White paper

Recommendations for sustainable and circular electronics from the Sustronics project

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Abstract

The Sustronics project (2023–2026) brought together a European electronics ecosystem of industry, research organisations and academia to demonstrate how sustainability and circular economy principles can be systematically integrated into electronics design, manufacturing and business models. This white paper synthesises the main outcomes of the project and translates them into actionable recommendations for sustainable and circular electronics. Drawing on the technology pilots across three use cases—circular electronic devices, sustainable electronics manufacturing, and environmentally compatible single-use electronics—the paper highlights practical lessons on material selection, additive and hybrid manufacturing, eco-design, software sustainability and end-of-life (EoL) strategies. Life cycle assessment (LCA) and eco-design methodologies were applied throughout the project to identify environmental hotspots, guide design decisions and quantify both footprint reductions and potential handprints.

The results demonstrate that early integration of sustainability considerations can significantly reduce environmental impacts while maintaining functionality, safety and economic viability, even in regulated sectors such as healthcare and automotive electronics. Beyond technical insights, the white paper addresses systemic challenges related to standards, recycling infrastructure, data availability and market uptake. Therefore, it formulates policy recommendations focusing on harmonised sustainability assessment, eco-design and recyclability standards, repairability requirements and financial support for sustainable manufacturing comprising material and technology development for each phase of product life cycles including EoL. The paper concludes with targeted recommendations for industrial companies, the research community, and policy makers, positioning sustainability and circularity as key design drivers for the future of the European electronics industry.

List of acronyms

ADP	Abiotic Depletion Potential
ASIC	Application-Specific Integrated Circuit
CBM	Circular Business Model
CRM	Critical Raw Material
DPP	Digital Product Passport
EEG	Electroencephalogram
EoL	End-of-Life
ESPR	Ecodesign for Sustainable Products Regulation
e-waste	Electronic and electric waste
GWP	Global Warming Potential
IC	Integrated Circuit
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDS-MID	Laser Direct Structuring – Moulded Interconnect Device
LED	Light Emitting Diode
ODP	Ozone Depletion
PCB	Printed Circuit Board
PCR	Product Category Rule
PEF	Product Environmental Footprint
PLA	Polylactic Acid
RTO	Research and Technology Organisation
TPU	Thermoplastic Polyurethane
TRL	Technology Readiness Level

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1. Introduction

Electronics industry is linked to a significant environmental burden resulting from a growing amount of production and product waste, a great demand for critical raw materials (CRMs) and high energy consumption during manufacturing. At the same time, the electronic and electric waste (e-waste) is one of the fastest growing global waste streams with only 20% globally and 40% in Europe collected and recycled properly. Furthermore, fast increase in global material consumption forces also the electronics industry to find substitutes and alternatives for rare, valuable and critical raw materials through, for example, the use of bio-based, renewable, abundant and recycled materials. [1-4]

Additive manufacturing based on printed and hybrid electronics with more sustainable materials is one opportunity for decreasing the environmental impact of electronics manufacturing, since it significantly reduces manufacturing and material costs, material and energy usage, and the amount of waste as compared to traditional electronics manufacturing based on etching and photolithography. With the additive methods, energy consumption during manufacturing can even be five times lower than with the conventional methods. [5-8]

Durability and lifetime extension of products are examples of sustainable product development strategies that provide a route for creating more resilience in the electronics industry. Circular economy enables new business models for the electronics industry, by introducing such improvements as product-as-a-service, material savings and reverse logistics. Product and service design approaches, such as the eco-design that considers all environmental impacts during a product's life cycle, and circular design that aims for products compatible with circular economy requirements, play a central role when moving towards more sustainable and circular electronic products. [9]

1.1. Sustronics project

Sustronics was a research project carried out in 2023-2026 between 46 partners from 11 European countries representing the industry, research organisations, and academia. The overall objective of Sustronics was to build an ecosystem to demonstrate how the electronics industry can benefit from sustainable materials and manufacturing, eco-design, energy-efficiency and circular business models. The research activities included:

- materials and process development,
- component and device development based on the novel materials and processes,
- development of sustainable electronics functionality relying on hardware and software integration,
- pilot integration to highlight arising opportunities for sustainability and circularity,
- quantification of sustainability and circularity including development of new methodologies,
- development of circular business models for new kinds of sustainable electronics,
- investigation of EoL management concepts, and
- activities to ensure community and stakeholder engagement.

1.2. Structure of the document

This white paper highlights the main outcomes and observations from the Sustronics project transformed into recommendations for the electronics industry related to sustainable and circular electronics development and integration. The takeaways from the integration of different technology pilots are described in Section 2. The environmental sustainability related to project outcomes, including eco-design, is described in Section 3. Section 4 summarises the observations related to standardisation and future oriented workshops. Section 5 concludes the white paper by summarising the recommendations and action plans related to sustainable and circular electronics for different stakeholder groups.

2. Take-aways from pilot integration

The Sustronics project included 10 pilots categorised under 3 use cases: circular electronic devices, sustainable manufacturing for electronics, and environmentally compatible single-use electronics. **Circular electronic devices** (use case 1 with Pilots 1.1-1.3) re-designed existing electronic devices to be compatible with circular economy strategies, such as remanufacturing, repair and recycling, while also benefitting from additive manufacturing and bio-based materials. **Sustainable manufacturing for electronics** (use case 2 with Pilots 2.1-2.3) decreased the environmental footprint of electronics by utilising bio-based materials together with sustainable manufacturing concepts based on printed electronics, hybrid integration and structural electronics. **Environmentally compatible single-use electronics** (use case 3 with Pilots 3.1-3.3, including two alternatives for Pilot 3.1) developed new diagnostics products designed to ensure that a new waste stream from disposable devices is not created while emphasising the social benefits.

This section describes the selected pilots and their key observations for sustainability.

2.1. Pilot 1.3 Sustainable luminaire

2.1.1. Short description and main achievements

In lighting, sustainability aspects are gaining importance, and customers are drawn to products with increased amount of bio-based and recycled materials, a lower carbon footprint, and better repair and recyclability options. The sustainable luminaire pilot demonstrated how more sustainable technologies and materials can contribute to lowering the ecological footprint of the manufacturing of the light luminaire itself and improve the repairability and recyclability of the final product (Figure 1). In case the functionalities of the luminaire, being mechanical construction, creating photons, directing photons, and managing optical paths. are discriminated and optimised for by selection of materials, the repair and refurbish potential is increased. The combination of materials is determining the efficiency of the recycling.

