Display technologies (like micro-LEDs, MEMS-mirrors, Phase Arrays) and sensors (e.g. for eye tracking) 	<ul style="list-style-type: none"> • Growth of light-emitting structures on silicon and integration into photonic platforms • Analogue and Neuromorphic photonic computing
	Topic 1.4: Flexible electronics	<ul style="list-style-type: none"> • Si devices compatible with integration to flexible devices; thinned IC etc. • New flexible non-fossil materials 	<ul style="list-style-type: none"> • Large area flexible and stretchable sensors and actuators • Organic and biocompatible materials 	<ul style="list-style-type: none"> • Stretchable smart systems for wearables combining simultaneous biochemical and biophysical sensing • Metamaterial

		for flexible and structural electronics including active components, transparent conductors, barriers.	<ul style="list-style-type: none"> Wearable smart systems combining simultaneous biochemical and biophysical sensing 	sensors
	Topic 1.5: Communications	<ul style="list-style-type: none"> Real-time, low-latency, low-power, context aware, fault-tolerant and self-repairing networks for edge and IoT devices High-speed photonics communications modules beyond 1Tb/s Reduction of EMI 	<ul style="list-style-type: none"> 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 Energy constraint aware and adaptive networks at node and network level Accurate and stable clocks for 6G and quantum devices 	<ul style="list-style-type: none"> Quantum internet and cryptography Beyond 6G Digital twins at node and network level to help design and optimize energy constraint aware WSN architectures at planning and operational stages
	Topic 1.6: Energy and thermal management	<ul style="list-style-type: none"> Lightweight energy harvesters and storage Multi source energy harvesting PMIC operating down below 10mV and 10μW Low power components Energy storage devices for extreme temperature and harsh environments Energy autonomous systems Thermal management at different integration levels including advanced and active cooling systems Multi-modal device and system level energy harvesting/power consumption simulation models 	<ul style="list-style-type: none"> Low/zero power components and systems Solution for thermal management in integrated photonics Advanced encapsulation materials for energy harvesters Extend chiplet concept (design and manufacturing) to no-IC components Sensors and actuators for the optimization of battery cells usage during their entire lifetime 	<ul style="list-style-type: none"> CO₂-neutrality and circular economy for ECS Energy harvesting PMICs embedded in MEMS & NEMS WSN nodes with MCU, sensors, transceivers, etc.. Sensors embedded in energy source components for performance and condition monitoring, lifetime provenance and anomaly detection

	<p>Topic 1.7:</p> <p>Information processing</p>	<ul style="list-style-type: none"> • Security and privacy • Explainable AI, edge computing (HW and SW) • Hybrid modelling (physical and data-driven) • Federated data collection from edge to gateway to cloud, to minimize strain • Energy constraint aware and adaptive networks and architectures, particularly for battery-powered edge devices 	<ul style="list-style-type: none"> • 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) 	<ul style="list-style-type: none"> • Low-power AI • Neuromorphic on-the-edge computing for sensors and actors • Quantum computing • Quantum simulation
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<p>Major Challenge 2:</p> <p>Integration technologies, processes and manufacturing</p>	<p>Topic 2.1:</p> <p>Advanced packaging and SiP technologies</p>	<ul style="list-style-type: none"> • 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 • Embedding of power sources (batteries, energy harvesting) in SiP and IC carriers with digital interfacing • Embedding of power sources, ASIC drivers and audio MEMS sensor and actuators such as microphones and micro speakers into a heterogeneous SiP 	<ul style="list-style-type: none"> • Integration for harsh environments, and implantable electronics • System health monitoring and self-diagnosis, self-healing • Self-cleaning and self-healing materials • Integration of different sensors and sensor hubs for sensor fusion (e.g. combination of acceleration sensor, microphone, micro-speaker for enhanced noise cancellation). 	<ul style="list-style-type: none"> • Maximum functional integration in minimum volume/footprint Advanced photonics • Biological-electronics hybrid systems
	<p>Topic 2.2:</p> <p>Integrated Photonics and co-integration with electronics</p>	<ul style="list-style-type: none"> • Photonics integration with RF, sensors; electro-optic co-packaging • High-precision component placement and bonding processes and equipment • Low-loss fiber coupling to PICs. 	<ul style="list-style-type: none"> • Heterogeneous integration of active components (e.g. III-V) on PICs on wafer scale. • Metamaterials for beam shaping 	<ul style="list-style-type: none"> • Combining electrical and optical interconnects into an electro-optical IC carrier • Monolithically integrated quantum photonics including III-V quantum dots

