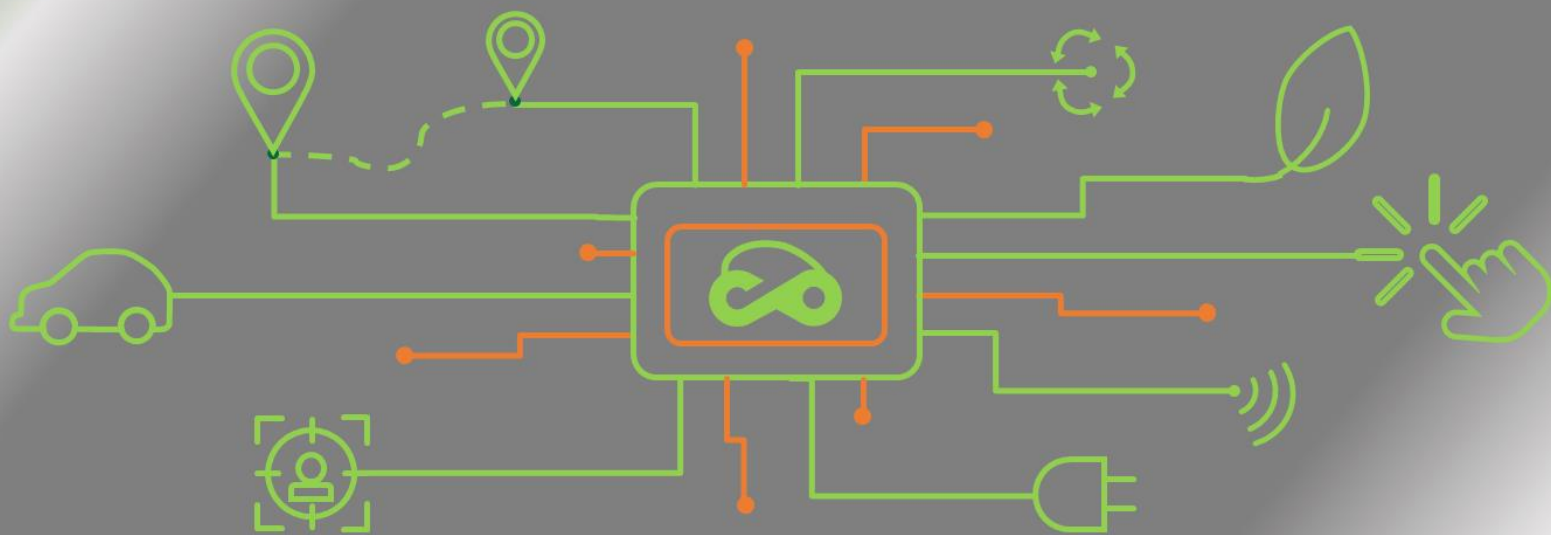




Unveiling Innovation Potential of Circular Approaches
in Automotive Electronics and Beyond

Vision for a circularity-driven functional electronics integration



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About UNICORN

The EU-Funded Research and Innovation Action UNICORN aims at supporting the green and digital Twin Transition. by promoting circularity in automotive electronics through decarbonisation, material recycling, utilisation improvement, and lifetime optimisation. The project emphasises the development and testing of innovative solutions, particularly in flexible and printed electronic systems, to drive a greener digital future.

<https://project-unicorn.eu/>

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1 Executive summary

The transition to a **circular economy** is a crucial step toward achieving sustainability in the automotive sector, aligning with the European Union's **green and digital transformation goals**. The UNICORN Research and Innovation Action (RIA), funded under the Framework Programme for Research and Innovation Horizon Europe, positions Functional Electronics (FE) as a key enabler of circular mobility systems. This initiative outlines a vision for the future of circularity in **printed and flexible electronics**, presenting a structured roadmap for integrating these innovations within the automotive industry. By accelerating this transition, UNICORN offers a scalable and replicable model for sustainable electronics applications.

Functional Electronics have transformative potential in automotive design and manufacturing, facilitating the use of **lightweight, low-impact, and bio-based materials** while leveraging resource-efficient production techniques such as additive and net-shape manufacturing. Embedding eco-design principles into automotive electronics allows for decoupling environmental impact from industrial growth, ensuring resource efficiency and lifecycle circularity. FE integration fosters **modularity, reparability, and improved material recovery**, catalysing the transition toward circular value chains.

At the heart of this deliverable is the **vision for circular printed electronics**, which serves as the foundation for achieving transformative sustainability outcomes, including reduced carbon emissions, improved modularity, and enhanced recyclability. This vision is built upon a comprehensive context map, which outlines the **complex regulatory framework**, evolving **mobility trends, market developments in functional electronics** for the automotive sector, and **key functionalities**. These interconnected elements provide the basis for a systematic roadmap for sustainable electronics integration.

Hereby, the UNICORN project conducts an in-depth analysis of global market trends, evolving mobility trends, and regulatory landscapes, highlighting the growing importance of lightweight, flexible, and multifunctional electronic systems. By **aligning with global decarbonisation goals and circular economy strategies**, functional electronics can play a pivotal role in accelerating sustainability initiatives across **multiple industries**.

Building upon the findings of this deliverable, a comprehensive roadmap will be developed and provide targeted recommendations for policymakers and industry stakeholders to facilitate the transition from technical feasibility to large-scale deployment. These next steps will further define how functional electronics can drive impactful contributions to global sustainability goals, shaping the future of circular and sustainable mobility. The vision outlined in UNICORN serves as the **guiding framework** for these efforts, ensuring that the proposed solutions are aligned with regulatory requirements, market demands, and environmental priorities. This work will lay the foundation for future advancements in sustainable technologies, ensuring their practical adoption and long-term impact within and **beyond the automotive sector**.

The **UNICORN vision for circular Functional Electronics in the automotive sector** is centred on achieving the **right amount of resources for the realisation of functionality**.

This means that materials and energy are used efficiently to enable high-performing, durable, and sustainable electronic components while aligning with circular economy principles. The goal is to transition towards a system where functional electronics are designed for longevity, adaptability, and end-of-life recovery, minimising waste and resource depletion.

The vision revolves around two transformative pillars:

- 1) Extended functionalisation of printed electronics to replace conventional electronics
- 2) Positioning printed electronics as a blueprint for sustainable electronics, with the introduction of a transversal "greening" functionality that can be adapted to conventional electronics.

These pillars reflect the dual need to enhance sustainability of the electronic sector while pushing the boundaries of performance and integration of printed electronics.

2 Introduction

2.1 The six functionalities of traditional electronics

Traditional electronics have been the backbone of technological development, with their six fundamental functionalities justifying their integration into a vast number of products and enabling their use across numerous application fields. These functionalities include sensing, actuating, signalling, processing, communicating, and powering. **Sensing** transforms analogue into digital signals and thereby allows devices to detect environmental stimuli, such as light, heat, motion, or pressure, providing critical data for decision-making processes. **Processing** transforms this data into consolidated information and actionable insights through computational algorithms and decision-making logic, ensuring the effective operation of electronic systems. **Actuating** converts these insights into tangible actions or movement, mostly of mechanical nature (motors that interact with the environment while **signalling** target actions to increase the interfacing with users such as light, haptic or acoustic signals.

Communicating ensures seamless data exchange between devices and systems, fostering interoperability and enabling smart, connected ecosystems. Finally, Energy supply (**powering**) underpins all functionalities providing the necessary power for device operation through innovative power management systems, including batteries, renewable sources and harvesting strategies.

The transition toward a circular economy necessitates reimagining these functionalities to align with principles of sustainability and resource efficiency. The 5E position paper emphasises the transformative potential of functional electronics (FE) in this context¹. Unlike traditional electronics, which often focus solely on performance, FE integrates advanced capabilities like recyclability, reduced environmental impact, and energy efficiency into its design. By embedding these principles from inception, FE not only addresses the growing challenges of electronic waste and resource depletion but also positions itself as a pivotal enabler of circular economic practices.

Functional electronics can serve as a blueprint for sustainable technological innovation. For instance, FE enhances material efficiency by leveraging additive manufacturing techniques that inherently minimise waste and promote resource reuse. These advancements support the European Union's Circular Economy Action Plan and Green Deal initiatives, which aim to reduce waste, lower emissions, and extend product life cycles. Moreover, FE's alignment with regulatory frameworks, such as the Eco-design Directive and the Safe and Sustainable by Design (SSbD) framework, ensures compliance with global sustainability standards while fostering innovation.

The interconnected nature of traditional electronics' functionalities and the transformative potential of functional electronics forms a crucial bridge to the UNICORN project's objectives, particularly in the automotive sector.

2.2 The UNICORN Vision – Bridging Functional Electronics, Circularity, and Future Mobility

The UNICORN project² is a pivotal initiative aimed at addressing the circularity challenges of functional electronics in the automotive sector, aligning with the European Union's goals for global competitiveness and resilience. Funded under the HORIZON-CL4-2021 program, specifically under the topic "Functional electronics for green and circular economy," UNICORN seeks to accelerate the green and digital (twin) transitions of key European ecosystems, with a particular focus on automotive electronics.

At its core, this Research and Innovation Action envisions functional electronics as both an enabler and a catalyser of Europe's mobility twin transition. The convergence of

¹ 5E Vision paper on the role and impact of functional electronics on the transition towards a circular economy, 2020, <https://hal.science/hal-03185801>

² <https://project-unicorn.eu/>

unconventional nano-electronics, flexible, organic, and printed electronics, and electronic smart systems defines functional electronics. First introduced as part of the EU-funded project 5E, functional electronics emphasises the integration of key digital technologies with cognitive functions, transitioning from purely physical integration to advanced functional integration.

UNICORN has been structured to drive fundamental systemic changes throughout the automotive electronics value chain. Its objectives include research, design and development of FE-based innovative green and circular technologies demonstrated across four industrial use cases: a battery casing, a dashboard, a seat/door system, and a tire. These solutions emphasise lightweight, low-impact, and bio-based materials for substrates, films, encapsulation, inks, adhesives, and cabling. They also validate resource-efficient, additive, and printing-based manufacturing processes for circuitry, sensors, antennas, and interconnects, alongside implementing circular design principles like modularity and reversibility to enhance disassembly and material recovery.

A critical aspect of the UNICORN project is the positioning of these functionalities as a bridge between emerging mobility trends and functional (printed) electronics. The ability of functional electronics to support electrification, connectivity, and sustainability underscores their role as a transformative force in reshaping automotive systems. By integrating lightweight and bio-based materials with innovative manufacturing processes, the project aligns with mobility trends while promoting environmental stewardship and resource efficiency.

Moreover, UNICORN serves as a lab for experimentation, where real-world use cases are tested to understand how pathways outlined in the circular car initiative can be practically implemented. This hands-on approach allows stakeholders to explore viable circular strategies in automotive applications, ensuring that theoretical frameworks translate into scalable and impactful solutions. By fostering collaboration between industry leaders, policymakers, and researchers, UNICORN provides a testbed to validate the feasibility of circularity-driven innovations in functional electronics, enhancing their adoption across the automotive sector.

From these developments, UNICORN is creating a comprehensive vision for circular functional electronics in the automotive sector. This vision will serve as the foundation for a structured roadmap, outlining clear implementation pathways and timelines for industry and policymakers. Ultimately, this roadmap will be translated into concrete policy recommendations, ensuring that the project's findings contribute to shaping regulatory frameworks and industrial strategies while also providing guidelines for the broader adoption of circular approaches in automotive electronics. The Vision will be the focus of the following chapters in this document, setting the stage for actionable steps towards a sustainable automotive ecosystem.

The interplay between functional electronics and mobility trends highlights their capacity to address both socio-economic and technological demands. For example, advancements in sensor technologies enable smarter and safer vehicles, while energy-efficient manufacturing processes support sustainability goals. Functional electronics thus act as a unifying framework that not only bridges these trends but also creates pathways for scalable circular practices within the automotive industry.