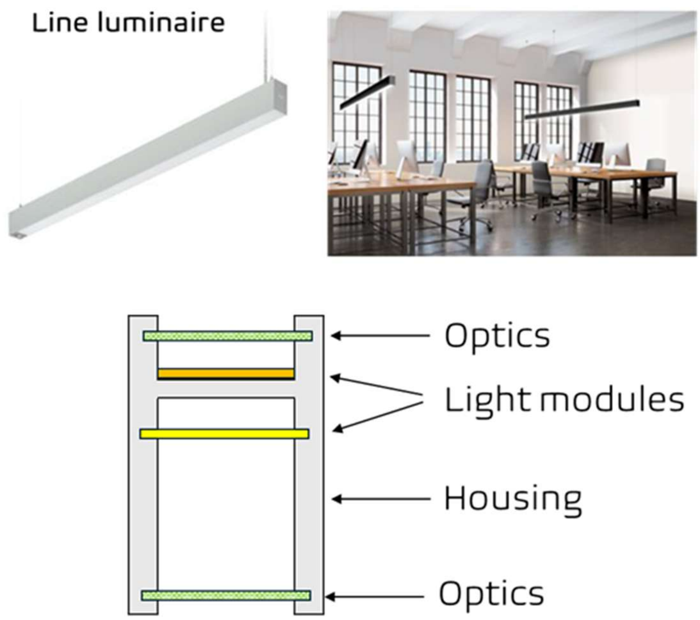

Figure 1. Sustainable line luminaire with device architecture showing the parts developed by Sustronics: optics, light modules and housing, all consisting of sustainable materials

2.1.2. Value propositions

Existing luminaires are usually constructed of plastic or metal luminaire housings containing an integrated light module that is normally a conventional electrochemically produced PCB (Printed Circuit Board) on FR4 board with LEDs (Light Emitting Diodes) soldered onto it. The subtractive technology that is applied to etch the copper circuits is energy intensive and creates more material waste. In addition, the FR4 board is poorly recyclable and contains flame retardants with environmental impact.

This pilot aimed to decrease dependency on fossil-based materials, decrease processing steps and impact of the manufacturing through use of printed and hybrid electronics and decrease the use of energy in manufacturing and generation of production waste. The additive technology that is applied by printed electronics provided these benefits.

2.1.3. Key technologies for sustainability and circularity

Pilot 1.3 explored different routes for more sustainable prototypes for luminaire products focussing on materials for carriers of the electronics, the electronics and the housing of the luminaire. The construction of the luminaire was optimised to allow repair, refurbishment and effective disassembly at the EoL.

2.1.4. Recommendations for environmental sustainability and circularity

Energy consumption during the use phase is the biggest contributor to the overall environmental impact of the lighting product. The energy consumption is mainly determined by the LEDs used, but also the optics used in the luminaire and the driver play an important role to increase the efficiency of the conversion of electronics to photons (to the external of the luminaire). As the LED and driver development was not part of the Sustronics project, focus was given to the materials including the optical properties of carriers of the light source and the luminaire housing and the construction of the luminaire. Alternative materials for carriers and housing were explored for which the set of requirements for these materials contained heat resistance, electrical safety, etc. Also, the optical properties were of importance as the use phase is the main source of environmental impacts due to the longevity of the luminaire. Any improvement of the energy efficiency of the total luminaire has a large impact on the overall environmental impact of the product when the use phase is taken into account.

For the EoL scenario, the exchange of materials can impact the compatibility of these more sustainable products with the current e-waste process technology. For the printed electronics a mismatch of the selection and separation methods was identified. This calls for adjustment of the recycling technology, adjustment of the product or alternative waste stream management.

2.1.5. Recommendations for social sustainability

Lighting is an essential functionality of the modern world and indispensable for productivity and quality of life. However, the environmental impacts of the use of lighting are dominant in the overall impacts of light sources and renewable energy sources like solar power or green energy mixes are to be preferred. As the quantity of light sources in the world is large, the Reuse – Refurbish and Recycle strategies are to be applied to make light sources available to all planet earth inhabitants.

2.1.6. Recommendations for economic sustainability

As the lighting product is a well-established product for which the competition is fierce, the cost levels are of prime importance and should balance with environmental requirements. The refurbish aspect of the product proposition will allow customers to keep cost levels low and prolong lifetimes.

2.1.7. Overall take-away

Alternative materials for luminaires and the use of printed electronics can decrease the environmental footprint, but their compatibility with EoL recycling requires development of new recycling methods. The modular approach of the construction allowing repair and refurbishment will increase the lifetime of the product and render it more accessible to more people as artificial lighting is an indispensable element of our daily lives.

2.2. Pilot 2.1 Embedded electronics for EEG monitoring

2.2.1. Short description and main achievements

Pilot 2.1 provided valuable insights into the integration of embedded electronics for electroencephalogram (EEG) monitoring when eco-design and sustainability principles are applied from the early development stages (Figure 2). While the original vision focused on reducing waste through material substitution and functional integration, the pilot as a whole highlighted that medical devices can be produced in a more sustainable way by looking into new materials and processes.

Figure 2. Concept of Pilot 2.1 for EEG monitoring.

2.2.2. Value propositions

While Laser Direct Structuring – Moulded Interconnect Device (LDS-MID) offers high integration potential and functional consolidation, current manufacturing constraints, particularly related to chemical baths and recycling readiness, limit its full sustainability potential. This highlighted the necessity of aligning technological innovation with manufacturing maturity, regulatory developments, and circular economy strategies.

2.2.3. Key technologies for sustainability and circularity

Some commercial substrates for LDS technology already incorporate post-consumer recycled material, reducing the carbon footprint of the product. LDS itself, as an additive method and contrary to the subtractive ones, reduces the usage of resources, positioning this technology as a good potential for sustainable applications (Figure 3).

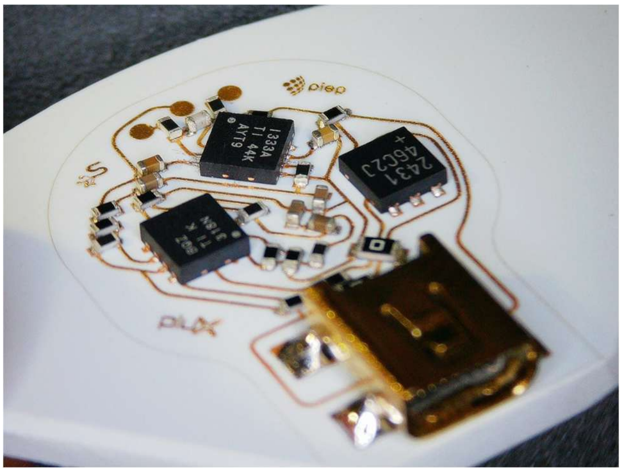

Figure 3. Electronic components manufactured by LDS technology.

2.2.4. Recommendations for environmental sustainability and circularity

The environmental assessment of the pilot clearly demonstrated its added value (Figure 4). Compared to a standard PCB-based EEG sensor, LDS-MID prototype showed a 40% lower environmental impact, confirming the effectiveness of functional integration and material reduction strategies. LCA results identified chemical baths used in the LDS process as the main environmental impact drivers, indicating a clear direction for future improvements through greener alternatives. The roadmap targeting the sustainability aspects was published as a result of the findings [10].

