Received 26 May 2025, accepted 24 June 2025, date of publication 2 July 2025, date of current version 11 July 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3585340

PERSPECTIVE

Defining and Achieving Next-Generation Green Electronics: A Perspective on Best Practices Through the Lens of Hybrid Printed Electronics

KEALIE VOGEL[1], SARA CARNIELLO[2], VALERIO BENI[3], AKSHAT SUDHESHWAR[1], NADIA MALINVERNO[1], YOLANDA ALESANCO[4], MAX TORRELLAS[5], STEPHAN HARKEMA[6], MARGREET DE KOK[6], CORNÉ RENTROP[6], IGNACIO ZURANO VILLASUSO[7], LOU BERNARD[7], ENRIQUE MOLINER[7], CHRISTIAN REIN[8], YVES BAYON[9], ZULFIQUR ALI[10], CAROLIN ZACHÄUS[11], NICOLAS GOUZE[11], MARIE BERTHUEL[12], CRISTINA GONZÁLEZ BUCH[13], FRUELA PÉREZ SÁNCHEZ[13], AND CLAUDIA SOM[1]

[1]Technology and Society Laboratory, Empa—Swiss Federal Laboratories for Material Science and Technology, 9014 St. Gallen, Switzerland
[2]Institute for Climate, Energy Systems, and Society, Joanneum Research Forschungsgesellschaft MbH, 8010 Graz, Austria
[3]Bioelectronics and Organic Electronics, Smart Hardware, Digital Systems, RISE Research Institutes of Sweden, 60233 Norrköping, Sweden
[4]CIDETEC, Basque Research and Technology Alliance (BRTA), 20014 Donostia-San Sebastián, Spain
[5]AIMPLAS, Technological Institute of Plastics, 46980 Valencia, Spain
[6]TNO at Holst Centre, 5656 AE Eindhoven, The Netherlands
[7]LOMARTOV S.L., 46100 Valencia, Spain
[8]Danish Technological Institute, 2630 Taastrup, Denmark
[9]Sofradim Production, 01600 Trévoux, France
[10]University of Cumbria, CA1 2HH Carlisle, U.K.
[11]VDI/VDE Innovation + Technik GmbH, 10623 Berlin, Germany
[12]BeFC, Bâtiment Nanobio, 38610 Gières, France
[13]Instituto Tecnologico Del Embalaje, Transporte y Logistica (ITENE), 46980 Valencia, Spain

Corresponding author: Claudia Som (claudia.som@empa.ch)

This work was supported in part by the European Union's Horizon Europe Research and Innovation Program under Grant 101070302 (HyPELignum), Grant 101070114 (CircEl-paper), Grant 101091490 (CIRC-UITS), Grant 101070169 (UNICORN), Grant 1010970167 (ECOTRON), Grant 101112109 (SUSTRONICS), Grant 101070556 (Sustain-a-Print), Grant 101070477 (SusFE), and Grant 101070255 (REFORM); in part by the Swiss State Secretariat for Education, Research, and Innovation (SERI), under Grant REF-1131-52302; and in part by the Dutch Ministry of Economic Affairs, and the European Union's Horizon 2020 Research and Innovation Programs under Grant 101003587 (EU TREASURE).

ABSTRACT As global electronics production and e-waste generation accelerate alongside efforts to reduce carbon emissions, the need for transformative solutions in the electronics sector has become urgent. Therefore, to support the transition to greener electronics, this work reviews existing research and legislation relevant to the field and considers the perspectives and ongoing efforts of the EU Green Electronics Working Group (comprised of 12 green electronics-focused Horizon Europe projects) to identify and define the most important aspects of green electronics. Given the absence of a widely accepted definition of what makes electronics truly "green," the most critical aspects are clarified to support the development of a common, unified definition: *Electronicsthat, when measured against their alternatives over their whole lifecycle and value chain,have a reduced environmental impact in terms of greenhouse gas emissions, toxicity, and resource depletion and avoid burden shifting from one impact to another or along the value chain, while fulfilling a given function.* A set of recommendations and best practices, informed by the latest advancements and ongoing research developments in green electronics, is then provided to address the entire lifecycle of electronic devices. These strategies offer a framework to guide the development and adoption of greener electronics.

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

INDEX TERMS E-waste, green electronics, sustainable electronics, WEEE.