<p>Major Challenge 3: Heterogeneous integration</p>	<p>Topic 3.1: Flexible electronics</p>	<ul style="list-style-type: none"> • Integration processes with flexible, structural and 3D conformable electronics • Materials for chip interconnection; ACA, ICA, flip chip etc. • Large area R2R compatible Interconnection processes and equipment for heterogeneous integration 	<ul style="list-style-type: none"> • Compostable and biodegradable substrate and housing materials • R2R compatible chip assembly and interconnection technologies on stretchable substrates 	<ul style="list-style-type: none"> • Stretchable electronics and system integration • Automated Interconnection processes and equipment for heterogeneous integration
	<p>Topic 3.2: Quantum systems</p>	<ul style="list-style-type: none"> • Materials and methods for quantum technology integration in cryogenic temperatures • Materials and components for low-loss and high quantum coherence • Cryogenic electronics, cryo-CMOS 	<ul style="list-style-type: none"> • Integration of quantum systems: superconducting, photonic, Silicon technologies • Solid state coolers • 	<ul style="list-style-type: none"> • Quantum SiP also in room temperature or with integrated cooling.
	<p>Topic 3.3: Manufacturing methodology, characterization and testing</p>	<ul style="list-style-type: none"> • I4.0 for manufacturing optimization • Additive manufacturing and rapid prototyping technologies and materials • Improved automation and customization in integration for smaller lots • Database of material properties for simulation and reliability • process model implementation as Digital Twins for Manufacturing Optimization 	<ul style="list-style-type: none"> • I4.0 for manufacturing optimization, Zero-defect integration • Automation and customization in integration for smaller lots. • Additive manufacturing and rapid prototyping technologies <p>Material by design approach</p>	<ul style="list-style-type: none"> • Automation and customization in integration, lot one. • Fully digitalized manufacturing process description – Digital Twin for Manufacturing

Major Challenge 4: Sustainability	Topic 4.1: Eco-design of ECS	<ul style="list-style-type: none"> • Replacement materials to comply with RoHS (e.g. PFAS) and minimize CRM dependence • Use of recyclable materials (e.g. moulds, resins) • Less materials for higher functionality • Life cycle analysis as tool for design • Development of design, fabrication, integration, recovery, reconfiguration/reuse, disassembly strategies • Designing for repairability, including modular approach, upgrades and maintenance • Certified up-to-date data for LCA, PEF, PCR and EDP • Eco-design benchmark values for electronic components • Availability and exchangeability of spare parts and tools • Improve system reliability to guarantee and extend the lifetime • Use low-power techniques with context awareness and/or energy harvesting 	<ul style="list-style-type: none"> • Cross-company reuse of “stable” chip designs, including More-than-Moore components • Methodologies allowing for the co-design of ECS hardware and software • Use of biodegradable, compostable, non-fossil materials • Breakthroughs in recycling processes, including energy storage components • Applying results of Green ECS to integrated photonics • Extensive use of SW to increase sustainability of ECS • Holistic sustainability assessment (social, economic, environmental) as tool for design • Recycling and materials for recycling (system level) • Energy efficient processes for manufacturing • Build sharing of information on LCA and Safe and sustainable by Design 	<ul style="list-style-type: none"> • Highly integrated re-usable circuit blocs • Circular economy of ECS • Solutions for full recycling and material recovery of ECS, including energy storage components • Environmental footprint and critically based recycling planning (final stage material recycling) • Set up repair process: failure characterization, repair and re-characterization; provide manuals, instructions, schematics and inexpensive spare parts • Warranties and safety-relevance need to be addressed
	Topic 4.2: Sustainable manufacturing of ECS	<ul style="list-style-type: none"> • Condition monitoring and predictive maintenance • Increasing the energy and resource efficiency and environmental footprint 	<ul style="list-style-type: none"> • Reducing energy consumption and CO₂ footprint of integration processes, tools and ECS systems • Inline sensors to research and mitigate 	<ul style="list-style-type: none"> • CO₂-neutral ECS economy • Zero waste added manufacturing to produce functional modules

		<p>of components, systems and modules</p> <ul style="list-style-type: none"> • Use of energy harvesting to minimize/eliminate battery replacement • Extension of additive manufacturing methods • Increase water reuse • Improved analytics for hazardous production remnants 	<p>environmental risks of GHGs, PFAS and hazardous materials and their integration to abatement systems and process equipment</p> <ul style="list-style-type: none"> • Processes for reuse and second life • Improved recycling and material recovery processes • Replacement of critical process steps to comply with RoHS (e.g. PFAS) • Work on alternative technology integration strategies 	<ul style="list-style-type: none"> • Recycling processes adapted for flexible, sustainable electronics with novel materials
	<p>Topic 4.3: Sustainable products and business models</p>	<ul style="list-style-type: none"> • Establish a repair index inspired by the French reparability index • Introduce product category rules and product indexes 	<ul style="list-style-type: none"> • Self-condition monitoring energy harvesting solutions to assure long term reliability and for anomaly detection • Repair as business (bonus-malus-systems) • A business model can emerge for third-party repair centers • Closing data gaps in circularity and recycling through Digital Product Passport • Improve efficiency of e-waste recyclability by robotics • Life cycle traceability of components and systems to capture condition, carbon footprint, authenticity and recyclability 	<ul style="list-style-type: none"> • Train skilled repairers; questions around re-certification