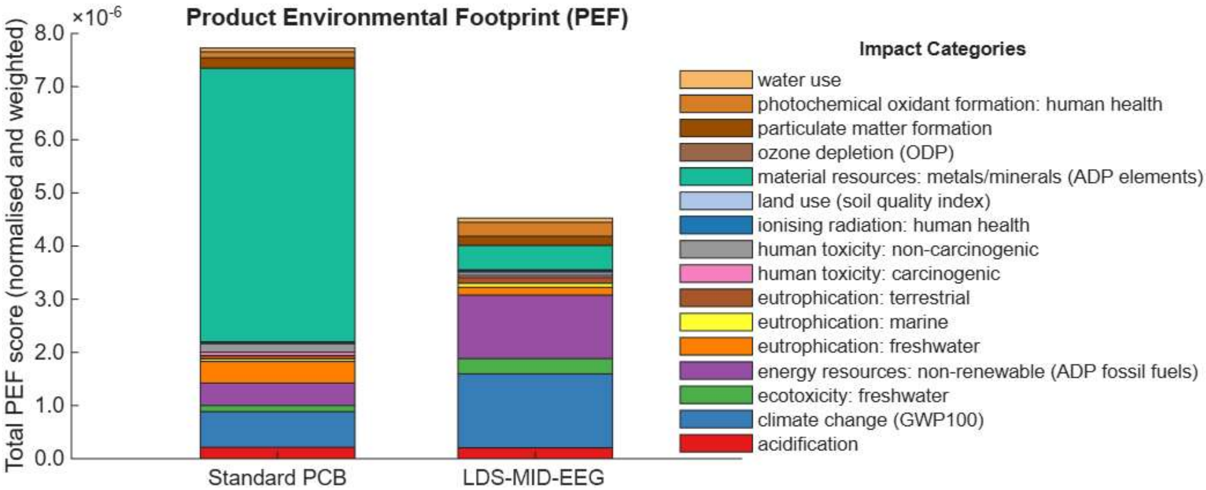

Figure 4. Environmental footprint of Pilot 2.1 benchmarked with a traditional PCB within different impact categories. (ADP = Abiotic Depletion Potential, GWP = Global Warming Potential)

2.2.5. Recommendations for social sustainability

The development of a more efficient and integrated EEG monitoring system has positive implications for healthcare. Improved signal quality, wearable integration, and potential comfort enhancements can contribute to better diagnostics and patient experience. In the longer term, more reliable and sustainable EEG devices may support earlier diagnosis and monitoring, thus potentially reducing healthcare costs and improving quality of life for patients requiring neurological assessment.

2.2.6. Recommendations for economic sustainability

From an economic perspective, the pilot demonstrated potential benefits from the use of more sustainable electrodes and sensors. Current LDS-MID manufacturing processes may involve higher manufacturing costs compared to standard PCB production, especially at low volumes. Yield optimisation and scale-up will be essential to improve cost competitiveness. Nonetheless, the increased functionality and reduced environmental footprint position the technology as a promising option for future high-value medical wearables.

2.2.7. Overall take-away

The replacement of a conventional PCB with an LDS-MID structure inside the EEG sensor demonstrated clear environmental benefits: the prototype achieved a 40% lower environmental impact in comparison to the baseline.

2.3. Pilot 2.3 Sustainable dashboard for automotive

2.3.1. Short description and main achievements

Pilot 2.3 investigated how sustainability considerations can be integrated into the early design of automotive electronic products, with a focus on material selection and EoL strategies. The device consists of a dashboard that combines In-Mold and printed electronics solutions, namely printed and 3D-formed decorative and technical films that are assembled through injection moulding (Figure 5). Preliminary LCA activities identified material composition as a key environmental hotspot and highlighted the benefits of using bio-based materials and avoid mixing of polymers to facilitate recyclability. The pilot demonstrated that EoL principles such as disassembly, recyclability and material recoverability can be conceptually embedded at the design stage, even under automotive constraints related to reliability, qualification and long service life.

Figure 5. Pilot 2.3 Dashboard developed in the Sustronics project consisting of bio-based materials with printed electronics.

2.3.2. Value propositions

The pilot aimed to align sustainability objectives with the stringent technical, safety and reliability requirements of automotive electronics. By addressing EoL considerations early, Pilot 2.3 sought to reduce life cycle environmental impacts, anticipate future regulatory and circularity requirements, and avoid late-stage redesigns. The value proposition lies in demonstrating that sustainability can act as a design driver rather than a constraint, even in highly regulated automotive contexts.

2.3.3. Key technologies for sustainability and circularity

The pilot highlighted the potential of alternative materials, including bio-based materials, to improve the environmental performance of automotive electronic components. However, the pilot also showed that direct substitution of conventional components is limited by automotive qualification standards, performance requirements, long-term reliability and supply chain availability. EoL scenarios developed within the pilot indicated potential gains in recyclability and recoverability, while revealing strong dependencies on existing vehicle dismantling practices and recycling infrastructures.

2.3.4. Recommendations for environmental sustainability and circularity

Environmental sustainability and circularity in automotive electronics should be supported by the systematic integration of EoL strategies at the earliest design stages, ensuring that disassembly, recyclability and recoverability are considered as core design parameters. The use of LCA as a decision-support tool is recommended to identify material-related environmental hotspots and to guide informed design trade-offs. Further efforts are needed to foster innovation and standardisation of sustainable materials that meet automotive qualification and lifetime requirements, while design assumptions should remain aligned with real vehicle dismantling and recycling ecosystems.

2.3.5. Recommendations for social sustainability

Social sustainability aspects should be addressed by increasing awareness of indirect social impacts related to material choices, particularly with respect to health and safety considerations across manufacturing, use and EoL stages. Emphasis should also be placed on product robustness and reliability, which contribute to long-term social benefits in safety-critical automotive applications. Knowledge sharing across the automotive value chain can further support the adoption of sustainable design practices.

2.3.6. Recommendations for economic sustainability

Economic sustainability requires aligning sustainability ambitions with the industrial maturity of materials and component ecosystems to ensure feasibility and scalability. Anticipating future automotive regulations related to circularity can help reduce long-term business risks, while incremental and scalable sustainability improvements should be favoured to remain compatible with cost, performance and supply chain constraints.

2.3.7. Overall take-away

Pilot 2.3 showed that sustainability improvements in automotive electronics are achievable when design ambition, material innovation and industrial reality are realistically aligned. Treating EoL considerations as an early design driver is a key to enabling more sustainable and circular automotive electronic systems.

2.4. Pilot 3.2 Smart hygiene

2.4.1. Short description and main achievements

This pilot introduced a sensor system for incontinence products (Figure 6). The single-use sensor labels include sensors for temperature, humidity, pH and enzyme detection. The sensor label is connected to a reusable wearable component that collects sensor data and transmits it wirelessly to the cloud or local storage via a base station or a mobile phone.