In conclusion, the UNICORN project exemplifies how functional electronics can play a transformative role in achieving circularity within the automotive sector. By bridging mobility trends with innovative technologies, it not only supports the EU's strategic goals but also sets a benchmark for future initiatives aiming to integrate circular economy principles into complex industrial ecosystems. This bridging role is pivotal in connecting emerging societal needs with sustainable technological advancements, ensuring the alignment of industrial practices with global environmental and economic objectives.

3 Methodology

The current vision is the result of a structured, multi-methodological approach, beginning with extensive desktop research to establish a solid knowledge base and identify drivers for Circular Functional Electronics in Automotive and key references for guiding further vision development. This research prioritised four main areas:

- (1) global societal trends with a direct impact on mobility,
- (2) the state of the art regarding the role and contribution of printed electronics in the automotive sector,
- (3) the regulatory landscape across the three pillars of the UNICORN project—Electronics, Automotive, and Circularity, and
- (4) the interplay between the pathways for full circularity as defined in the context of the WEF Circular Car Initiative and the 10 Rs for circularity.

The insights gained from this desktop research provided the foundation for designing and structuring participatory workshops, where informed stakeholders were engaged to validate initial hypotheses and refine the vision. To ensure the robustness of the workshop methodology, a preliminary internal brainstorming session was conducted. This exercise confirmed the strong interconnections between current technological developments and emerging mobility trends, demonstrating how specific functionalities could be articulated to bridge the gap between supply and demand.

Building on the outcomes of these participatory workshops, the vision was further consolidated, integrating the various elements into a comprehensive and structured framework. Particular attention was given to visualising the vision and the interdependencies between key components within the context map.

4 Drivers for Circular Functional Electronics in Automotive

4.1 Circular Car Initiative

The **Circular Car Initiative**, launched as part of the World Economic Forum's broader focus on sustainable mobility, is a collaborative effort involving policymakers, industry leaders, and researchers aimed at accelerating the transition to circularity within the automotive sector. Its intent is to reimagine the automotive value chain, reducing waste and optimising the use of resources throughout the lifecycle of vehicles. The initiative seeks to integrate innovative design, manufacturing, and end-of-life practices that align with circular economy principles. By leveraging partnerships and promoting cross-sector collaboration, the Circular Car Initiative aspires to create systems where vehicles are designed to be more sustainable, modular, and capable of supporting a low-carbon future.

This initiative identifies critical pathways for incorporating circularity in automotive design and production (see Figure 1³). These pathways focus on optimising resource consumption throughout the lifecycle of vehicles and components:



Figure 1: Four Transformation Pathways for the Circular Car

- **Energy Use:** Promoting the use of renewable energy and efficient fuel consumption to reduce the carbon footprint per kilometre.
- **Materials:** Encouraging the use of materials with minimal waste by prioritising reduction, reuse, recycling, and adoption of renewable resources.
- **Lifetime Optimisation:** Designing vehicles and components for resource efficiency through modularity, reparability, and remanufacturing. This includes purpose-built vehicles and reversible design to maximise the lifecycle of valuable materials.
- **Use Rates:** Optimising the utilisation of vehicles through shared mobility solutions and accounting for resiliency requirements in system design.

These pathways are supported by collaboration across the automotive value chain to ensure transparency and innovation in sustainable practices like closed-loop recycling, advanced disassembly technologies, and material recovery systems. The Circular Car Initiative envisions a progressive transformation along levels of circularity, from low circularity today to achieving net positivity in system impact by 2040 (see Figure 2⁴). For energy pathways, this entails a shift from renewable energy integration at the production level to full energy grid integration with vehicles. Material pathways emphasise upcycling of waste materials to high-value uses. Lifetime optimisation evolves from modular design for reparability to second-life applications that maximise the utility of components. Lastly, usage pathways transform from private

³ own graphic, adapted from Accenture Strategy

⁴ own graphic, adapted from Accenture Strategy, 2021

ownership models to shared mobility systems integrated with advanced fleet management. By integrating these approaches, the initiative aligns with broader circular economy goals and promotes long-term sustainability. The initiative highlights innovative approaches such as closed-loop recycling systems and advanced sorting technologies to maximise the value of end-of-life vehicles. Additionally, it emphasises the importance of collaboration across the supply chain to ensure transparency and support sustainable practices like reusing, refurbishing, and remanufacturing components to minimise waste and environmental impact.

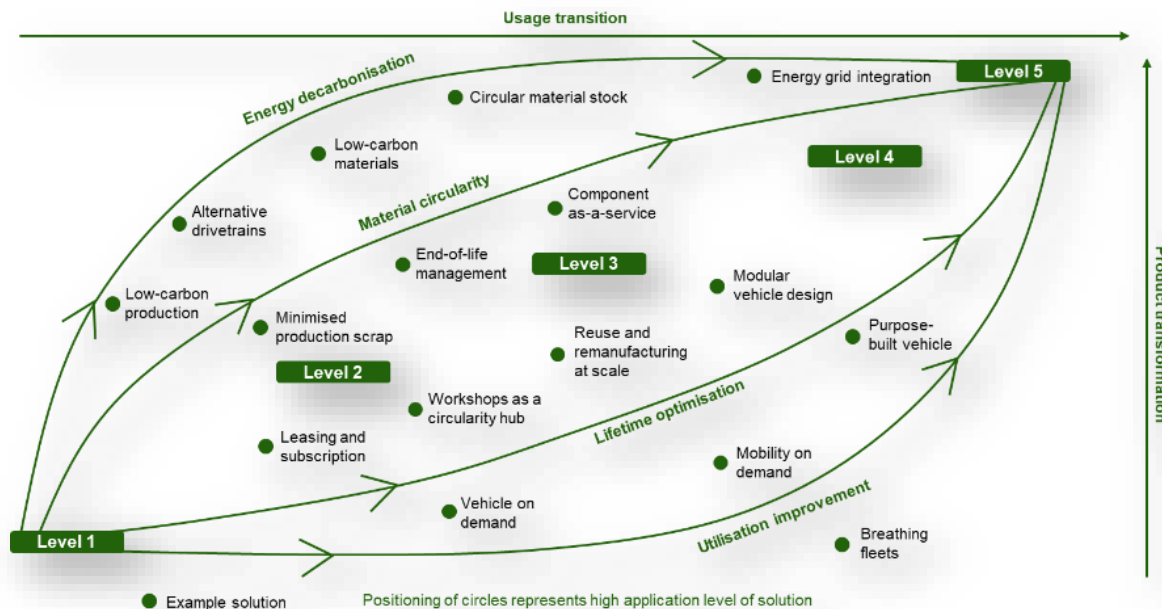


Figure 2: Circular Car Vision including Example Solutions per Advancement Level

4.2 Mobility Trends

The mobility trends that shape the future of the automotive sector are directly derived from the interplay of technology push and socio-economic pull factors. On the one hand, technological advancements such as electrification, autonomous systems, and digital platforms are driving innovation at an unprecedented pace. On the other hand, socio-economic factors like urbanisation, climate action imperatives, and shifting consumer expectations are creating a strong demand for sustainable, efficient, and inclusive mobility solutions. By analysing these drivers, we identify key mobility trends that inform the role of Functional Electronics (FE) in automotive development.

Technology Push

The rapid evolution of artificial intelligence (AI), machine learning, virtualisation, advanced computing technologies, 5G/6G networks, and digitalisation is fundamentally reshaping mobility trends. These technologies collectively enable smarter, safer, and more efficient transportation systems. Recent breakthroughs in autonomous driving systems leverage AI and real-time machine learning to process vast datasets, allowing vehicles to adapt dynamically to traffic conditions. Predictive maintenance systems, powered by advanced analytics, ensure the reliability and longevity of automotive components by identifying potential failures before they occur⁵.

5G/6G networks have been transformative in vehicle-to-everything (V2X) communication, providing the low-latency, high-bandwidth connectivity needed for autonomous driving and advanced driver-assistance systems (ADAS). These networks enable seamless data exchange between vehicles, infrastructure, and users, supporting applications such as platooning and smart traffic systems that reduce congestion and improve energy efficiency.

⁵ Gao et al., 2022

Battery technology advancements, including solid-state batteries and ultra-fast charging solutions, are key drivers of the shift toward electric mobility. These innovations provide longer ranges, improved safety, and faster charging times, addressing critical challenges faced by electric vehicles (EVs). Renewable energy integration in charging infrastructure reduces the carbon footprint of EVs, contributing to a sustainable mobility ecosystem⁶.

Material innovations, such as lightweight composites, bio-based alternatives, and advanced alloys, are reducing vehicle weight while enhancing strength and durability. This directly improves energy efficiency and supports modular vehicle designs that facilitate disassembly and recycling. Technologies like additive manufacturing, in-mould electronics, and printed sensors are also expanding functional capabilities, enabling the creation of customisable and repairable components. Flexible and stretchable sensors, for instance, enhance human-machine interfaces while providing crucial data for predictive diagnostics and safety systems⁷.

The digital twin concept is gaining traction, allowing manufacturers to simulate, optimise, and monitor vehicle performance across its lifecycle. Coupled with advancements in energy storage and renewable energy technologies, these developments are critical for achieving circularity and sustainability goals in mobility.

Socio-economic Pull

Socio-economic pull factors, including increasing consumer awareness of sustainability, new working models, and regulatory requirements, shape the adoption of functional electronics and drive upcoming mobility trends. Factors such as urbanisation and demographic changes are pivotal. Urbanisation accelerates the demand for multimodal transport systems that prioritise convenience, connectivity, and eco-friendliness, with increasing emphasis on shared and autonomous mobility solutions. Demographic shifts, such as aging populations and the rise of younger, tech-savvy generations, influence the design of transportation systems that are both inclusive and adaptable, ensuring accessibility for all.

New working models, including hybrid and remote setups, have reshaped commuting patterns. Reduced daily commutes are increasing demand for flexible, on-demand, and shared transport options. The gig economy, coupled with the rise of digital platforms, has also amplified the need for adaptive and cost-efficient logistics systems⁸.

Safety remains a critical socio-economic driver, with advanced driver-assistance systems (ADAS), vehicle-to-everything (V2X) communication, and predictive analytics pushing for safer roads and efficient travel. Inclusiveness in mobility is also becoming a priority, fostering the development of solutions that cater to individuals with disabilities or limited access to traditional transportation.

Eco-friendly mobility solutions are gaining prominence as environmental awareness grows among consumers and policymakers. Initiatives such as the EU's Green Deal and Sustainable and Smart Mobility Strategy underline the urgency for low-carbon transport systems. These initiatives foster innovation in green technologies and align mobility systems with broader sustainability goals⁹.

Globalisation and economic significance further shape mobility trends, encouraging international collaboration to establish global standards for sustainability and circularity. Transparency and ethical sourcing of materials are increasingly prioritised, with regulatory frameworks ensuring accountability in environmental and social practices¹⁰.

⁶ <https://www.iea.org/reports/global-ev-outlook-2023>

⁷ <https://onlinelibrary.wiley.com/doi/abs/10.1002/sml.202306655>

⁸ McKinsey, 2023 <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/The-future-of-mobility-the-future-landscape>

⁹ European Commission, 2022 - "Sustainable and Smart Mobility Strategy." European Commission. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12438-Sustainable-and-Smart-Mobility-Strategy_en

¹⁰ <https://www.iea.org/reports/global-ev-outlook-2023>

Derived Mobility Trends

Mobility trends are arising as a direct result of the factors discussed under "Technology Push" and "Socio-economic Pull" (see Figure 3¹¹ below). The technological advancements described—such as electrification, automation, connectivity through 5G/6G, and innovations in battery systems—are revolutionising the way vehicles operate and interact with their environments. These innovations provide the backbone for smarter, greener transportation systems by enabling real-time data exchange, enhanced energy efficiency, and autonomous functionality. For instance, predictive analytics and digital twin technologies discussed in "Technology Push" are critical for optimising vehicle lifecycle performance and enabling seamless integration with smart city infrastructure.