I. INTRODUCTION

As global demand for electronics rises [1], so too does the quantity of discarded electronics entering global waste streams. In 2022, a record 62 billion kg of electrical and electronic waste (e-waste) was generated worldwide, averaging 7.8 kg per capita [2]. Europe leads in per-capita e-waste generation, reaching 15 kg in 2019 [2]. E-waste generation far outpaces e-waste recycling, with only 13.8 billion kg (less than 25%) properly collected and recycled in 2022 [2].

E-waste growth is driven by planned obsolescence, limited repairability, the rise of the Internet of Things (IoT) which embeds electronics into everyday objects, complicating collection and sorting [3], [4], and conventional electronics' materials and production methods challenging recycling efforts [2].

Conventional electronics combine integrated circuits (ICs), resistors, and capacitors on the mechanical backbone of an electronic circuit, printed circuit boards (PCBs), themselves comprised of glass-fiber epoxy substrates with copper conductive tracks etched on top [5]. These electronics rely on resource-intensive production methods, incorporating toxic chemicals and hard-to-recycle components [6]. These processes consume significant energy and rely on scarce raw materials, making sustainable alternatives increasingly necessary [5]. As such, opportunities exist for reducing e-waste through sustainable design, alternative materials, and improved end-of-life (EoL) strategies [5].

Therefore, to combat the e-waste problem, the EU has set new goals related to e-waste reduction and electronic sustainability (e.g. the Waste from Electrical and Electronic Equipment Directive or Ecodesign for Sustainable Products Regulation), driving new research into greener electronics [7], [8], although, to date, a common or unified definition of what, exactly, it means for electronics to be more "green" does not clearly exist. However, is it clear that green chemistry principles, emphasizing resource efficiency, waste reduction, and safer alternatives, are central to this shift [9].

Among electronics advancements utilizing the principles of green chemistry, printed electronics (PEs) have emerged as a promising frontier, gaining significant attention in recent years for their potential to provide cost-effective, energy-efficient, and environmentally-friendly alternatives to conventional electronics manufacturing [10], [11]. Manufactured using additive processes that deposit functional inks onto recyclable or biodegradable substrates, PEs reduce material waste and energy use compared to traditional subtractive methods on fossil-based substrates (see Table 1). Studies show PE-based PCBs have lower production impacts (e.g., Nassajfar et al. report that PE-based PCBs exhibit a reduction of over 20% in environmental impact relative to conventional PCBs over a cradle-to-grave lifecycle) while offering flexibility and lightweight properties suited for consumer, healthcare, and automotive applications [5], [11], [12].

PEs can function as standalone devices (e.g., healthcare sensors) or be integrated into larger applications (e.g., smart furniture, automotive systems) [11]. PE-based sensors can also play a relevant role for the IoT by addressing related e-waste and resource consumption concerns through the use of biodegradable materials and lower-impact production processes [12].

Despite their potential, PEs still face challenges in functionality, reliability, and long-term stability [12], [13]. While solutions to these problems are the focus of ongoing research, silicon microelectronic components are still unmatched functionality- and reliability-wise and cannot (yet) be replaced by printed components [14]. Therefore, the current state-of-the-art is hybrid printed electronics, defined as electronics that combine conventional surface-mount technologies (SMT) like silicon-based microelectronics with printed substrates [15]. In this way, superior functionality can be combined with sustainability advantages [11], [16]. Although hybrid PEs continue to drive advancements in sustainability and innovation, they too do not yet currently exhibit the required functionality to meet the needs of all electronics applications [17].

TABLE 1. A comparison of conventional electronics and printed electronics. Hybrid printed electronics are printed electronics that combine printed substrates with conventional surface-mount devices [14], [18].

Feature	Conventional Electronics	(Hybrid) Printed Electronics
Design Characteristics	Rigid structures	Potentially flexible substrates
Materials	Plastics, brominated flame retardants, epoxy resins, base metals (aluminum, copper, iron, tin), rare metals, precious metals (silver, gold, platinum, palladium) and hazardous metals (e.g. lead or zinc) Conventional surface-mount devices	Bio-based or recyclable substrate materials (paper, wood, recyclable plastic), conductive inks made from carbon, silver, or copper Conventional surface-mount devices
Manufacturing	Subtractive (e.g. etching, machining)	Additive (e.g. printing)
Current Suitable Applications	High-speed, high-power, wide-ranging applications	Lower-power, more lightweight applications
Sustainability	Energy- and resource-intensive	Less waste and lower energy consumption

While there is a vision that (hybrid) printed electronics could one day replace conventional electronics entirely, current limitations make this impractical, as printed substrates cannot always support complex components without sacrificing performance [17]. Instead, the principles underlying printed electronics - rooted in green chemistry - can be applied to make electronics as a whole more sustainable.