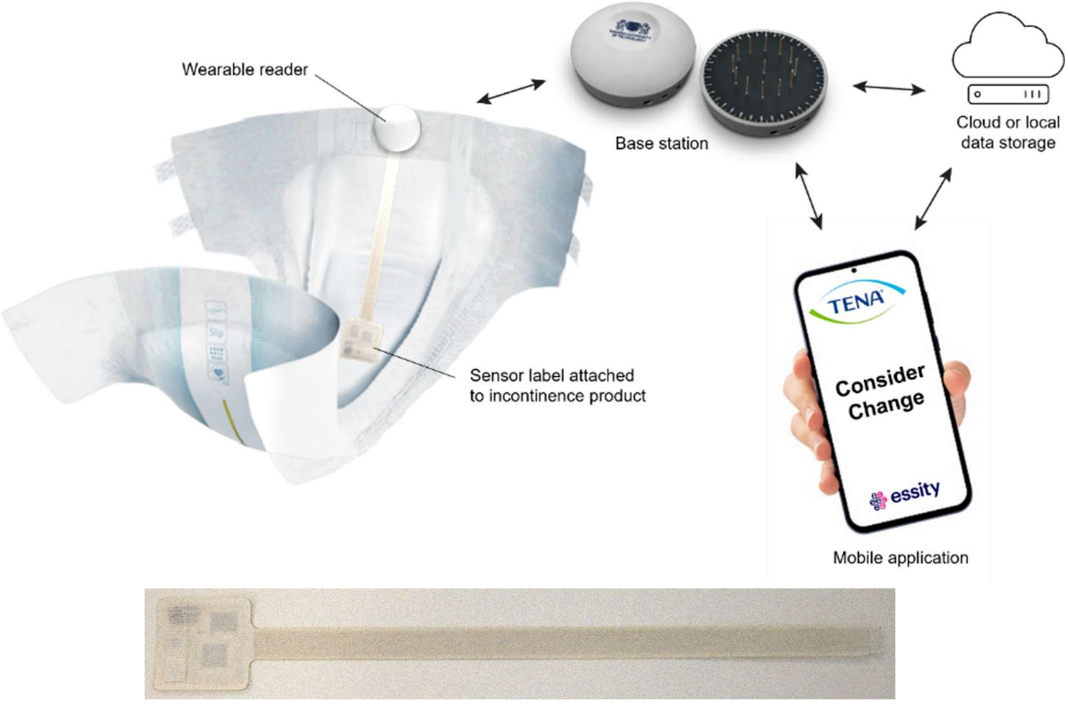

Figure 6. Concept of Pilot 3.2 (top) and a printed sensor label (bottom).

2.4.2. Value propositions

The sensor system, also called the SmartCare Change Indicator, is a sustainable digital health technology solution. The sensor label is attached to an absorbent product. The caregiver is promptly notified via a smartphone app when it is time to consider a change. The system also provides an overview and statistics of continence care and staff performance to administrators, helping to further optimise care efficiency. The system reduces the need for frequent manual checks that otherwise can be intrusive and disturb the user's vital activities such as sleep. Moreover, the system also prevents the user from prolonged skin exposure to urine, or even worse, faeces with risk for potential skin damage.

2.4.3. Key technologies for sustainability and circularity

The fact that the sensor label is discarded after each use (up to four times daily) reinforces the need for a modular design. However, the disposable component continues to drive manufacturing-related emissions. Among the two explored design architectures, the wireless option with an NFC-based sensor label showed a significantly higher impact due to additional electronics in the disposable part, primarily an ASIC (Application-Specific Integrated Circuit), for sensor readout and communication. This impact could be reduced by selecting lower-impact ICs (Integrated Circuits) than the current ASIC. Switching to more sustainable inks, e.g. replacing silver with copper, offered potential improvement for both architectures. While the substrate's environmental impact was minimal, careful material selection, particularly for the disposable part, can enhance recyclability.

2.4.4. Recommendations for environmental sustainability and circularity

As part of the environmental assessment, the LCA model was extended to cover all stages of the life cycle and to represent both design architectures. The manufacturing of the single-use sensor label remained the largest contributor to environmental impacts, thus making product design the most critical stage for reducing overall impact.

2.4.5. Recommendations for social sustainability

The SmartCare Change Indicator is a discreet, sensor-based solution designed to alert caregivers via an app when absorbent products may need changing. By reducing unnecessary checks, the system protects the users' privacy, enhances comfort, and supports more respectful, personalised, and dignified care. Additionally, it provides valuable data to improve care routines and staff efficiency.

2.4.6. Recommendations for economic sustainability

In sight of continuously increasing health treatment costs, fuelled by aging population, increasing medical knowledge and decreasing human resources in the health care system, decentralised health monitoring becomes more important supported by digital transformation of healthcare technologies

2.4.7. Overall take-away

The environmental footprint can be minimised by decreasing the number of components and manufacturing process steps for the disposable sensor label together with more sustainable materials, such as replacing silver with copper.

2.5. Pilot 3.3 Smart wound dressing

2.5.1. Short description and main achievements

This pilot focused on creating an innovative solution by integrating a sensor label into dressing materials to be used to measure critical wound parameters such as temperature, pH and relevant biomarkers. The aim was to enhance patient comfort while simultaneously reducing healthcare costs.

2.5.2. Value propositions

The smart wound dressing pilot started at a low TRL (Technology Readiness Level). Requirements, functionalities, and prototypes had to be developed simultaneously with sustainable choices for materials, technology, and design. A research platform was conceived to allow sensor functionalities to be developed, complemented with a readout unit, data processing and storage, and a dashboard for user interface. The impact in the use phase has been quantified, and it is huge: adding an electronic element to wound dressings reduces material usage of dressings and, most importantly, reduces the impact related to efforts from healthcare professionals travelling to and from patients. Furthermore, improved care reduces hospitalisation and complications by enabling earlier detection of infections.

2.5.3. Key technologies for sustainability and circularity

Two technologies were applied (Figure 7). The subtractive lithographic technology creates copper circuitry on stretchable, partly bio-based TPU (Thermoplastic Polyurethane) as a carrier. This offers high conductivity and reliability, and enables the use of ultrathin, skin-conformable 50 µm thin TPU substrates. However, it presents challenges in implementing shielding layers and offers a smaller selection window for biodegradable carrier materials. The additive printed electronics technology uses carriers like polyesters and sustainable materials such as paper and PLA (Polylactic Acid) films. This process technology is more sustainable in energy consumption and material usage, entails fewer process steps at less elevated temperatures, and supports a wider range of substrate materials. Non-metallic materials such as carbon can be used, which in combination with a biodegradable carrier like paper renders the entire stack biodegradable. Shielding functionalities are also readily achieved in the printed layer buildup.