On the other hand, socio-economic factors, including urbanisation and demographic shifts, as detailed in "Socio-economic Pull", are driving changes in consumer expectations and regulatory pressures. Urbanisation has spurred demand for shared and multimodal transport solutions that cater to increasingly crowded cityscapes. Meanwhile, demographic changes are pushing mobility providers to design inclusive systems that accommodate aging populations and prioritise accessibility for all. Together, these interlinked factors foster the development of mobility ecosystems that prioritise sustainability, inclusiveness, and adaptability.

Key mobility trends include:

Connected, Cooperative, and Automated Mobility (CCAM): CCAM represents a transformative trend in which vehicles, infrastructure, and users are seamlessly connected to enhance safety, efficiency, and convenience. Functional Electronics play a critical role in enabling vehicle-to-everything (V2X) communication, advanced driver assistance systems (ADAS), and fully autonomous driving capabilities.

Electrification: The shift towards electric vehicles (EVs) is one of the most significant mobility trends, driven by the urgent need to reduce greenhouse gas emissions and transition to renewable energy sources. Functional Electronics are essential for efficient battery management systems, power electronics, and energy recovery technologies.

Mobility-as-a-Service (MaaS): MaaS integrates various transportation modes into a single, user-friendly platform that prioritises convenience and accessibility. Functional Electronics contribute by enabling seamless digital integration of mobility services, from ride-hailing and car-sharing to public transport and micromobility options.

Multi-modality: Multi-modal transportation focuses on optimising the use of different transport modes to reduce congestion and carbon emissions. Functional Electronics facilitate efficient route planning, dynamic traffic management, and user-centric interfaces.

Last-mile/First-mile Solutions: Addressing the first and last segments of a journey is critical for creating a seamless and inclusive mobility ecosystem. Solutions such as autonomous shuttles, delivery robots, and bike-sharing systems rely on Functional Electronics for precise navigation and secure transactions.

Micromobility: The rise of micromobility—including e-scooters, e-bikes, and other lightweight vehicles—responds to urban congestion and environmental concerns. Functional Electronics underpin these solutions by providing advanced battery systems, connectivity features, and safety mechanisms.

Sharing Economy: Shared mobility options such as carpooling, ride-sharing, and vehicle-sharing are gaining traction as cost-effective and environmentally friendly alternatives. Functional Electronics enable these services by ensuring secure authentication, efficient fleet management, and real-time tracking of shared assets.

¹¹ own graphic

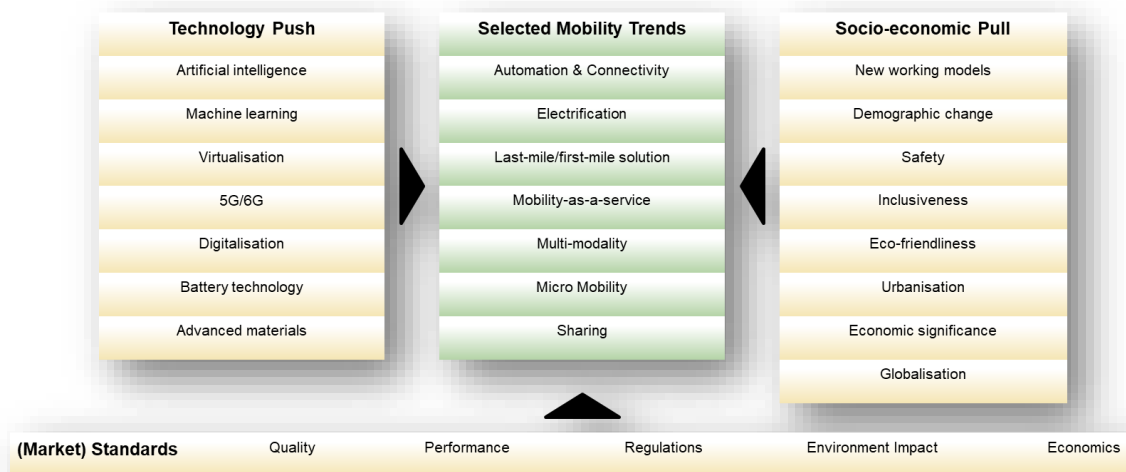


Figure 3: Mobility Trends shaped by Technologies, Socio-economic factors and (Market) Standards

Within a recent workshop (WS), CCAM, Electrification, and MaaS were identified as the most important mobility trends for shaping the future of transportation systems. These priorities will also play a central role in Use Case 5 (UC5), which considers the integration of MaaS with CCAM and Electrification solutions. This approach aims to create a seamless, efficient, and sustainable mobility ecosystem that aligns with technological advancements and evolving socio-economic needs. These interrelated factors collectively define and drive the evolution of contemporary mobility trends, emphasising the central role of Functional Electronics in shaping the future of transportation.

4.3 Trends in Functional Printed Electronics

Global Market Trends in Functional Printed Electronics

The global market for functional printed electronics is expanding rapidly, driven by advancements across various industries, including consumer electronics, healthcare, packaging, and energy. The market is projected to grow at a significant compound annual growth rate (CAGR), reaching an estimated value of USD 40 billion by 2030¹². This growth is fuelled by the increasing adoption of advanced technologies, such as flexible displays, printed sensors, and energy storage devices, which enable innovative applications across diverse sectors.

In the consumer electronics sector, functional printed electronics are revolutionising product design by enabling thinner, lighter, and more flexible components. These include flexible displays, wearable devices, and touchscreens, which leverage printed conductive inks and substrates for improved performance and user experience¹³. In healthcare, printed biosensors are gaining traction for applications such as real-time health monitoring and diagnostics, offering cost-effective and scalable solutions for wearable medical devices.

The packaging industry is another key area of growth, with smart packaging solutions that incorporate printed electronics for tracking, authentication, and enhanced consumer engagement. These innovations are particularly important in sectors like food, pharmaceuticals, and logistics, where traceability and safety are critical. Additionally, energy storage devices, including printed batteries and supercapacitors, are being integrated into renewable energy systems and portable electronics, contributing to the global shift toward sustainable energy solutions¹⁴.

¹² Fairfield Market Research, 2023 "Global Automotive Printed Electronics Market." Fairfield Market Research Report.

¹³ <https://www.sciencedirect.com/science/article/pii/S1364032123003751>

¹⁴ <https://www.iea.org/reports/global-ev-outlook-2023>

Advanced manufacturing techniques, such as inkjet printing, screen printing, and roll-to-roll processing, are central to this market's scalability and cost efficiency. These methods enable mass production of high-performance components while minimising material waste and supporting the development of lightweight, adaptable products. The emphasis on circular economy principles further underscores the importance of functional printed electronics in achieving sustainability goals across multiple industries.

Linking Global Trends to Automotive Applications

The advancements in functional printed electronics discussed above are also transforming the automotive sector, where the demand for innovative and sustainable solutions is particularly strong. The global automotive printed electronics market is projected to reach a value of USD 13 billion by 2030, with a CAGR of 22.1% from 2023 to 2030¹⁵. Asia Pacific leads in adoption, driven by increasing automotive production and rapid technological advancements.

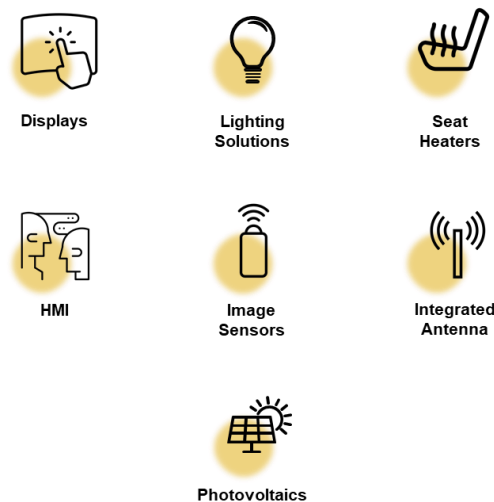


Figure 4: Printable Electronic Applications used in the Automotive¹⁶

Emerging applications in the automotive sector include human-machine interfaces (HMI), integrated antennas, image sensors, photovoltaics (PV), seat heaters, lighting solutions, and advanced displays (see Figure 4). HMIs are pivotal to modern vehicle design, providing intuitive and interactive control systems that enhance driver and passenger experiences. Integrated antennas facilitate advanced communication systems such as 5G/6G networks and vehicle-to-everything (V2X) communication, ensuring seamless connectivity. Photovoltaic systems are increasingly used for powering auxiliary systems, reducing reliance on non-renewable energy, and promoting sustainability in automotive applications¹⁷.

Lighting solutions and displays benefit significantly from printed electronics, as they offer lightweight, energy-efficient, and flexible components that cater to modern automotive aesthetic and functional requirements¹⁸. For instance, printed seat heaters provide efficient heating solutions by utilising lightweight conductive materials that integrate seamlessly into vehicle interiors. Image sensors, essential for autonomous and driver-assistance systems, leverage printed electronics for compact, cost-effective, and high-performance designs.

Advanced manufacturing techniques such as additive manufacturing, inkjet printing, and screen printing are critical enablers for these applications. These technologies support scalability, circularity, and innovation by reducing material waste and enabling the creation of lightweight, adaptable components. Printed sensors embedded within automotive components further enhance safety and structural health monitoring, offering real-time data for predictive diagnostics and system optimisation.

¹⁵ Fairfield Market Research, 2023 "Global Automotive Printed Electronics Market." Fairfield Market Research Report.

¹⁶ Source Icons (top left to bottom to bottom): Ali Nur Rohman (Noun Project); Own Image; Nykyta Kravchuck (Noun Project); Flatart (Noun Project); Abdul Matic (Noun Project); INA (Noun Project); Own Image.

¹⁷ <https://www.iea.org/reports/global-ev-outlook-2023>

¹⁸ <https://www.sciencedirect.com/science/article/pii/S1364032123003751>

This market reflects a shift toward printed and functional electronics, aligning with global sustainability and regulatory demands. The emphasis on integrating advanced functionalities and sustainable materials within automotive systems positions functional electronics as a key driver in the transition toward circular economy principles and low-carbon mobility solutions.

4.4 Functionalities

Automotive electronic systems—whether based on Flexible, Organic, Printed Electronics, conventional electronics, or hybrid approaches—enable a combination of six fundamental functionalities, as outlined in the 5E paper. A dashboard interface (HMI), for example, operates by converting user input (such as pressing a button or touchscreen, voice commands, or gestures) into processed signals that are transmitted to various connected subsystems within the vehicle, including infotainment, interior controls, and driving features.

The user then receives feedback confirming whether the requested action has been successfully executed in compliance with safety standards. This feedback can be conveyed through visual signals (e.g., indicator lights), auditory cues (e.g., sounds or voice prompts), or haptic responses (e.g., vibration). The core functionalities underpinning any HMI—sensing, processing, communication, and actuation/signalling—remain consistent regardless of the specific technological solutions used to implement them.

When discussing HMIs, both technology providers and end users can focus on the system's input and output interactions without delving into complex technological details. This shared understanding facilitates communication and innovation while ensuring that HMIs remain intuitive and user-friendly.

An optimised Human-Machine Interface (HMI) plays a crucial role in enhancing driving safety, improving comfort, and promoting inclusivity. It ensures accessibility for all users—both drivers and passengers—regardless of cognitive or physical disabilities, age, origin, or gender.

Furthermore, an advanced HMI must be clear and precise to prevent misunderstandings, minimise errors, and reduce driver distraction. Responsiveness is also essential, ensuring that user inputs are swiftly processed and implemented. Additionally, HMIs can contribute to sustainability by optimising energy consumption, encouraging environmentally responsible vehicle usage, and providing proactive maintenance alerts to enhance the longevity and efficiency of automotive systems.

Beyond aligning technological advancements with societal needs, a functionality-driven approach is essential for enabling circular economy principles, particularly in extending the lifespan of electronic systems. When considering second-life applications, it is not the specific automotive components that remain relevant but rather the core functionalities they provide.