TABLE 2. Overview of the 12 Horizon Europe or Horizon 2020 projects involved in this work (descriptions adapted from CORDIS) [20].

HORIZON-CL4-2021-DIGITAL-EMERGING-01-31 - Functional Electronics for Green and Circular Economy		
Project & Description		**Focus**
CircEl-Paper - Circular Economy Applied To Electronic Printed Circuit Boards Based On Paper	CircEl-Paper aims to increase e-waste recycling by developing materials and technologies for PCB manufacturing that enable recycling in the common paper recycling process.	PCBs
ECOTRON - How to minimize the ecological footprint for functional electronics?	ECOTRON develops sustainable alternatives for PCBs through printed electronics. By changing to additive organic and eco-friendly printed electronics solutions, complemented with improved and expanded recycling techniques, a more sustainable PCB alternative is created.	PCBs
HyPELignum - Exploring wooden materials in hybrid printed electronics: a holistic approach towards functional electronics with net zero emissions	HyPELignum seeks to demonstrate that electronics can be made more sustainable by combining additive manufacturing and wood-based materials to create PCBs and sensors.	PCBs, Sensors, Microchips, Supercapacitors
SusFE - Innovative Processes & Methodologies for Next Generation Sustainable Functional Electronic Components and Systems	SusFE aims to develop a sustainable design and production platform for the next generation of wearable and diagnostic devices. This initiative is within the framework of a green and circular economy, combining novel flexible integrated circuits (FlexIC), printed sensors, and a compostable paper-based power source with a roll-to-roll manufacturing platform.	Integrated Circuits, Power Sources
SUINK - SUstainable self-charging power systems developed by INKjet printing	SUINK seeks to meet sustainability indicators along the entire value chain by designing and implementing sustainable, flexible, and printable self-charging power systems (SCPS) that supply power to several sensors.	Power Sources
Sustain-a-Print - Sustainable materials and process for green printed electronics	Sustain-a-Print is developing sustainable materials and formulations for PEs, focusing on reusing and recycling valuable PE materials and using recycled, bio-based, and biodegradable alternatives to replace fossil-based materials for production.	Printed Electronics (General)
UNICORN - Unveiling Innovation Potential of Circular Approaches in Automotive Electronics and Beyond	UNICORN increases the circularity-driven functional integration of electronics in automotives. Specifically, the project will design and develop innovative green and circular technologies for automotive electronics.	Automotive Electronics (General)
REFORM - pRinted Electronics FOR the circular econoMy	REFORM develops environmentally benign electronic building blocks focusing on green, bio-derived adhesives, conductive inks and flexible substrates. The outcome of REFORM will be a green smart logistics tag, a green embedded wireless sensor and a microsupercapacitor.	Smart Tags, Sensors, Supercapacitors
HORIZON-KDT-JU-2022-RIA - Focus Topic 2: Eco-designed Smart Electronic Systems Supporting the Green Deal Objectives		
EECONE - European ECOsystem for greeN Electronics	EECONE, in collaboration with 54 entities across the value chain, aims to deploy various methodologies and actions to facilitate related progress focused on enhancing the design of electronics to improve reliability, repairability, reusability, refurbishability, and recyclability, thus reducing e-waste and contributing to a more sustainable approach.	Electronics (General)
SUSTRONICS - Sustainable and green electronics for circular economy	SUSTRONICS' primary objective is to redesign electronics with a focus on implementing circular value chains, enhancing reusability, incorporating eco-design principles, using bio-based materials and improving recyclability.	Medical/Personal Electronics, Lighting
HORIZON-CL4-2022-TWIN-TRANSITION-01-07 - Digital tools to support the engineering of a Circular Economy (RIA)		
CIRC-UITS - Circular Integration of independent Reverse supply Chains for the smart reUse of IndusTrially relevant Semiconductors	The CIRC-UITS project focuses on demonstrating the improvement of the circularity in the automotive and mass electronics sectors by reusing semiconductors from different sources, as well as supporting the reuse and remanufacturing of semiconductors.	Semiconductors
CE-SC5-25-2020 -Understanding the transition to a circular economy and its implications on the environment, economy, & society		
TREASURE - leading the TRansition of the European Automotive Supply chain towards a circulaR FuturE	TREASURE supported the transition of the automotive sector towards Circular Economy by filling in the existing information gap among automotive actors, both at design and EoL stage.	Automotive Electronics (General)

Without major breakthroughs, conventional electronics as currently manufactured and consumed fall short of contributing to global sustainability goals. Therefore, a transition to greener electronics is needed. Given the absence of a widely accepted definition of what makes electronics truly "green," this work aims to identify and clarify their most critical aspects to create a common, unified definition of green electronics through the lens of hybrid printed electronics.