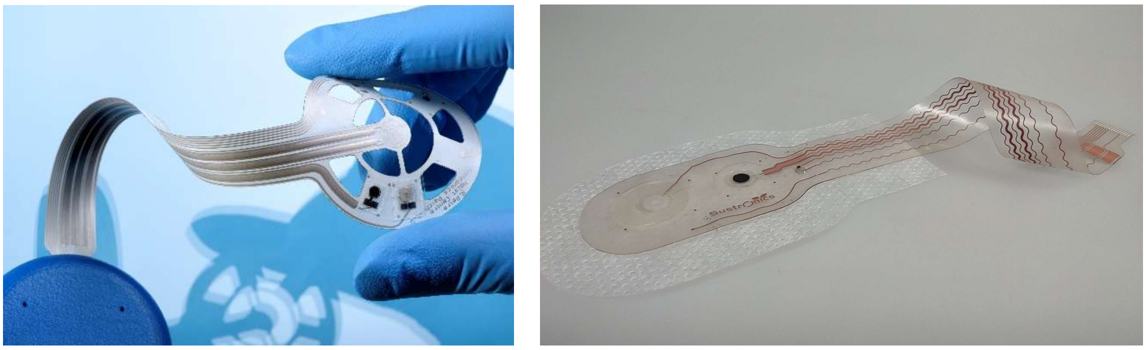

Figure 7. Flexible, disposable electronic part with pH and temperature sensors, to be included in the wound dressing layer stack, based on (left) additive printed electronics and (right) subtractive technology using stretchable bio-TPU substrate. The reusable readout unit and its blue casing is visible in the left image.

Regarding sensor development, directly printing pH sensors proved to better meet the requirements for signal stability over several days of wound monitoring compared to the sticker concept with separate electronic parts. The mounting and encapsulation of sticker foil sensors onto TPU substrates was developed and appeared compatible with the conformal stretchable substrate, though integration remained technologically challenging. Temperature sensing was included as a surface-mounted component; other biomarkers like uric acid are still in development.

2.5.4. Recommendations for environmental sustainability and circularity

It is important to make a critical distinction between reusable and disposable parts. The reusable part should contain as many electronic components as possible, since the CO_2 impact of packaged ICs is the most significant contributor for small electronic systems. Reuse of the disposable part is excluded due to hygienic requirements. However, retrieval of valuable metal content can be achieved with maximum efficiency through dedicated incineration of collected smart wound dressings, which requires a collection facility to be installed. Where possible, additive manufacturing should be favoured, as it is more sustainable in energy and material usage and enables the use of fully biodegradable stacks such as carbon ink on paper. Furthermore, the ease of production and environmental impact of directly printed sensors may be preferable over the sticker concept.

2.5.5. Recommendations for social sustainability

The impact on quality of life is huge, as patients are not subjected to painful, cumbersome dressing changes when unnecessary. And the times they need to meet with a health care professional will decrease. Early detection of infections allows patients to remain reassured about their healing process. In addition, prolonged dressing change intervals help preserve newly formed tissue and reduce pain. Healthcare professionals also benefit from a reduced workload by avoiding unnecessary visits and dressing changes.

2.5.6. Recommendations for economic sustainability

The smart wound dressing contributes to reduced healthcare costs through fewer dressing changes, less material waste, and fewer professional visits. Significant cost savings are achieved when early infection detection prevents hospitalisation of wounded patients. Prolonged dressing intervals reduce unnecessary workload and waste, which in total can drastically reduce overall healthcare costs.

2.5.7. Overall take-away

The smart wound dressing pilot demonstrated that even at a low initial TRL, combining sustainable manufacturing technologies with smart sensor integration can deliver substantial benefits across all sustainability dimensions. Additive printed electronics on biodegradable substrates offered the most promising pathway toward circular economy, while the separation into reusable and disposable parts is critical for minimising environmental impact. The greatest value lies in the use phase — where reduced dressing changes, early infection detection, and remote monitoring collectively improve patient quality of life, lower healthcare costs, and reduce environmental footprint.

3. Environmental sustainability

Environmental impact assessments, such as LCA and eco-design framework, were used to guide development of technologies and integration of project pilots in Sustronics.

3.1. Methodology

Within Sustronics, we approached sustainability through different methods to develop sustainable technologies and materials. Based on eco-design principles, the pilot products were designed so that they include sustainable materials and utilise green software. In addition, each pilot project developed a product-specific circular business model consisting of the circular value propositions, as well as the descriptions for the value creation, value delivery and value capture elements aiming to ensure circularity and targeting to fulfil circular economy requirements.

We supported the development of more sustainable materials, technologies and pilot products through **LCAs** for all three product development generations. As a baseline, we used either an existing prior product generation or, in case of newly developed technologies, the first generation of the pilot product to identify environmental hot-spots and set environmental targets. Insights from the LCAs were summarised in the form of eco-design recommendations. For some of the pilots, an environmental handprint was calculated that described the potential positive environmental impacts of activities achieved by replacing the baseline solution with a new solution.

The methodology for **developing sustainable materials and technologies** by the research organisations was characterised by an iterative, collaborative approach that integrated stakeholder-driven requirements, LCA insights, and material innovation. Initial requirements were generated by pilot owners and end-users, distinguishing between established products and those still under development, and were refined as the project progressed. Material and technology choices were guided by compatibility, performance, and sustainability, with LCA analyses informing the selection and benchmarking of alternatives. Practical evaluation involved parallel exploration of technology pathways, ranking requirements, and prioritising options based on performance, cost, and environmental impact. Decisions to continue or halt development were made through testing and benchmarking protocols.

The development of **Circular Business Models** (CBMs) was facilitated through a structured approach using an adapted CBM design template, which guided project partners in conceptualising and refining CBMs for the ten pilot cases. Partners engaged in workshops and interviews to systematically integrate circular economy principles – such as modularity, repairability, and resource efficiency – into their business models. LCAs played a pivotal role in this process by identifying environmental hotspots and informing eco-design strategies, such as material substitution and modular design, which were then mapped into CBM value dimensions (creation, delivery, capture).

Sustainable software development was divided into three steps:

1) Establishing a baseline,
2) Quantifying environmental performance against baseline, and
3) Documenting both functional performance and the sustainability outcomes.

Two approaches were taken:

1) Minimising the environmental footprint of the software itself or the device the software is running on, and
2) Maximising the handprint of the pilot products through the software.

The software development was guided by five core sustainability principles:

1) Energy efficiency and low power operation,
2) Circularity & resource efficiency,
3) Sustainable AI,
4) Data governance & digital infrastructure sustainability, and

5) Health & societal sustainability.

3.2. Eco2Design Process

Based on the insights of the project, we created an Eco²Design process framework with five interrelated and parallel strands of development:

1) **Circular Business Model Development** ensures that circular design perspectives, environmental ambitions and business viability are connected to the product development activities from the start.
2) **Value Network Creation** builds the network to enable the testing and initial implementation of a circular solution.
3) **Environmental Assessment** evaluates environmental performance of the technology, product and overall circular system.
4) **Technology and Product Development** cover the design and engineering work needed to implement the intended model.
5) **Data collection and Management** support all strands and enable transparency and iteration.