By focusing on functionalities rather than rigid system architectures, electronic components from automotive applications can be repurposed in other industries based on their capabilities, such as sensing, processing, communication, or actuation. This cross-sectoral adaptability facilitates the transfer of technologies between industries, creating new opportunities for second-life applications and reducing electronic waste. Ultimately, functionalities serve as the critical link in bridging sectors, ensuring that valuable technologies are efficiently reused rather than discarded.

Currently Printed Electronics is already a technological solution to efficiently realise a certain number of core functionalities in the automotive sector, at the first place sensing and signalling (lighting). Actual developments push toward realising further functionalities such as Actuating (vibrations, heating, ...), communicating (antennas for RFID, ...) or powering (printed solar cells or batteries), even if they do not cover the whole spectrum of possibilities or of performances. Last but not least current developments of printed electronics are no alternatives to processing (computing, data storage) but can be hybridised to offer viable solutions.

Printed Electronics is already an established technological solution for implementing key functionalities in the automotive sector, particularly in sensing and signalling (e.g., lighting). Current advancements are driving the integration of additional functionalities, such as

actuation (e.g., vibrations, heating), communication (e.g., RFID antennas), and power generation (e.g., printed solar cells and batteries). While these developments do not yet encompass the full range of automotive electronic capabilities or performance levels, they represent significant progress towards more efficient, lightweight, and sustainable solutions.

Crucially, printed electronics is not positioned as a standalone alternative for processing functions such as computing and data storage. However, its potential for hybridisation with conventional electronics enables the development of optimised, high-performance systems that combine the best of both technologies. By leveraging this hybrid approach, the automotive sector can benefit from printed electronics' advantages—such as material efficiency, design flexibility, and lower environmental impact—while maintaining the computational power necessary for advanced vehicle functionalities.

4.5 Regulatory Frameworks Driving Circular Functional Electronics

The regulatory landscape driving the adoption of circular functional electronics is marked by its complexity and breadth, addressing diverse aspects of sustainability, innovation, and resource management. Regulations play a pivotal role in driving innovation, protecting the environment, and harmonising industry practices with societal objectives. For instance, the Eco-design Directive has driven advancements in modular and recyclable designs for functional electronics, enabling manufacturers to create energy-efficient automotive components that are easier to disassemble and recycle. Similarly, the Circular Economy Action Plan has spurred innovation in the use of sustainable materials and processes, encouraging the development of printed electronics that minimise raw material consumption and waste. These examples highlight how regulatory frameworks serve dual roles: ensuring compliance while driving technological progress in functional electronics, especially in the automotive sector. By providing structured guidelines, they create a predictable framework within which industries can operate, enabling collaboration and cross-sector alignment.

This regulatory framework spans multiple dimensions of Circularity, Electronics, and Automotive, creating a tetrahedron of interconnected strategies, regulations, and directives (see Figure 5). This complexity requires a structured approach to identify opportunities and challenges within the regulatory landscape. For example, the UNICORN project analysed these interrelations to align functional electronics with circular economy principles while addressing practical challenges within the automotive value chain.

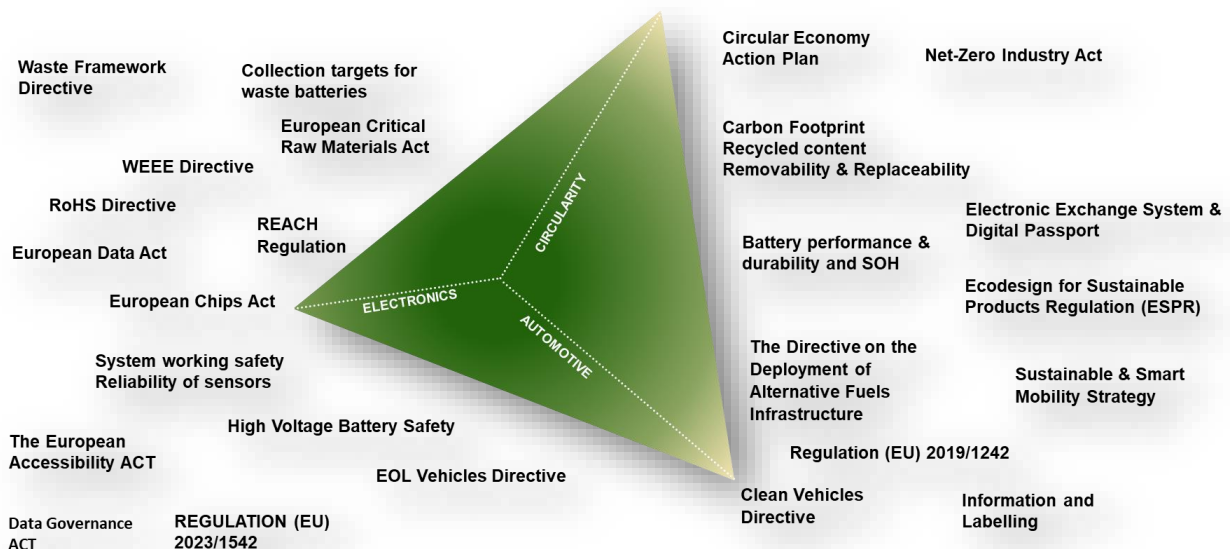


Figure 5: Complex Regulatory Landscape for FE in the Automotive¹⁹

¹⁹ Own graphic

However, regulations can also present limitations. Overly stringent or fragmented rules can hinder innovation by elevating compliance costs and delaying the adoption of cutting-edge technologies, highlighting the need for harmonised and adaptive regulations. For instance, the lack of harmonised standards across regions can create bottlenecks for global trade and complicate the integration of new sustainable technologies. A notable case is the inconsistency in recycling regulations across EU member states, which has delayed the establishment of unified systems for recovering critical raw materials from electronic waste. Additionally, requirements for extensive documentation and compliance testing under directives such as RoHS can increase time-to-market for functional electronics innovations, particularly in the automotive sector. Furthermore, the rapid pace of technological advancements can outstrip the ability of regulatory bodies to adapt, leaving gaps or creating ambiguities that hinder progress, such as in the regulation of advanced materials used in printed electronics.

Despite these challenges, the European Union's regulatory framework remains a robust system designed to balance innovation and compliance. It integrates circularity across industries, ensuring alignment with environmental and economic goals. Notable strategies include the development of Digital Product Passports (DPPs) to improve traceability and material recovery for functional electronics, fostering a more sustainable and competitive European automotive industry.

The UNICORN project extensively analysed and addressed these challenges by systematically examining regulations related to circularity, electronics, and the automotive sector. This included identifying opportunities for innovation and barriers to implementation, ultimately supporting the development of a roadmap for circular functional electronics and actionable policy recommendations. The project systematically analysed regulations related to circularity, electronics, and the automotive sector to identify opportunities for innovation and pinpoint barriers to implementation. Specifically, it addressed the challenges posed by overlapping and fragmented regulations, such as inconsistencies in recycling standards across EU member states and varying compliance requirements under directives like the Eco-design and WEEE Directives. These insights will be further used in the next steps to develop a roadmap for circular functional electronics for the automotive and beyond and to derive policy recommendations to foster a more sustainable and competitive European automotive industry by addressing critical regulatory gaps and promoting cross-sector innovation.

By aligning interrelated regulations with circular economy principles, the framework addresses practical challenges in the automotive value chain while emphasising innovation and sustainability across industries. The framework incorporates multiple strategies and directives to promote collaboration and innovation, demonstrating the European Union's ability to integrate sustainability with technological advancement in a complex regulatory environment spanning circularity, electronics and automotive.

4.5.1 Circularity

Circular Economy Action Plan

At its core, the Circular Economy Action Plan outlines a roadmap for creating circular value chains, targeting critical areas such as electronics and batteries. This comprehensive framework emphasises extending product life cycles, minimising waste, and promoting repair and recycling. By fostering sustainable design and enhancing material recovery throughout the value chain, the plan supports the European Union's broader environmental objectives, including achieving climate neutrality and reducing resource dependency.

Key Insights:

- Encourages modularity and recyclability in design to extend product lifespan.
- Targets for increased recycled content in batteries and electronics by 2030 (e.g., 50% of critical raw materials from recycled sources).
- Supports material efficiency and energy savings to contribute to net-zero goals.
- Aims to develop a standardised regulatory framework for sustainable electronic components in vehicles.

For functional electronics in the automotive sector, the **Circular Economy Action Plan** is particularly significant. The automotive industry contributes significantly to electronic waste and resource consumption. By promoting design principles such as modularity and recyclability, the plan directly influences how electronic components are manufactured, used, and repurposed. For instance, targets for increased recycled content in batteries and electronics align with functional electronics' capacity to incorporate sustainable materials and processes.

By guiding industries to adopt innovative production methods and material recovery strategies, the Circular Economy Action Plan serves as a foundational policy. It ensures that functional electronics evolve as sustainable solutions, meeting both environmental and economic objectives within the automotive industry and beyond.

European Industrial Strategy

The European Industrial Strategy is a pivotal initiative designed to strengthen the industrial base of the European Union by promoting sustainability, innovation, and resilience. This strategy fosters the twin transitions toward a green and digital economy while enhancing global competitiveness. It prioritises the development of advanced technologies that improve performance while minimising environmental impact.

Key aspects of the strategy include:

- Prioritises material recovery and resource recycling to reduce dependencies on non-EU suppliers.
- Supports the integration of functional electronics into sustainable manufacturing (e.g., digital twins, AI-driven resource management).
- Enhances Europe's resilience by fostering strategic independence in raw materials supply.
- Encourages public-private partnerships to accelerate innovation in sustainable electronic manufacturing

For functional electronics (FE) in the automotive sector, the **European Industrial Strategy** underscores sustainability at every stage of the value chain. By aligning FE development with principles of modularity, recyclability, and resource efficiency, it addresses growing environmental challenges. Functional electronics, such as lightweight printed circuits, flexible sensors, and energy-efficient systems, embody the goals of the European Industrial Strategy by reducing material use, enabling innovative designs, and supporting the transition to electric and autonomous vehicles.

The strategy also facilitates the green and digital transitions by integrating functional electronics into smart manufacturing processes, such as digital twins and AI-driven resource management systems. These approaches streamline production, reduce material waste, and accelerate the adoption of sustainable technologies. While challenges remain—such as high initial costs and supply chain disruptions—the strategy aims to address these barriers through targeted investments and regulatory harmonisation.

In summary, the European Industrial Strategy positions functional electronics as a critical enabler of technological progress and sustainability. By driving innovation in materials and production methods, it ensures that Europe's automotive ecosystem remains competitive while advancing green and digital goals.

Net-Zero Industry Act - Regulation (EU) 2024/1735

The Net-Zero Industry Act aims to establish a comprehensive framework to scale up the manufacturing and deployment of net-zero technologies within the European Union, ensuring a competitive and resilient green technology ecosystem. It seeks to accelerate the

development and production of clean technologies essential for the EU's energy transition, including key components for functional electronics.

Key Insights:

- Sets targets to produce 40% of the EU's strategic net-zero technologies domestically by 2030.
- Streamlines permitting and financing for energy-efficient sensors and flexible electronics in automotive applications.
- Enhances supply chain resilience through domestic recycling of critical materials.
- Introduces incentives for sustainable electronic manufacturing and lifecycle management.

Functional electronics, such as lightweight printed circuits and flexible sensors, are key to achieving the objectives of the **Net-Zero Industry Act**. These technologies contribute to reducing energy consumption in automotive applications, supporting the electrification of transport, and enabling next-generation mobility solutions. The Act also introduces measures to streamline approvals for sustainable electronic manufacturing projects and enhance financial support for green technology start-ups.