II. METHODS

This work is jointly undertaken by the EU Green Electronics Working Group, an initiative involving 12 projects funded chiefly under the Horizon Europe calls focusing on green electronics, as described in Table 2. This working group brings together European academia, research institutes, and industry with a shared vision toward greener electronics.

Thus, this work first reviews the current state of EU guidelines and regulations with relevancy to greener electronics, followed by a brief review of relevant literature. Next, a unified definition of green electronics is proposed, followed by a perspective on best practices for the achievement of greener electronics through every stage of an electronic's life cycle, in line with the proposed definition. The definition and best practices discussed within this work are constructed, in part, based on the expertise and topics of focus of the members of the working group, in addition to a review of recent legislation and literature relevant to the topic of green electronics. Ongoing work from these projects is used to exemplify the best practices reviewed within this work. These examples contribute to a structured understanding of how greener electronics can be defined, designed, and realized in practice.

It is important to note that green electronics can be viewed from two perspectives: direct enabling (making electronics sustainable) and indirect enabling (supporting sustainability, like energy savings through smart devices) [19]. This work primarily focuses on direct enabling strategies.

III. SNAPSHOT OF EU SUSTAINABILITY GUIDELINES & REGULATIONS FOR ELECTRONICS

With the approval of the EU Green Deal, the EU aims for climate neutrality by 2050 and a 55% emissions reduction by 2030 [21]. To support these goals, the electronics industry must cut energy use, reduce emissions across the lifecycle, and adopt renewable energy. The EU's Circular Economy Action Plan promotes durable products, waste reduction, and sustainable practices like reuse and recycling [22]. Complementing this, the European Industrial Strategy and newly-launched Clean Industrial Deal aim to strengthen Europe's industrial base while driving sustainability and innovation [23], [24]. The electronics industry is called upon to develop technologies that improve performance and minimize environmental impact, while creating value chains focused on material recovery and recycling. Beyond the sustainability aspects, the electronic industry is called to find innovative solutions to achieve two important economic objectives, insourcing of electronic supply chains after decades of outsourcing to Asia [25], and reducing reliance on critical raw materials [26]. Furthermore, the European Chemicals Strategy for Sustainability aims to further climate neutrality, a circular economy, and zero pollution for chemicals [27]. This aligns with the EU Green Deal to boost innovation and regulatory coherence [21].

Recent changes in EU regulations related to sustainability and the circular economy include the Ecodesign for Sustainable Products Regulation (ESPR) [8], which aims to make sustainable products the norm by reducing their carbon and environmental footprints. A sustainable product is likely to display one or more of the following characteristics: i) uses less energy and lasts longer, ii) can be easily repaired, iii) can be easily disassembled and reused, iv) contains fewer substances of concern, v) can be easily recycled, vi) contains more recycled content, and vii) has a lower lifecycle carbon and environmental footprint. ESPR updates and extends the existing Ecodesign Directive [28], expanding its scope from energy-related products to almost any physical goods placed on the market, with new priority targets including electronic goods (e.g., computers, servers, and electronic displays).

Key changes arising from ESPR also include the introduction of Digital Product Passports (DPPs), mandatory Green Public Procurement criteria, and a framework to prevent the destruction of unsold consumer products. The regulation sets out a process for establishing ecodesign requirements through secondary legislation, which will be fully harmonized at the EU level. With the same aim to enhance the sustainability and circularity of products, the Circular Electronics Initiative, announced in March 2020 as part of the European Commission's new Circular Economy Action Plan, focuses on extending the lifespan and improving the recyclability of electronic products [22]. Similarly, the Right to Repair Directive, proposed in March 2023, aims to make repairs more accessible and cost-effective, encouraging a design for repairability approach throughout the product lifecycle [29].