Those strands are separated in five phases (see Figure 8):

1) **State-of-the-art analysis:** This phase aims to map the current value chain, identify key stakeholders, and assess existing environmental performance through a baseline LCA or similar fast-track analysis. The scope covers both product and business system boundaries, stakeholder relationships, material/data flows, and initial identification of environmental hotspots and uncaptured values. The main result is a clear understanding of systemic impacts and opportunities that sets the foundation for targeted circular product development and required interventions to the baseline solution.
2) **Concept Definition:** In this phase, the goal is to define ambitious but achievable environmental targets and specify the most suitable circular business strategies and R-strategies, based on the insights from the state-of-the-art analysis. The scope includes articulating a sustainable value proposition, ranking technical and sustainability requirements, and translating uncaptured value into concrete new opportunities. The main result is a well-founded concept and a set of requirements guiding subsequent product, technology, and ecosystem development.
3) **Circular Product-Service-System development:** This phase focuses on developing the integrated product, service, and business model concepts, selecting and prototyping suitable technologies, and designing collaborative value networks. The scope covers lab-scale realisation, technology pathway selection, partner engagement, circular business model development, and validation via scenario-based LCAs. The main result is a functional prototype and circular solution demonstrating improved sustainability, partner collaboration, and circularity aligned with the defined goals.
4) **Piloting circular solution:** Here, the goal is to test and demonstrate the circular solution under real conditions, verify feasibility and performance, and track environmental impacts by updating LCAs with pilot data. The scope includes monitoring operational, technical, and environmental KPIs (Key Performance Indicators); validating business models and circular processes; and capturing pilot usage and life cycle data. The main results are lessons learned about implementation, updated sustainability performance values, and actionable insights for further refinement.
5) **Validation, adaption and scaling** (not fully aimed in Sustronics, as the targeted TRL was only on levels 5-6 and not targeting system demonstration in the real world nor full commercialisation): The objective of this phase is to optimise the solution based on pilot feedback, adapt the value proposition and circular business model, and plan for large-scale deployment and ongoing improvement. The scope includes

institutionalising circular R&D practices, updating KPI tracking systems, refining requirements, and ensuring readiness for scaling across products, regions, or markets. The main result is a robust, validated framework and solution ready for broader adoption, with continuous monitoring and improvement mechanisms in place. The objectives of this phase are to: (i) use the pilot results to optimise the system, (ii) plan the scaling of the solution, (iii) institutionalise circular R&D practices, (iv) reduce the overall environmental footprint of the system further, (v) optimise the offering, (vi) revisit the CBM elements, and (vii) improve the commercial viability through monitoring the individual and common metrics.

3.3. Overall takeaways

The Sustronics project demonstrated that integrating LCA and eco-design from the outset enables measurable sustainability improvements in electronics sector. CBMs and data-driven approaches are essential for developing and scaling circular products and solutions. We identified several “calls-to-action” for different stakeholders as highlighted in the Conclusions section.

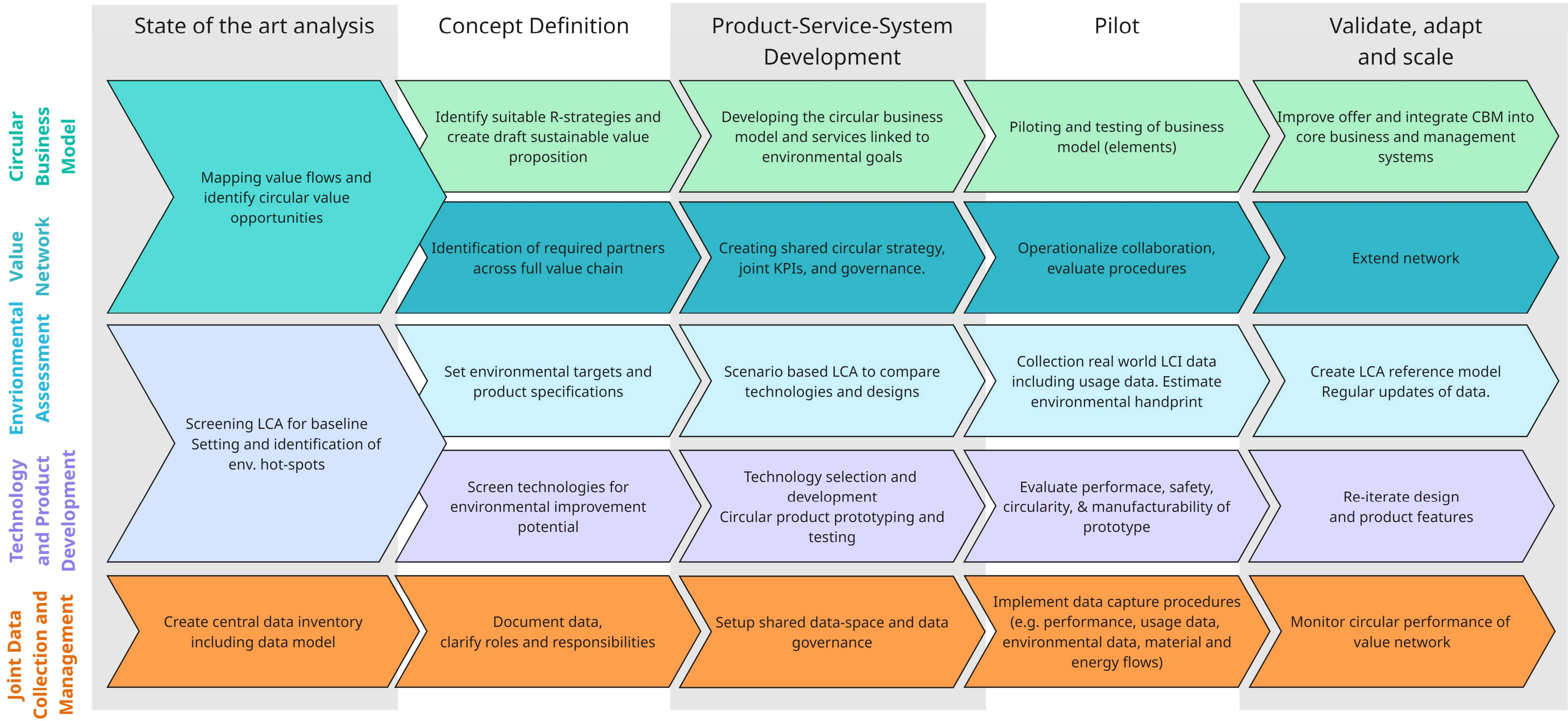

Figure 8. The five phases of the proposed Eco²Design process.

4. Policy brief

During the Sustronics project, it became evident that the **existing standards need further development and new standards need to be established** to support the companies in the transition towards sustainable and circular electronics. The identified challenges specifically included lack of industry drivers, fragmentation of global standards, insufficient collaboration among the stakeholders and the current lack of proof on economic viability.