European Chemicals Strategy for Sustainability

The European Chemicals Strategy for Sustainability is a cornerstone initiative under the EU Green Deal, aiming to achieve climate neutrality, a circular economy, and zero pollution within the chemical and materials industries. This strategy emphasises the importance of safe, innovative, and sustainable chemicals throughout their lifecycle, establishing stricter regulations on hazardous substances and promotes the development of sustainable alternatives in the production.

Key focus areas are:

- Implements the Safe and Sustainable by Design (SSbD) framework for sustainable materials and chemicals.
- Encourages bio-based polymers and non-toxic adhesives for functional electronics.
- Harmonises EU standards with global regulations to enhance competitiveness.
- Phases out hazardous substances in electronic manufacturing, promoting safer alternatives.

The **European Chemicals Strategy** has significant implications for functional electronics (FE) in automotive applications. Automotive systems increasingly rely on advanced materials, including flexible substrates, conductive inks, and encapsulates, many of which are rooted in chemical innovations. The SSbD framework ensures that these materials meet sustainability benchmarks, facilitating the production of FE components that are both high-performing and environmentally friendly. For instance, printed electronics for dashboards or seat heaters can now incorporate sustainable adhesives and recyclable materials, reducing waste and enhancing recyclability. The strategy's emphasis on harmonising EU standards with global regulations further bolsters the competitiveness of European automotive manufacturers while aligning with circular economy objectives. Moreover, by incentivising innovation, the strategy encourages the development of novel FE materials and eco-design principles that enable cleaner and safer automotive solutions.

European Critical Raw Materials Act

The European Critical Raw Materials Act is a cornerstone regulation aimed at safeguarding the availability of critical raw materials essential for emerging technologies. It addresses the

strategic importance of securing a stable and sustainable supply of materials like rare earths, lithium, cobalt, and other key components that underpin the green transition. The Act ensures resilience in supply chains by:

- Prioritising the sustainable extraction, recycling, and reuse of these materials.
- Mandating at least 15% of the EU's annual demand for strategic materials to be sourced through recycling by 2030, reducing dependency on imports.
- Promoting ethical sourcing and transparency in global supply chains.
- Encouraging innovation in alternative materials to reduce dependency on rare earth elements.

For functional electronics in the automotive sector, the **European Critical Raw Materials Act** has direct implications. Automotive applications such as electric vehicle (EV) batteries, lightweight composite materials, and advanced electronics rely heavily on critical raw materials. By promoting sustainable practices, such as EU-supported recycling programs for rare earth elements, the Act supports the development of energy-efficient and circular solutions in functional electronics. Additionally, advancements in material science, such as synthetic substitutes for rare earths, reduce reliance on imports while maintaining performance standards. The Act also ensures ethical sourcing practices, improving global supply chain transparency and fostering consumer trust in sustainable automotive technologies. By aligning with circular economy principles, the Act strengthens the EU's competitive edge in the automotive industry while driving innovation in recycling and materials science.

Eco-design Directive (Directive 2009/125/EC)

The Eco-design Directive introduces comprehensive guidelines for improving the environmental performance of electronic products. It serves as a cornerstone of the European Union's circular economy policies, aiming to reduce energy consumption and enhance resource efficiency across product life cycles.

Recent amendments include:

- Introduces Digital Product Passports (DPPs) for lifecycle transparency.
- Encourages modular design to facilitate repair, upgrade, and recycling.
- Establishes of a framework to prevent the destruction of unsold goods, promoting the reuse and redistribution of surplus products
- Mandates Green Public Procurement (GPP) criteria, which encourage public institutions to prioritise sustainable products in their purchasing decisions.
- Mandates minimum sustainability performance criteria for electronic components.

For functional electronics in the automotive sector, the **Eco-design Directive** has profound implications. By embedding requirements for modularity and recyclability into product designs, it fosters the development of electronics that can be easily repaired, upgraded, or recycled. This is particularly relevant for automotive applications, where the integration of functional electronics like sensors, displays, and energy management systems must align with circular principles. The directive's emphasis on durability and resource efficiency supports the automotive industry's transition toward electrification and low-carbon mobility, ensuring that vehicles and their components meet high sustainability standards while enhancing competitiveness in global markets.

Ecodesign for Sustainable Products Regulation (ESPR 2024/1781)

The Environmental Product Regulation (ESPR) replace the 2019 Eco-design Directive (see above) and establishes comprehensive requirements for sustainable products, aiming to improve circularity and optimise product lifecycle management across various sectors.

The regulation:

- Mandates that products meet strict criteria for durability, reparability, and recyclability, while also emphasising the use of sustainable and ethically sourced materials.
- Includes provisions for eco-design, which require manufacturers to integrate modular designs and reduce energy consumption during production and usage.
- Assigns requirement for Digital Product Passports (DPPs), which provide detailed information on a product's material composition, environmental footprint, and end-of-life management options to enhance transparency, enabling consumers and recyclers to make informed decisions and facilitating the recovery and reuse of valuable materials.

The **Ecodesign for Sustainable Products Regulation** has significant implications for functional electronics (FE) in automotive applications. By enforcing modularity and recyclability, the regulation supports the integration of FE components such as sensors, displays, and energy management systems that are designed for disassembly and material recovery. DPPs ensure that the materials used in FE, including printed circuits and conductive inks, can be efficiently traced and recycled, aligning with circular economy principles. Additionally, the ESPR's focus on durability encourages the development of robust FE technologies that can withstand demanding automotive environments while maintaining high performance. By aligning with the ESPR, the automotive industry can leverage functional electronics to meet sustainability targets, enhance resource efficiency, and ensure compliance with evolving regulatory requirements, positioning Europe as a leader in green innovation and circularity.

Corporate Sustainability Reporting Directive (CSRD) and EU Taxonomy for Sustainability

Frameworks like the Corporate Sustainability Reporting Directive (CSRD) and the EU Taxonomy for Sustainability play an essential role in advancing sustainable practices across industries, including the automotive sector.

The CSRD requires companies to disclose detailed information about their sustainability practices, ensuring accountability and transparency in environmental, social, and governance (ESG) criteria. This directive emphasises standardised reporting to enhance comparability and reliability of sustainability data. For the automotive industry, the CSRD compels manufacturers to integrate circularity principles into their operations and supply chains, highlighting areas such as material sourcing, energy usage, and end-of-life product management.

The EU Taxonomy for Sustainability provides a science-based classification system to identify environmentally sustainable economic activities. This taxonomy guides investments toward projects and technologies that contribute to the EU's environmental objectives, such as climate change mitigation, sustainable resource use, and pollution prevention.

For functional electronics in automotive applications, both frameworks, the **Corporate Sustainability Reporting Directive** and the **EU Taxonomy for Sustainability**, are highly relevant. The CSRD ensures that manufacturers and suppliers of functional electronics are held accountable for the sustainability of their materials and production processes. This includes reporting on the recyclability of materials, energy efficiency of manufacturing methods, and the environmental impact of the entire product lifecycle. The EU Taxonomy incentivises investment in sustainable functional electronics technologies by classifying them as green innovations when they meet specific criteria. For instance, the use of recyclable substrates, energy-efficient components, and non-toxic materials in printed and flexible electronics aligns with the taxonomy's goals.

Together, the CSRD and the EU Taxonomy provide the foundation for driving innovation in functional electronics while ensuring that these advancements align with Europe's sustainability targets, fostering a circular economy in the automotive sector.

Green Public Procurement (GPP) Strategy

The Green Public Procurement (GPP) Strategy is a vital component of the European Union's circular economy agenda, encouraging public institutions to prioritise the procurement of environmentally sustainable products. This strategy aims to leverage the significant purchasing power of public authorities to drive market demand for circular and responsibly produced goods. The GPP Strategy sets specific criteria for environmental performance, resource efficiency, and life cycle impacts that public sector entities must consider when making procurement decisions.

The key elements of the GPP Strategy are:

- Mandating that products meet stringent sustainability standards such as reduced energy consumption, recyclability, and the use of non-toxic materials.
- Encouraging the inclusion of design features that facilitate repair, reuse, and recycling, thereby extending the lifecycle of products.
- Emphasising transparency and accountability through the adoption of standards for verifying the environmental impact and compliance of procured goods.

For Functional Electronics in the automotive sector, the **Green Public Procurement Strategy** provides an opportunity to align product development with circular economy principles. Public sector demand for sustainable components incentivises manufacturers to design and produce electronics that meet rigorous environmental standards. For instance, functional electronics used in vehicles, such as energy-efficient sensors, flexible displays, and lightweight electronic circuits, can be developed using recyclable substrates and eco-friendly materials to align with GPP criteria. Moreover, the focus on lifecycle impact ensures that automotive electronic components are designed for easy disassembly and material recovery at the end of their use. This not only supports compliance with procurement standards but also positions functional electronics as a key enabler of circularity in the automotive sector, driving innovation and environmental stewardship.

4.5.2 Electronics

European Chips Act

The European Chips Act represents a significant step in securing the EU's position as a global leader in semiconductor manufacturing and innovation. By addressing Europe's dependency on non-EU semiconductor suppliers, which has been identified as a critical vulnerability due to recent supply chain disruptions, the act seeks to ensure technological sovereignty and foster

cross-industry innovation. The act aims to double the EU's share of global semiconductor production from 10% to 20% by 2030 through targeted investments and initiatives.

Central to the Chips Act is its focus on:

- Boosting research and development through a network of competence centres that advance semiconductor technologies. These centres drive continuous innovation, providing a foundation for next-generation chips tailored to industry-specific needs.
- Enhancing production capacity by allocating substantial financial support for state-of-the-art manufacturing facilities, ensuring the availability of high-performance chips for diverse sectors, including automotive.
- Strengthening supply chain resilience by fostering partnerships across the semiconductor value chain, from raw material suppliers to manufacturers and end-users, to reduce dependency on external suppliers.
- Accelerating semiconductor innovation and ensuring a coordinated response to global supply challenges by promoting public-private partnerships and cross-border collaboration among EU member states.
- Investing in education and workforce development, creating a skilled talent pool to sustain the semiconductor industry's growth.

For the automotive sector, the **European Chips Act** holds particular relevance. Advanced driver-assistance systems (ADAS), vehicle-to-everything (V2X) communication, and energy management systems require high-performance and energy-efficient semiconductors. The act ensures a stable supply of these critical components, reducing production delays and enhancing supply chain security. Moreover, its focus on innovation supports the development of specialised chips, such as flexible and energy-efficient microprocessors used in functional electronics, aligning with the broader goals of electrification and autonomous mobility. By integrating semiconductors with functional electronics, the Chips Act drives innovation, sustainability, and competitiveness in automotive design and manufacturing.

European Data Strategy

The European Data Strategy highlights the establishment of the European Green Deal Data Space and the Mobility Data Space, which aim to enable data sharing for advancing circular economy practices and integrated mobility systems. These data spaces are designed to foster collaboration among industries, researchers, and public authorities by providing secure and interoperable platforms for sharing environmental and mobility data.

At the heart of this strategy are two key legislative frameworks.

- **The European Data Governance Act:** Ensuring secure and trustworthy cross-border data sharing while safeguarding the data sovereignty of EU member states. It introduces the concept of data altruism, which allows individuals and organisations to voluntarily share data for public good under strict privacy guidelines.
- **The Data Act:** Setting out rules for fair access to and use of data generated by connected devices, ensuring equitable benefits for manufacturers, service providers, and end-users from data-driven innovations.

These frameworks support the European Green Deal Data Space, which focuses on the collection and sharing of data related to environmental sustainability, resource efficiency, and emissions reductions. This data is critical for monitoring circular economy progress and achieving compliance with EU sustainability goals. Similarly, the Mobility Data Space integrates data from various transportation modes, enabling the development of smart, interconnected mobility systems that reduce emissions and enhance efficiency.