ESPR also interfaces with other EU regulations, such as the Extended Producer Responsibility (EPR) environmental policy [30], the Restriction of Hazardous Substances (RoHS) Directive [31], the New Batteries and Waste Batteries Regulation [32], and the Waste Electrical and Electronic Equipment Directive (WEEE) [7]. EPR holds producers accountable for the collection, recycling, and disposal of post-consumer products. The RoHS Directive limits hazardous materials in electronic products to protect health and the environment. Separately, the Conflict Minerals Regulation [33], effective from 2021, applies to the electronics industry by preventing the trade of tin, tantalum, tungsten, and gold (3TG) from financing armed conflict or being mined using forced labor. The New Batteries Regulation mandates sustainability standards and recycling for all battery types. The WEEE Directive aims to promote re-use, recycling, and other forms of recovery of waste electrical and electronic equipment.

To guide ecodesign of materials and chemicals, the Joint Research Centre (JRC) of the European Commission proposed the safe and sustainable by design (SSbD) framework [34]. The SSbD framework supports investment and innovation in sustainable chemicals, integrating with the EU's research and innovation agenda and Strategic Research and Innovation Plan (SRIP) for chemicals and materials [35]. SSbD is a voluntary framework that helps companies, research institutions, and governments develop chemicals and materials that are safe throughout their lifecycle, with an ultimate goal to develop criteria for safe and sustainable chemicals and materials.

Other important EU initiatives include the Corporate Sustainability Reporting Directive (CSRD) which modernizes and strengthens the rules for social and environmental reporting by companies [36]. In a complementary direction, the EU Taxonomy for Sustainable Activities is a science-based classification system that identifies environmentally sustainable

TABLE 3. Summary of key takeaways from the reviewed literature on green electronics, categorized into five overarching themes.

	Design for Circularity: Reuse/Repair/Recycling	Biobased Materials/ Minimize Non-Renewable Materials	Greener Manufacturing (incl. No or Minimal Hazardous Materials)	Use-Phase Efficiency	EoL Circularity
Meskers et al. [46]	Increased disassembly improves metal recovery.				
Hu and Ismail [47]	Promotes longer product lives, reuse, and recycling.		Supports cleaner manufacturing avoiding hazardous materials.	Promotes efficient computing to reduce energy and emissions.	Recommends cleaner materials to reduce waste.
Irimia-Vladu et al. [48]		Proposes biodegradable organics to replace short-lived plastics.			
Irimia-Vladu [40]		Defines green electronics as low-energy/cost, and natural materials-based.	Endorses solvent-free, degradable synthetic materials.		
Tan et al. [49]		Describes green electronics as biodegradable, organic printed electronics.			
O'Connor et al. [50]	Highlights disassembly as key to electronics sustainability.		Discusses manufacturing with recycled materials, fabrication efficiency, and material substitution.		Promotes better e-waste collection and recovery.
Ellen MacArthur Foundation [44]	Calls for longer life and cascading reuse in electronics.				
PACE [1]	Supports closed-loop, dematerialized electronics.				
Zvezdin et al. [51]	Emphasizes durability, repairability, and circular design.	Advocates for standardized biodegradable materials.			
Norgren et al. [52]	Stresses design-for-recycling and avoiding incompatible materials.				
Li et al. [39]		Recommends greener processes to improve degradability. Supports developing less-precious metals for degradable electrodes.	Calls for nontoxic, low-cost, solvent-free production. Advocates modifying high-performance materials to increase solubility.		Supports layer-by-layer recycling to cut e-waste.
Cenci et al. [42]	Eco-friendly electronics should be durable and repairable.		Manufacture with green processes and safer materials.	Use power-saving features to lower EoL impacts.	
Alsharif et al. [53]				Improve energy efficiency.	
Min et al. [41]		Use biodegradable, biocompatible, eco-friendly materials.	Promotes net-zero, low-toxicity manufacturing with abundant, easily biodegradable, low-toxicity resources.		Supports reducing e-waste and carbon emissions.
Hui et al. [54]		Use nontoxic, low-cost, abundant, biocompatible natural materials.			
McCulloch et al. [43]	Use cradle-to-cradle designs for disassembly and reuse.				
Györvary et al. [45]	Calls for modular, recyclable, and longer-lasting devices. Supports reliability and reuse for a circular economy.	Asserts the need for novel devices with advanced functionality via renewable and bio-based feedstocks and process chemicals.	Encourages additive manufacturing techniques without hazardous/critical materials. Use less water and energy with renewables/reuse.	Supports the reduction of electronics' energy consumption via ultra-low-power components or increased energy harvesting.	Reviews the need for improving the efficiency of e-waste recycling.
Harkema et al. [55]	Promotes modularity and disassemblability to improve recycling while keeping performance.				