4.1. Workshopping

To address the identified challenges, the Sustronics consortium joined forces to workshop on proposals for standardisation work to support and speed up the adoption of sustainable and circular electronics product development and CBM innovation practices. Furthermore, the Sustronics project implemented future-oriented workshops among the project consortium to specify the **desired future for sustainable and circular electronics and the steps to reach this specified future**. During the workshops, regulations and policies were identified as the primary drivers for accelerating the development and growth of the markets for sustainable and circular electronic products. These outcomes set the framework that the companies are recommended to follow, influencing both the development of sustainable circular products based on eco-design principles and sustainable manufacturing.

Figure 9 shows a hierarchical prioritisation of actions supporting product eco-design and lifetime extension. It shows that progress towards product eco-design and lifetime extension depends on **consistency between EU policy and standards, traceability tools, product design choices, technological solutions and social conditions**. The order of priorities shows that decisions at the policy and standards level shape how traceability systems, design practices, and technologies are applied in practice. The green dashed lines depict that social aspects remain important at all priority levels, as awareness, trust in repair and recycled options, certification, and education affect how policies, systems, design choices, and technologies are used. The figure illustrates how the consideration of measures that promote repair, reuse, and material recovery according to eco-design principles could support the development of a sustainable and circular electronics sector.

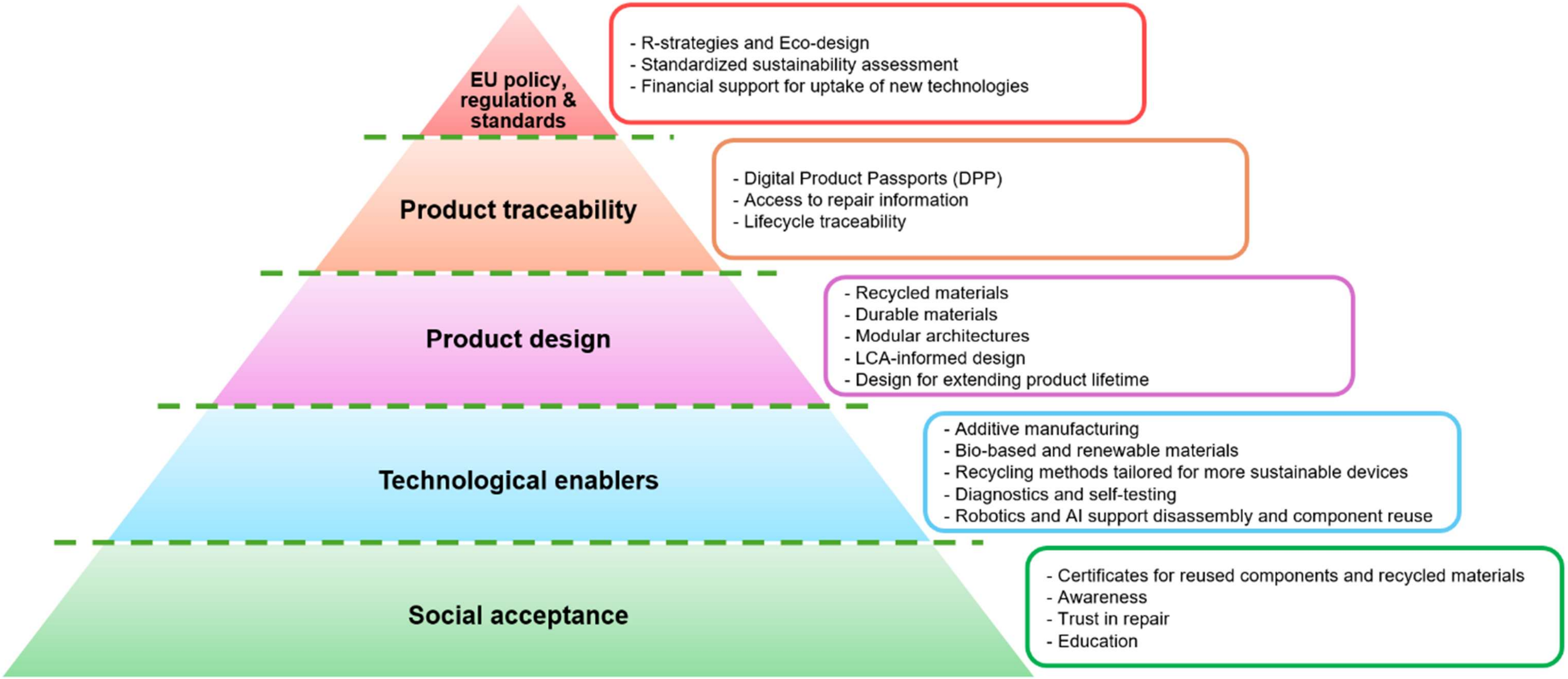

Figure 9. Hierarchy of priorities supporting product eco-design and lifetime extension.

4.2. Policy recommendations

As a result of the standardisation workshops, future-oriented workshops and learnings from the pilot cases, the Sustronics consortium has specified five policy recommendations that can support the future development of a sustainable and circular electronics sector and related standardisation work.

4.2.1. Harmonising regulations, standards and guidelines related to sustainability, circularity and recyclability assessment

Challenge: Lack of standardised data formats, databases and methodology for LCA, including assessment of products' EoL and sustainability of developed software.

Enablers: LCA-based labels to enable comparison (similar to energy labels). Sustainability readiness level score. Guidelines on how to assess recyclability and circularity of products.

Action plan: Establishment of standards on how to implement sustainability, recyclability and circularity assessment (including LCA) for electronic products, including standardised data formats. Establishment of a clear and unambiguous scoring on how to benchmark different products. Develop LCA methodology for software sustainability.

4.2.2. Financial support to companies moving towards sustainable electronics manufacturing

Challenge: Sustainable electronics manufacturing, such as printed electronics, has not yet been scaled up for high-throughput production. Bio-based and renewable materials are expensive and not available on a large scale. High development and production costs can prevent customers from buying electronics products with bio-based materials.

Enablers: Investments in increased production capacity of sustainable manufacturing and production of bio-based materials. Tax benefits for "green" products.

Action plan: Financial support from the EU and/or the national governments for companies willing to move towards sustainable electronics manufacturing and production of new materials. Implement tax incentives for use of recycled and bio-based materials. Increase prices of virgin plastics through taxation to make recycled and bio-based materials financially more attractive.

4.2.3. Harmonising eco-design and material recovery standards

Challenge: Lack of transparent reporting of recycled content and bio-based raw materials used in electronic products. Printed electronics not fully compatible with existing e-waste management processes.

Enablers: Common definitions for recycled, bio-based, renewable, biodegradable, etc. raw materials. Guidelines on reporting the use of such materials. Development of EoL management concepts for printed electronics, e.g. using compostable and biodegradable substrates.

Action plan: Development of LCA databases for the new materials. Development of (mandatory) reporting guidelines for use of the new materials. Set and apply common standards and guidelines for recycling of printed electronics. Develop guidelines for recyclability assessment to ensure comparable results. Establish material certification for recycled and bio-based content. Ensure R&D funding for development of new EoL concepts beyond existing e-waste management. Define minimum requirements for recycled content in products. Develop biodegradability and compostability standards for electronics.