The **European Data Strategy** has significant implications for Functional Electronics in the automotive sector. Real-time data sharing through these data spaces facilitates the optimisation of design, performance, and lifecycle management for functional electronics such as sensors, energy management systems, and displays. For instance, real-time data on material usage and recyclability can guide the development of more sustainable components, while shared mobility data enhances the integration of functional electronics into electric and autonomous vehicles. By leveraging the insights enabled by the European Data Strategy, the automotive industry can advance circular economy practices, meet EU sustainability objectives, and drive innovation in green mobility systems.

WEEE Directive 2012/19

The WEEE Directive aims to minimise the environmental impact of electrical and electronic equipment (EEE) by mandating their collection, treatment, recycling, and proper disposal.

The Directive:

- Sets specific collection and recycling targets for Member States (MS) - MS are required to achieve a collection rate of 65% of EEE placed on the market or 85% of generated e-waste.
- Establishes minimum recovery targets for specific EEE categories, including up to 80% for large appliances and IT equipment, emphasising the recovery of critical raw materials (CRMs) such as rare earth metals essential for advanced electronic technologies.
- Holds manufacturers accountable for the lifecycle management of their products under the Extended Producer Responsibility (EPR) principle.
- Obligates manufacturers to finance the collection, treatment, and recycling of their products, incentivising sustainable design and material efficiency.
- Emphasise modularity and recyclability by encouraging the design of components that can be easily disassembled and their materials efficiently recovered, aligning with circular economy principles.

The **WEEE Directive** has significant implications for Functional Electronics (FE) in the automotive sector, where components such as sensors, displays, and printed circuits contribute to e-waste generation. Innovations like recyclable substrates and non-toxic conductive inks facilitate compliance with WEEE requirements, while modular designs enable easy disassembly of electronic components at the end of their lifecycle. These practices not only enhance material recovery and reduce waste but also support the sustainability goals of the automotive industry by promoting circularity and resource efficiency.

Restriction of Hazardous Substances (RoHS) Directive

The Restriction of Hazardous Substances (RoHS) Directive aims to reduce environmental and health risks by restricting the use of hazardous materials in electrical and electronic equipment (EEE). The directive specifically targets substances such as lead, mercury, cadmium, hexavalent chromium, and specific brominated flame retardants, mandating that manufacturers design products that comply with stringent chemical limits. Non-compliance can lead to significant penalties or market withdrawal, emphasising the importance of adherence for manufacturers.

The **Restriction of Hazardous Substances Directive** has direct implications for functional electronics in the automotive sector, as components like sensors, printed circuits, and energy management systems often involve materials traditionally containing restricted substances. By transitioning to eco-friendly alternatives such as lead-free soldering, non-toxic conductive inks, and recyclable substrates, manufacturers not only meet regulatory requirements but also advance sustainability and safety standards. Compliance with RoHS ensures that automotive electronics are safer for consumers and easier to recycle, aligning with broader goals of reducing environmental impact and enhancing circularity in the automotive industry.

System Working Safety and Reliability of Sensors (ISO 26262 / ASIL D)

System working safety and reliability are critical for functional electronics in automotive applications, particularly in advanced driver-assistance systems (ADAS) and autonomous vehicles. Standards like ISO 26262 and Automotive Safety Integrity Level (ASIL) D provide comprehensive frameworks to ensure the functional safety of electrical and electronic systems in vehicles.

ISO 26262 outlines the development processes and safety requirements for automotive electronic systems, ensuring components such as sensors meet stringent criteria to prevent failures that could lead to accidents. For instance, energy-efficient sensors and safety-critical systems must detect and mitigate potential faults to align with these safety standards. ASIL D, the highest safety integrity level under ISO 26262, applies to systems where failures could have life-threatening consequences. Sensors used in autonomous vehicles, for example, must process real-time data with high reliability, enabling accurate decision-making in complex environments.

Functional Electronics adhering to **ISO 26262 “System Working Safety and Reliability of Sensors”** and **ASIL D** standards incorporate fail-safe mechanisms, redundancy, and robust diagnostics to maintain operational safety. This has led to innovations in sensor design, flexible printed circuits, and energy management systems that ensure reliability under harsh automotive conditions. By aligning with these standards, functional electronics not only enhance safety and reliability but also support the automotive industry's transition to electrification and autonomy, fostering consumer trust and compliance with global safety regulations.

4.5.3 Mobility

Sustainable and Smart Mobility Strategy

The Sustainable and Smart Mobility Strategy is a cornerstone of the European Union's vision to revolutionise transportation systems by aligning them with circular economy goals. This comprehensive roadmap aims to decarbonise transport networks, enhance digital connectivity, and promote multimodal mobility options, contributing to the EU's broader objectives under the European Green Deal.

The strategy focuses on several key areas:

- **Decarbonisation:** Accelerating the transition to zero-emission vehicles and promoting the use of renewable energy sources for transportation systems.
- **Energy Efficiency:** Encouraging innovations in vehicle design and manufacturing to optimise energy use, reducing overall emissions and resource consumption.
- **Digital Connectivity:** Leveraging advanced technologies like 5G and V2X communication to enable connected and autonomous transport systems.

- **Multimodal Mobility:** Supporting the integration of various transport modes to create seamless, efficient, and sustainable urban and inter-urban mobility solutions.

Functional Electronics (FE) play a critical role in realising the goals set in the **Sustainable and Smart Mobility Strategy**. Advanced sensors, lightweight energy management systems, and flexible displays enable smarter, more sustainable vehicles. For instance, FE technologies facilitate real-time communication and data processing, which are essential for autonomous driving and predictive maintenance. Moreover, FE supports modular and energy-efficient vehicle designs, aligning with the strategy's emphasis on circularity. By integrating functional electronics, automotive systems can achieve greater energy efficiency, reduced material use, and improved end-of-life recyclability. This ensures that mobility systems are not only smarter and more efficient but also environmentally sustainable and resilient.

Cooperative, Connected, and Automated Mobility (CCAM) Strategy

The Cooperative, Connected, and Automated Mobility (CCAM) strategy is a key initiative by the European Commission to enhance the safety, efficiency, and sustainability of transportation systems. By integrating connected vehicle systems, autonomous driving solutions, and cooperative communication platforms, CCAM aims to create a seamless and resilient mobility ecosystem.

CCAM emphasises:

- **Road Safety:** Reducing accidents through advanced driver-assistance systems (ADAS) and vehicle-to-everything (V2X) communication.
- **Traffic Efficiency:** Minimising congestion by enabling real-time traffic management and dynamic routing.
- **Environmental Sustainability:** Lowering emissions through optimised transport flows and smarter vehicle operations.

The Intelligent Transport Systems (ITS) Directive complements CCAM by promoting the deployment of intelligent solutions across European transportation systems. ITS focuses on real-time traffic management, dynamic routing, and interoperability between systems, fostering innovation in transport technologies.

Functional Electronics underpin the advancements targeted in the **Cooperative, Connected, and Automated Mobility Strategy**. Sensors, radar systems, and communication modules enable V2X interactions, improving traffic efficiency and road safety. Lightweight and adaptive displays contribute to vehicle weight reduction and energy savings, aligning with sustainability goals. The modular and scalable nature of FE ensures seamless integration across vehicle platforms and infrastructure, driving progress in safer and smarter mobility.

EU Urban Mobility Framework

Introduced as part of the European Green Deal, the EU Urban Mobility Framework supports the development of sustainable urban transport systems. Its primary objectives are to reduce greenhouse gas emissions, alleviate congestion, and improve air quality in urban areas. Central to the framework is the promotion of Sustainable Urban Mobility Plans (SUMP), which integrate various transport modes—public transit, cycling, and walking—into cohesive systems.

Key pillars of the framework include:

- **Mobility-as-a-Service (MaaS):** Encouraging shared and integrated mobility solutions.

- **Digital Connectivity:** Supporting the adoption of intelligent transport systems and real-time data sharing.
- **Low-Emission Transport:** Promoting the use of electric vehicles and renewable energy.

Functional electronics are integral to achieving these objectives. For example, sensors and energy-efficient circuits in shared mobility fleets enable real-time vehicle tracking and operational efficiency. Advanced traffic management systems, powered by FE, support dynamic routing and congestion reduction. Additionally, FE solutions in electric vehicles and charging infrastructure contribute to the framework's emphasis on clean energy adoption. By facilitating the transition to sustainable and integrated urban transport systems, functional electronics play a pivotal role in the EU Urban Mobility Framework.

The Sustainable and Smart Mobility Strategy, CCAM Strategy, and EU Urban Mobility Framework are interlinked through their shared goals of decarbonisation, digital connectivity, and multimodal transport integration. The Sustainable and Smart Mobility Strategy provides the overarching vision, setting ambitious targets for decarbonisation and energy efficiency. CCAM builds on this foundation by focusing on technological advancements in connected and automated systems to enhance road safety and efficiency. The Urban Mobility Framework complements these strategies by addressing the specific challenges of urban environments, promoting MaaS and shared mobility solutions.

Functional Electronics serve as a unifying element across all three strategies encompassed under the **EU Urban Mobility Framework**, enabling the technologies required to achieve their objectives. Whether through advanced sensors for autonomous vehicles, energy-efficient circuits for electric mobility, or adaptive displays for multimodal integration, FE drives innovation and sustainability across Europe's evolving transport ecosystem.

Battery Regulation (EU 2023/1112)

The Battery Regulation establishes comprehensive benchmarks for the entire lifecycle of batteries, directly supporting the European Union's ambitious sustainability objectives, such as those outlined in the Green Deal. It addresses key aspects of sustainability, durability, recyclability, and ethical sourcing, ensuring that batteries contribute to a circular economy while supporting the transition to electric mobility and other high-demand applications.

Provisions Ensuring Sustainability and Efficiency:

- **Durability:** Stringent standards for battery performance aim to ensure long lifespans and reduce the need for frequent replacements. This includes requirements for batteries to maintain a minimum energy retention capacity over their lifecycle, critical for electric vehicles (EVs) and other energy-intensive applications, thus reducing waste and enhancing consumer trust.
- **Recyclability:** The regulation mandates specific recycling efficiency targets for critical materials such as lithium, cobalt, and nickel. By setting progressive goals for recycling rates, such as achieving 95% efficiency for key metals, the regulation minimises reliance on finite resources and supports circularity while fostering innovation in recycling technologies.
- **Sourcing:** Emphasises ethical and sustainable sourcing of raw materials, including compliance with environmental standards and adherence to responsible labour practices. This includes mandatory due diligence processes for supply chains to mitigate social and environmental risks associated with extraction activities.
- **Labelling and Transparency:** Introduces mandatory carbon footprint labelling for all battery types, accompanied by detailed product performance and recyclability data. This fosters informed consumer decisions, promotes supply chain accountability, and allows stakeholders to evaluate the environmental impact of batteries across their lifecycle.

- **End-of-Life Management:** Obligates manufacturers to implement comprehensive systems for the collection, treatment, and recycling of used batteries. These systems must ensure efficient recovery of valuable materials, such as lithium and nickel, while adhering to environmental standards for waste processing.

For Functional Electronics in the automotive sector, the **Battery Regulation** has transformative implications. Batteries are foundational for electric vehicles and integral to advanced automotive systems such as energy management, sensors, and displays. By emphasising durability and recyclability, the regulation fosters innovations in functional electronics, encouraging modular designs and the use of sustainable materials to align with circular economy principles. Lightweight and energy-efficient battery systems enhance EV sustainability while maintaining high performance standards. Transparency requirements, such as mandatory carbon footprint labelling and detailed performance reporting, enhance the integration of functional electronics into vehicle designs by ensuring traceability and compliance with sustainability objectives. This comprehensive framework drives innovation in battery technologies, strengthens the European automotive and electronics industries, and aligns with global environmental goals.

High-Voltage Battery Regulation (EU 2022/542)

The High Voltage Battery Regulation establishes stringent sustainability, safety, and performance standards for electric vehicle (EV) batteries, ensuring their reliable and efficient operation throughout their lifecycle while complementing the broader Battery Regulation. It complements the Battery Regulation by focusing on specific technical and safety aspects of high-voltage battery systems.