economic activities [37]. Additionally, the Directive on Corporate Sustainability Due Diligence (CSDDD) mandates large companies to identify, prevent, mitigate, and account for human rights and environmental impacts throughout their value chains [38]. Finally, the Critical Raw Materials Act, adopted by the EU in May 2024, aims to ensure a secure and sustainable supply of critical raw materials essential for the green and digital transitions [26], supporting research into more green electronics that use fewer critical materials than conventional electronics.

IV. REVIEW OF GREEN ELECTRONICS RESEARCH

The EU's regulatory landscape emphasizes the need for sustainability in the electronics industry, with policies like ESPR driving goals for reduced environmental impact, innovation, and circularity. Achieving these objectives requires harmonization between regulatory frameworks and the research driving advancements in green electronics.

Research on green electronics has surged in recent years, with publications growing from 73 in 2007 to over 250 in 2023 and 2024, as shown by a Scopus keyword search for "green" and "electronics."

This upward trajectory highlights increasing interest and advancements in this field, with notable surges occurring after 2020.

A literature review was completed on Scopus in June 2024 and encompassed the search terms "definition of green sustainable electronics", "meaning of green sustainable electronics", "developing green sustainable electronics", "what are green sustainable electronics?", "green, sustainable, circular electronics", "defining green electronics sustainable electronics circular electronics", "understanding green electronics sustainable electronics circular electronics", "future of green sustainable electronics", "green electronics review", and "criteria for green/sustainable electronics".

The reviewed literature highlights a broad range of innovative approaches and solutions but also underscores the existence of unresolved questions and conflicting priorities, such as the choice between prioritizing solvent-free [39] versus non-toxic solvent processes [40], [41] or biodegradable, low-cost [40] versus long-lasting, advanced [42] materials in product development. This review therefore consolidates and synthesizes key characteristics of green electronics from the literature into overarching themes, summarized below and in Table 3.

The first theme, "Design for Circularity: Reuse/Repair/Recycling", is often identified in the literature as key to the recovery of materials and enhancing EoL options for electronics. This theme includes strategies for increasing product lifespans, enhancing disassemblability, and designing for repairability. Sources such as McCulloch et al. [43], the Platform for Accelerating the Circular Economy (PACE) [1] and the Ellen MacArthur Foundation [44] emphasize cradle-to-cradle principles, while others highlight the importance of system modularity and avoiding obsolescence.

The second theme, "Biobased Materials/Minimize Non-Renewable Materials", emphasizes the necessity of using biobased materials while minimizing the use of non-renewable and hazardous materials. These materials are also often identified in the literature as being key to green electronics by reducing climate impacts and human health hazards. Many works advocate for substituting scarce, fossil-based, or toxic materials with biobased, abundant, and biodegradable alternatives. These include low-embodied-energy materials, biocompatible substrates, and biodegradable polymers, as discussed by Irimia-Vladu [40], Min et al. [41], and others.

Similarly, in the third theme, "Greener Manufacturing (including No or Minimal Hazardous Materials)", greener manufacturing techniques emphasizing energy efficiency and cleaner process chemicals and materials are also called out as being key to green electronics. Several studies stress the importance of minimizing toxic chemicals and solvents in electronics fabrication, advancing green processing techniques, and reducing energy and water usage during manufacturing. Authors such as Li et al. [39] and Györvary et al. [45] propose engineering approaches that support low impact production without sacrificing performance.

The fourth theme, "Use-Phase Efficiency", appears in some of the reviewed literature as a necessity to reduce environmental impacts overall. Some sources call attention to the operational phase of electronic products, encouraging designs that minimize energy consumption through power-efficient components or energy harvesting technologies.

Finally, the fifth theme, "EoL Circularity", identifies the most preferred EoL choices for greener electronics in the literature as avoiding waste generation and promoting recycling. At the final stage of the product lifecycle, the literature supports improved recycling practices and infrastructure, enhanced e-waste management, and better recovery of valuable or critical materials (e.g., rare earth elements).

V. DEFINITION OF GREEN ELECTRONICS

Despite progress in the field of green electronics, a fundamental challenge remains: the lack of a universally accepted definition, which hinders standardization, evaluation, and adoption. To address this, a consolidation of existing knowledge and ongoing research is undertaken to define the core principles of green electronics, providing guidance for future research and regulation.