4.2.4. Consistent Implementation of Digital Product Passports (DPP)

Challenge: Lack of transparency across product life cycles. Insufficient data for repair, recycling, and raw material use. No standardised format for sustainability data. Difficulties in tracking material authenticity and carbon footprint.

Enablers: Working groups on DPP standardisation in Europe. Digital twins with power models and sustainability metrics. AI-based data analysis tools.

Action Plan: Ensure consistent implementation of DPPs across all electronics categories. Mandate DPPs with LCA data according to legislation. Include minimum data requirements for repair, recycling, and raw material use. Establish data verification mechanisms to minimise product fraud and counterfeiting. Enable real-time tracking of carbon footprint, material authenticity, and recyclability.

4.2.5. Strengthening EU-level repairability requirements

Challenge: Lack of warranty and certification for repaired and reused devices making end users unwilling to buy such products. Repair is laborious and thus costly, and the availability of repair shops for end users is still scarce.

Enablers: Companies take responsibility of arranging repair services for products and developing the value chain and markets for offering reused devices. Availability of diagnostics, self-testing and advanced sorting tools to identify repairable and reusable devices. Adoption of DPPs that support the linking of products to replacement parts and repair manual. Wider adoption of EU's product sustainability regulations. Longer warranty requirements.

Action plan: Development of common warranty and certification rules to ensure that circular products meet the end user needs and to decrease the end users' risks when purchasing such products. R&D support for development of diagnostics and testing tools to ensure high quality of such products, and for the adoption of DPPs. Coordination across societal, regulatory, technological and design domains. Create collaboration platforms connecting designers, manufacturers, recyclers, and repair professionals. Provide consumers and end users easy access to repair manuals, training and spare parts.

5. Conclusions

This white paper has developed recommendations based on activities carried out during the Sustronics project. These are transformed here into an action plan for three stakeholder groups: industrial companies, the research community and policy makers complemented with cross-cutting actions relevant for all stakeholders. These call-to-actions reflect the urgent need for coordinated effort across all stakeholders to accelerate the transition to sustainable and circular electronics through **strong EU policy, financial support, harmonised standards, technology development, and stakeholder collaboration**.

5.1. Industrial companies

5.1.1. Product design on company level

- Institutionalise **eco-design and LCA** in R&D and product development: integrate R-strategies and adopt eco-design principles
- Monitor and adapt **circular KPIs** when scaling solutions
- Align realistically design ambition, material innovation and industrial reality and continue to **conduct circular product development in multiple development cycles** (across different product development generations)
- Treat **EoL considerations** as an early design driver
- Design products for repairability from the outset with **modular architecture**

5.1.2. Technologies and digital tools

- Invest in **recycling technologies**
- Replace traditional PCBs with **additive manufacturing** when feasible to achieve environmental benefits
- **Implement DPPs** with LCA data, repair and diagnostics manuals and links to replacement parts
- Enable **real-time tracking** of carbon footprint, material authenticity, and recycling rates

5.1.3. Circular value chain development

- Establish **take-back schemes** for repair, refurbishment, parts harvesting and recycling
- Foster **cross-sector collaboration** to build circular ecosystems and address challenges such as data availability and recycling infrastructure
- Create **circular value networks** with clear roles, responsibilities, and shared objectives, including governance frameworks and shared data systems

5.1.4. Industry level activities

- Continue developing **data standards** and DPPs for the electronics industry
- Invest in and develop **infrastructure for printed electronics**
- Establish **re-certification protocols** for refurbished devices
- Join **industry associations and standardisation groups** to strengthen collective influence of the printed electronics industry

5.2. Research community

5.2.1. Research on materials

- Develop **alternatives for harmful and hazardous materials**
- Investigate **recycled material properties** and their performance in electronics

- Develop **Product Category Rules (PCR)** for printed electronics with bio-based materials
- **Validate biodegradable and compostable solutions** for relevant use cases

5.2.2. Development of recycling, disassembly, and reuse related processes, technologies and guidelines

- Conduct further **research on recyclability** of printed electronics, develop recycling technologies and estimate recycling rates
- Create guidelines for **recyclability assessment** ensuring comparable results
- Develop **robotics and AI solutions** for easier disassembly and component reuse

5.2.3. Test different sources of data and develop digital tools

- **Integrate diverse data flows** for holistic impact assessment available even at the design phase
- Create **LCI (Life Cycle Inventory) data with open access for benchmarking** and EoL treatment of new materials
- Develop **standardised data formats for LCA** to enable comparative studies
- Create **digital traceability tools** with open access for circular data and decision-making

5.2.4. Develop new methodologies

- Create **LCA methodologies** for software sustainability and EoL assessment
- Develop design rules and **co-design methodologies for eco-design**
- Develop and harmonise **methods to test** electronics biodegradation
- Develop new methods that allow for **faster recyclability of the products**, like super-biodegradability, for better EoL management [11]
- Develop and introduce innovative ways for **sustainability-oriented product design** involving its reconfigurability and adaptability throughout the life cycle [12] to increase the overall economic viability of new products and services

5.3. Policy makers

5.3.1. Standards and regulations

- Develop and support **standards regarding cleanliness, hygiene, and safety for medical devices**, especially when introducing new material solutions such as bio-based or recycled materials
- Address recycling limitations by establishing **take-back schemes and biodegradation standards**
- Establish common **standards and guidelines for recycling of printed electronics and biodegradation of electronics**
- Establish **standards on how to implement sustainability and circularity assessment** (including LCA) for electronic products, including standardised data formats and creation of up-to-date databases for new materials. Establish a clear and unambiguous **scoring on how to benchmark** different products
- **Extend ESPR** (Ecodesign for Sustainable Products Regulation) to more electronics categories

5.3.2. Product warranties

- Develop common **warranty and certification rules** for circular electronic devices.
- Mandate **longer warranty** requirements

5.3.3. Financial drivers

- Provide **financial support for companies** willing to move towards sustainable electronics manufacturing and production of new materials
- Implement **tax incentives for** the use of bio-based or recycled materials and increase the price of virgin materials (based on environmental impact assessments)

5.3.4. Promotion of sustainability and repair culture

- Strengthen **EU-level repairability requirements** with standardised repair index
- Launch **consumer awareness campaigns about sustainability and repair**
- Create **collaboration platforms** connecting all value chain actors

5.4. Cross-cutting actions for all stakeholders

- Participate in EU projects with consortia covering full value chains
- Join standardisation working groups relevant to sustainable electronics
- Share knowledge and best practices across value chains
- Support technology transfer from research to industry
- Engage in lobbying through coordinated industry efforts
- Promote international harmonisation of standards to avoid fragmentation
- Monitor geopolitical developments affecting material and component access
- Balance technology innovation with environmental and social responsibility

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Further information on the Sustronics project's public outcomes can be found in Cordis: https://cordis.europa.eu/project/id/101112109/results and on the project website: www.sustronics.eu

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