Comprehensive Sustainability Standards:

- **Performance Standards:** Sets detailed benchmarks for reliability, energy efficiency, and consistent power output. These include minimum thresholds for energy density and charging efficiency, ensuring extended driving ranges and enhanced performance under diverse operating conditions.
- **Durability:** Mandates rigorous resistance to degradation over time through standards for energy retention and cycle life, ensuring longer battery lifespans, reduced waste, and sustained high performance for EV applications.
- **Recycling and Recovery Targets:** Sets ambitious recycling efficiency goals, such as achieving 95% recovery for critical materials like lithium, cobalt, and nickel. This fosters advanced resource recovery methods, supports circularity, and reduces dependency on raw material extraction.
- **Sustainable Sourcing:** Enforces compliance with ethical and environmentally sustainable practices in supply chains. This includes mandatory due diligence for labor rights, biodiversity protection, and adherence to stringent environmental extraction standards.
- **Transparency and Reporting:** Mandates comprehensive carbon footprint labelling, material composition disclosures, and reporting on recycling performance. These measures enhance accountability, allow stakeholders to evaluate environmental impact, and support informed decision-making across the supply chain.
- **End-of-Life Management:** Implements robust systems for the collection, treatment, and recycling of used batteries, including clear guidelines for dismantling and material recovery. This ensures maximum recovery of valuable resources, such as lithium and nickel, while adhering to strict environmental standards for waste treatment.

The **High-Voltage Battery Regulation** reinforces the integration of sustainable practices in functional electronics for automotive applications. EV batteries power critical FE components, including energy management systems, advanced sensors, and displays. By ensuring high performance and recyclability, these regulations enable FE technologies to operate reliably in demanding automotive environments while supporting broader circular economy objectives. The transparency and reporting obligations ensure robust traceability of materials used in functional electronics, fostering compliance with sustainability goals and enabling informed decision-making across the supply chain.

Vehicle General Safety Regulation

The Vehicle General Safety Regulation harmonises EU safety legislation with global technical standards, introducing advanced measures to protect road users and enhance vehicle safety. By aligning with global standards, this regulation ensures that European manufacturers can compete more effectively in international markets, as harmonisation reduces the need for region-specific adaptations, simplifies compliance processes, and fosters innovation across a unified technical landscape. The regulation mandates the adoption of innovative technologies such as advanced driver-assistance systems (ADAS) and vehicle-to-everything (V2X) communication.

Core Advancements of the Regulation:

- **Advanced Driver-Assistance Systems (ADAS):** ADAS encompasses a range of technologies including automated emergency braking, adaptive cruise control, lane-keeping assistance, and collision avoidance systems. These systems rely on advanced sensors and predictive algorithms to enhance driver safety, reduce human error, and mitigate accidents. By significantly lowering road fatalities and injuries, ADAS aligns with the regulation's overarching safety objectives, supporting the broader vision of safer and more efficient mobility systems. These systems include technologies such as automated emergency braking, adaptive cruise control, lane-keeping assistance, and collision avoidance systems. By leveraging advanced sensors and predictive algorithms, ADAS improves driver safety, reduces human error, and mitigates accidents, thereby enhancing road safety. This includes automated braking, lane-keeping assistance, and collision avoidance systems to improve road safety and reduce accidents.
- **Vehicle-to-Everything (V2X) Communication:** Facilitates seamless real-time data exchange between vehicles, infrastructure, and other road users. This includes vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communication, improving traffic flow, optimising energy usage, and reducing congestion while enhancing safety.
- **Sustainability Linkage:** Optimises energy consumption and minimises resource use by reducing the frequency and severity of accidents. Advanced safety features limit the need for extensive repairs, decrease waste generation, and contribute to the broader goals of resource efficiency and circularity.

For Functional Electronics, the Vehicle General Safety Regulation drives demand for advanced sensors, flexible displays, and energy-efficient components essential for ADAS and V2X systems. FE technologies facilitate lightweight and modular designs, improving vehicle efficiency and sustainability. By supporting real-time data exchange and predictive capabilities, these components align with the regulation's goals of improving safety and reducing environmental impacts.

End-of-Life Vehicles (ELV) Directive

The End-of-Life Vehicles (ELV) Directive is a cornerstone of the EU's circular economy agenda, focusing on reducing the environmental impact of vehicles at the end of their lifecycle. It mandates sustainable design, recycling, and resource recovery practices across the automotive sector.

Key Measures:

- **Modular Design and Recycling:** Encourages vehicle designs that facilitate the disassembly, repair, and recycling of components. This measure ensures the recovery of valuable resources, such as critical raw materials (CRMs), plastics, steel, and aluminium. By prioritising modular design, manufacturers can streamline end-of-life processes, enhancing recyclability and minimising waste streams while recovering high-value materials efficiently.
- **Recycling Targets for Plastics:** Sets a requirement that at least 25% of the plastics used in vehicle manufacturing come from recycled sources, with a substantial portion originating from end-of-life vehicles (ELVs). This target supports the development of closed-loop recycling systems and minimises the demand for virgin plastics.
- **Producer Responsibility:** Holds manufacturers financially accountable for the proper treatment and recycling of ELVs, incentivising them to adopt sustainable design principles. This includes collaborating with recyclers to improve the quality and efficiency of material recovery operations.
- **Material Recovery:** Prioritises the recovery of high-quality CRMs, such as rare earth metals, to reduce dependency on primary resource extraction. This measure enhances resource circularity while securing the supply of materials critical for modern automotive technologies.
- **Export Controls:** Introduces stricter measures to prevent the export of non-roadworthy vehicles, ensuring that ELVs are processed appropriately within the EU, thereby minimising illegal exports and environmental dumping. This measure also reduces the risk of vehicles "going missing" and improves compliance with recycling standards.
- **Scope Expansion:** Gradually extends the directive's application to encompass additional vehicle categories, including motorcycles, lorries, and buses, ensuring a comprehensive approach to end-of-life vehicle management. This expansion ensures comprehensive coverage of end-of-life management practices across a wider range of vehicle types.

For Functional Electronics in automotive systems, the **End-of-Life Vehicles Directive** promotes modular and repairable designs that support disassembly and recyclability, fostering a significant reduction in waste and resource consumption. This directive aligns with circular economy principles and drives the adoption of innovative FE materials, such as recyclable substrates, biodegradable polymers, and non-toxic conductive inks, which enhance material recovery and environmental sustainability. By integrating FE solutions into vehicle designs, manufacturers not only meet regulatory compliance but also reduce their carbon footprint and operational costs. Furthermore, the directive's focus on material recovery incentivises the development of advanced recycling technologies and modular components that extend product lifecycles, ensuring that the automotive industry can maintain competitiveness while advancing environmental stewardship and resource efficiency.

4.5.4 Conclusion on Regulatory Landscape and Interlinkages

The regulatory landscape for circular functional electronics (FE) in the automotive sector demonstrates a highly interconnected framework, where sustainability, innovation, and compliance converge to shape the industry's trajectory. Each regulation, directive, and strategy—from the Circular Economy Action Plan to the European Chips Act—addresses

distinct aspects of circularity, material efficiency, and sustainability while collectively fostering a holistic approach to transitioning toward a circular economy.

The interlinkages between these regulatory frameworks reveal several synergies:

- **Harmonisation across Sectors:** Directives like the Eco-design Directive and the Circular Economy Action Plan align sustainability principles across industries, creating a foundation for modularity, recyclability, and energy efficiency in automotive electronics.
- **Support for Innovation:** Regulations such as the European Chips Act and the Environmental Product Regulation incentivise advancements in material science and manufacturing technologies, ensuring that functional electronics meet both performance and sustainability standards.
- **Supply Chain Resilience:** Policies like the Critical Raw Materials Act and the Net-Zero Industry Act address supply chain vulnerabilities, promoting recycling, reuse, and sustainable sourcing of key materials used in FE components.
- **Circularity and Resource Efficiency:** Frameworks such as the End-of-Life Vehicles Directive and Battery Regulation emphasise the recovery of critical raw materials, ensuring that FE components are designed to enable efficient disassembly and recycling.

These interconnected frameworks underscore the importance of integrating regulatory goals with industry practices. By aligning compliance requirements with circular economy principles, the regulatory landscape supports the transition to sustainable mobility while enhancing global competitiveness.

4.6 Context Map

The context map provides a comprehensive view of the dynamic interplay between mobility trends, technological innovations, and regulatory frameworks shaping the transition to a circular automotive industry. This evolving landscape underscores the critical role of functional electronics (FE) as both a driver and enabler of sustainable mobility solutions.

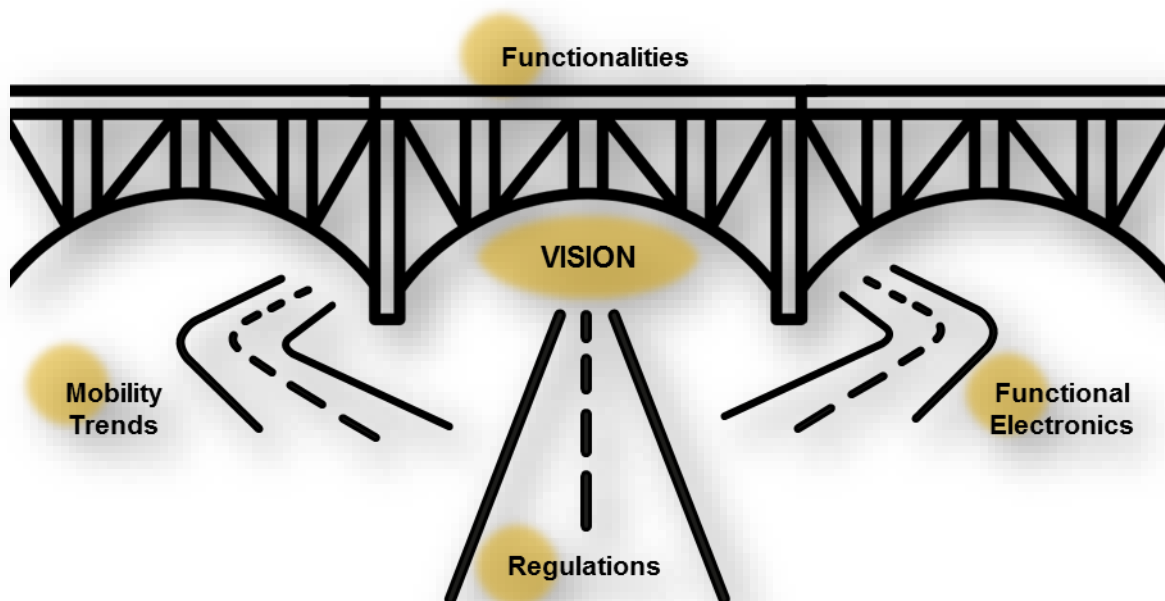


Figure 6: Vision for FE in the Future Automotive and Contextual Factors

Technological advancements are at the forefront of this transformation. Innovations in electrification, automation, and digitalisation are not only enhancing vehicle performance but also laying the groundwork for smarter, greener, and more connected transportation systems.

Functional electronics, such as sensors, energy-efficient circuits, and adaptive displays, underpin these technological shifts by improving vehicle efficiency, safety, and modularity.

Simultaneously, the regulatory framework within the European Union acts as a catalyst for change. Policies such as the Circular Economy Action Plan, Eco-design Directive, and Battery Regulation provide a structured pathway for integrating sustainability and circularity into the automotive value chain. These regulations ensure that functional electronics contribute to energy efficiency, material recovery, and reduced environmental impact, while fostering cross-sector collaboration and innovation.

Socio-economic factors further reinforce the urgency of adopting circular mobility systems. Urbanisation, shifting demographics, and growing consumer awareness of sustainability are driving demand for eco-friendly and inclusive transportation options. These trends align with regulatory goals and technological capabilities, creating a synergistic environment for the adoption of circular practices.

The interlinkage of regulatory frameworks, technological advancements, and socio-economic drivers facilitates the integration of circular economy principles across the automotive sector. By promoting waste reduction, optimising resource efficiency, and encouraging sustainable practices, these interconnected factors support a holistic approach to achieving circularity.

In conclusion, the context map highlights the importance of a coordinated effort among policymakers, industry stakeholders, and researchers to realise the vision of a sustainable and circular automotive industry. Functional electronics remain central to this vision, bridging the gap between regulatory objectives and technological innovation.

The context map captures the evolving landscape of mobility trends, technological advancements, and regulatory frameworks driving the transition to a circular automotive industry. Key takeaways include:

- **Technological Drivers:** Innovations in electrification, automation, and digitalisation are reshaping the automotive sector, supported by advancements in FE technologies such as sensors, energy-efficient circuits, and adaptive displays.
- **Regulatory Catalysts:** The robust regulatory framework within the European Union emphasises sustainability, circularity, and innovation. These policies provide clear guidelines for integrating FE into sustainable mobility solutions while fostering cross-sector collaboration.
- **Socio-Economic Pull Factors:** Urbanisation, demographic shifts, and consumer demand for eco-friendly solutions create a strong impetus for adopting circular and inclusive mobility systems.
- **Circular Economy Integration:** The interlinkage of regulatory frameworks facilitates a cohesive approach to reducing waste, optimising resource efficiency, and promoting sustainable practices throughout the automotive value chain.

5 Vision and enablers for a circularity-driven functional electronics integration

The automotive industry is at a transition point, shaped by transformative mobility trends driven by technological innovation and evolving socio-economic demands. The "technology push" is accelerating the adoption of for example connected, cooperative, and automated mobility solutions, while the shift toward electrification and digitalisation is reshaping vehicles into software-defined platforms. The "socio-economic pull", on the other hand, is pressing for sustainable, accessible, and resource-efficient mobility options that address environmental and societal challenges.

In parallel, the concept of circularity is gaining momentum as a guiding principle to mitigate environmental impacts, conserve finite resources, and create value across the entire lifecycle of products. The regulatory landscape is responding with frameworks such as the EU Circular Economy Action Plan, which emphasises resource efficiency, extended producer responsibility, and the need for traceable and repairable electronics. For the automotive sector, the intersection of these trends has profound implications for functional electronics (FE), which underpin critical systems like sensors, ECUs (electronic control units), and connectivity modules.

This vision for circular FE in automotive encompasses the entire value chain—from the design of modular, recyclable electronics to the establishment of reverse logistics for recovery and remanufacturing towards the end-of-life management. By integrating principles of circularity with advanced digital tools and innovative materials, the automotive industry can unlock new opportunities for sustainable growth, align with emerging regulations, and deliver on the promise of a green and connected mobility future.

The UNICORN vision for circular Functional Electronics in the automotive sector is centred on achieving the right amount of resources for the realisation of functionality.

This means that materials and energy are used efficiently to enable high-performing, durable, and sustainable electronic components while aligning with circular economy principles. The goal is to transition towards a system where functional electronics are designed for longevity, adaptability, and end-of-life recovery, minimising waste and resource depletion.

The vision revolves around two transformative pillars:

- 1) Extended functionalisation of printed electronics to replace conventional electronics and**
- 2) Positioning printed electronics as a blueprint for sustainable electronics, with the introduction of a transversal "greening" functionality that can be adapted to conventional electronics.**

These pillars reflect the dual need to enhance sustainability of the electronic sector while pushing the boundaries of performance and integration of printed electronics.

Extended Functionalisation of Printed Electronics to Replace Conventional Electronics

Printed electronics represent a transformative step forward in replacing conventional electronics, offering a versatile, lightweight, and cost-effective alternative. Through extended functionalisation, printed electronics can move beyond their traditional applications, such as sensors or simple circuits, to take on roles historically reserved for conventional electronics. This is especially important for **Data Processing and Storage** and **Powering Capabilities**, meaning to advance printed electronics to handle data processing tasks and energy management, potentially integrating energy harvesting or storage directly into printed components by improving performance. While printed electronics may not yet match the performance of traditional electronics in all areas, ongoing innovations aim to bridge this gap, especially in applications where size, weight, substrate and environmental considerations outweigh sheer processing power. By focusing on these advancements, printed electronics can offer a green, lightweight, and scalable alternative to conventional electronics, aligning with the automotive industry's goals for sustainability and efficiency.

Positioning Printed Electronics as a Blueprint for Sustainable Electronics

Printed electronics are uniquely positioned to serve as a blueprint for sustainable electronics, setting a precedent for how electronic systems can be designed, manufactured, and deployed with circularity in mind. This vision is centred on their ability to inspire sustainable practices across the broader electronics sector e.g. through energy and material efficiency, direct integration and circular design.

The transition to circular FE in the automotive sector is driven by a series of interconnected enablers that span design, manufacturing, and end-of-life management. These enablers work together to ensure that FE is not only high-performing and cost-effective but also sustainable and aligned with circular economy principles.

Central to this vision is the **"Rs of Circularity" framework**²⁰, which provides a foundation for minimising waste and maximising resource efficiency. At its core, it begins with Refusing unnecessary consumption and Rethinking product designs to embed functionality and circular principles into materials and systems. Reducing the use of materials and energy is a priority, while Reusing products and components, Repairing items to extend their usability, and Refurbishing them for renewed functionality ensure their continued value. Further steps include Remanufacturing products to meet original specifications and Repurposing materials for alternative uses. Recycling plays a critical role in closing the loop by Recovering valuable raw materials, and recovering energy or materials from waste further ensures that no resource is left unused. Together, these strategies create a holistic system where waste is minimised, and resources are continuously cycled for maximum value that can also be directly linked to the four pathways of the Circular Car Initiative, which aims to create a fully circular automotive industry by addressing material flows, life-cycle assessment, and systemic innovation.

The transition to circular FE in the automotive sector is furthermore driven by a comprehensive set of enablers that integrate sustainability into every stage of the product lifecycle. These enablers ensure that FE systems are not only high-performing and cost-effective but also environmentally sustainable and aligned with circular economy principles.

At the heart of this transformation is **circular design**, which prioritises eco-design principles and ensures that FE components are built for longevity and adaptability. **Modular architectures** play a key role, allowing individual components to be easily disassembled, repaired, or upgraded without replacing entire systems. This design philosophy ensures that FE can adapt to evolving technological needs while minimising waste. Additionally, materials are carefully selected to align with sustainability goals, focusing on resource efficiency, recyclability, and transparency in sourcing. **Bio-based substrates** and **non-toxic inks** replace conventional materials, reducing environmental impacts and aligning with responsible supply chain practices.

²⁰ <http://dx.doi.org/10.1016/j.resconrec.2017.09.005>

Transparency in functionality is a crucial enabler for circularity. Printed electronics enable **seamless integration** of electronic functionalities into materials, making them an intrinsic part of vehicle surfaces such as dashboards, seats, or windows. This reduces the complexity of electronic assemblies by eliminating the need for specific substrates (PCBs) with high environmental imprint while enhancing user understanding and interaction. Systems designed with visible functionality simplify diagnostics, repairs, and upgrades, further extending the life of electronic components.

A key innovation in this context is the **Digital Product Passport (DPP)**, which provides structured, standardised information about a product's composition, sustainability credentials, and recyclability potential. The DPP allows manufacturers, consumers, and recyclers to track material flows, optimise end-of-life recovery, and ensure compliance with circular economy principles. By facilitating transparency in sourcing and performance, the DPP helps establish a data-driven approach to sustainable FE manufacturing and disposal.

Resource efficiency and energy optimisation are equally critical. **Additive manufacturing**, such as roll-to-roll printing, minimises material waste and energy consumption, enabling scalable production of lightweight and multifunctional components. These processes ensure that the environmental footprint of FE is reduced not only during operation but also throughout manufacturing. Energy-efficient designs further enhance sustainability by reducing operational energy requirements.

Durability by design ensures that components can withstand the demanding conditions of automotive applications. Upgradability is seamlessly integrated into systems, enabling users to enhance functionality over time without the need for complete replacements. This not only reduces costs but also supports sustainable consumption patterns. FE components must be designed for longevity, incorporating software updates, interchangeable parts, and reparability to avoid premature obsolescence.

Closing the loop on FE production involves **designing components for reuse and easy dismantling**, allowing materials and components to be efficiently recovered and reintegrated into production cycles. Recycling processes must be tailored to recover valuable resources such as metals, ensuring that no resource is left unused. Additionally, robust e-waste management systems must be in place to ensure that discarded components are processed responsibly, reducing environmental harm.

As an outlook, **hybrid printed electronics**, which combine traditional electronic components with printed functionalities, play a significant role in this transition. They allow for increased performance and durability while benefiting from the advantages of additive manufacturing and modularity. By leveraging hybrid printed electronics, the automotive industry can integrate sustainable materials, optimise production efficiency, and enhance recyclability.

The realisation of this vision for circular FE depends on a collaborative approach that integrates design, manufacturing, and policy strategies. By embedding circularity into functional electronics, the automotive sector can drive resource efficiency, reduce environmental impacts, and contribute to a more sustainable and connected mobility future. This approach not only supports the European Union's sustainability goals but also positions the industry at the forefront of technological innovation in green electronics.

6 Conclusions & Outlook

Printed electronics (PE) offer significant advantages over conventional electronics, including flexibility, conformability, stretchability, and thermoformability, making them ideal for integration into automotive applications. These features enable innovations such as touch-sensitive controls, heating elements for vehicle surfaces, and safety-enhancing sensors. However, challenges remain, particularly regarding the functionality, reliability, and long-term stability of fully printed devices²¹.

The opportunity to reduce global e-waste through more sustainable design choices, alternative production methods, and improved end-of-life strategies is substantial²². Despite the progress in functional printing, limitations in performance and durability persist, requiring further research and development. Additionally, while hybrid PEs continue to drive advancements in sustainability and innovation, they do not yet meet the full functionality requirements of all electronic applications.

Market potential for PE is growing, with a projected value exceeding \$15 billion by the end of 2024²³. This expansion is driven by increasing demand in consumer electronics, automotive, and healthcare sectors. However, cost considerations remain a barrier, as sustainable materials and advanced manufacturing processes often entail higher initial investment costs. To make sustainability a viable economic choice, cost-efficient production techniques and economies of scale must be pursued.

Moving forward, three key areas will shape the transition toward circular FE:

- **SWOT Analysis** – A structured evaluation of strengths, weaknesses, opportunities, and threats will help identify key factors influencing circular FE adoption. Strengths include advancements in energy-efficient components and modular designs, while weaknesses involve high production costs and fragmented regulatory standards.
- **Roadmap Development** – Establishing a milestone-driven strategy to align technological innovation, regulatory compliance, and collaboration across stakeholders. Priorities include integrating digital twins, scaling additive manufacturing, and harmonising sustainability standards.
- **Policy Recommendations** – Encouraging policymakers to facilitate collaboration, promote transparency (e.g. Digital Product Passports), support research funding, and align global regulatory standards to foster circular FE adoption.

By addressing these areas, the automotive sector can ensure that functional electronics contribute meaningfully to the circular economy, driving sustainability while maintaining global competitiveness. Through a balanced approach to innovation, policy, and cost-effectiveness, circular FE can redefine the future of mobility electronics.

²¹ Sudheshwar, A., Beni, V., Malinverno, N., Hischier, R., Nevo, Y., Dhuiege, B., et al. (2022). Assessing Sustainability Hotspots in the Production of Paper-based Printed Electronics. *Flexible and Printed Electronics* 8. doi: 10.1088/2058-8585/acacab

²² Nassajfar, M. N., Deviatkin, I., Leminen, V., and Horttanainen, M. (2021). Alternative materials for printed circuit board production: An environmental perspective. *Sustainability (Switzerland)* 13. doi: 10.3390/su132112126

²³ <https://www.voltera.io/blog/2024-trends-printed-electronics>