Several existing definitions in the literature offer valuable contributions toward this goal. Irimia-Vladu emphasized that green technologies must align with the United Nations' sustainability definition: "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [40]. Cenci et al. defined eco-friendly electronics as those with a net positive environmental impact compared to alternatives [42]. Similarly, the European Technology Platform on Smart Systems Integration (EPoSS) in 2023 proposed that green electronics use fewer materials, integrate recycled content, and rely on low-impact solvents and chemicals [45]. Min et al. defined green electronics as devices made from biodegradable, eco-friendly materials and manufactured with net-zero processes, reducing e-waste and carbon emissions [41]. Hu and Ismail described eco-friendly

TABLE 4. Electronic categories as defined by the WEEE Directive and the global recycling rate of each [2], [7].

Product Category	Examples	Recycling Rate
Category 1: Temperature exchange equipment	Refrigerators, freezers, air conditioners	12%
Category 2: Screens, monitors, and equipment containing screens with a surface greater than 100 cm^2	Laptops, TVs, computer monitors	34%
Category 3: Lamps	Fluorescent lamps, light-emitting diode (LED) lamps	27%
Category 4: Large equipment (any external dimension >50 cm)	Household appliances; information technology (IT) and telecommunication equipment; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sports equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.	25%
Category 5: Small equipment (no external dimension >50 cm)	Household appliances; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sports equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.	22%
Category 6: Small IT and telecommunication equipment (no external dimension >50 cm)	Cell phones, printers	5%

electronics as those that avoid hazardous materials, reduce manufacturing waste, prioritize longevity, reuse, recycling, and energy efficiency [47].

As a last point toward creating a unified definition, the most important criteria defining green electronics should be evaluated within a framework that reflects a clear sustainability vision, like the EU Taxonomy for Sustainable Activities [37]. Key environmental metrics for electronics under this taxonomy include greenhouse gas emissions, resource depletion, and pollution, with indirect metrics on water use and biodiversity.

Therefore, based on a review of previous research and legislation, relevant ongoing work, and key impact metrics from the green taxonomy, the following common vision and unified definition for green electronics is proposed:

Electronicsthat, when measured against their alternatives over their whole lifecycle and value chain,have a reduced environmental impact in terms of greenhouse gas emissions, toxicity, and resource depletion, avoiding burden shifting from one impact to another or along the value chain, while fulfilling a given function.

Based on this definition, possible strategies open up to implement greener electronics relevant to both hybrid printed and other types of electronics by incorporating green chemistry principles and greener design from the beginning until the end of life, embodying principles of recyclability, repairability, and other principles of circularity concepts, utilizing less hazardous or non-renewable materials, displaying lower resource consumption, and less waste generation: these will be explored in detail in the following section.

VI. PERSPECTIVE ON BEST PRACTICES FOR GREEN ELECTRONICS

Building on the above definition and research conducted within green electronics-focused projects, the following best practices and recommendations are reviewed and discussed to guide decision-making for greener electronics at each stage of the product life cycle.

A. DEFINING CATEGORIES AND COMPONENTS OF ELECTRONICS

Recommendations that are appropriate for one category of electronics may be less applicable to another, as the intended application of an electronic device significantly influences its design process, material selection, and anticipated EoL considerations (e.g. a recycling EoL may be more realistic for certain electronics, see Table 4). To address this variability, subcategories of electronics are defined in alignment with the WEEE Directive (Table 4) [7]. These subcategories will serve as a framework for tailoring the guidance in this section.

An electronic system is itself made up of fundamental electronic components, which are discrete devices or physical entities that, when interconnected on a board like a PCB, form a functional system. Figure 1 illustrates common electronic components that make up such systems.

Therefore, best practices reviewed in each lifecycle stage subsection will also be summarized with a table (Table 5, Table 6, Table 7, Table 8, Table 9) outlining accompanying examples to best practices and their relevance to specific components or systems. However, care should be taken to maintain an understanding of the entire electronic system to prevent burden shifting, where efficiency gains in one area lead to increased consumption elsewhere.

B. TOOLS TO EVALUATE SUSTAINABILITY

Quantifying and understanding the environmental impacts of proposed materials or production pathways for electronics is key to informed decision-making, as these decisions influence the entire product lifecycle [56].

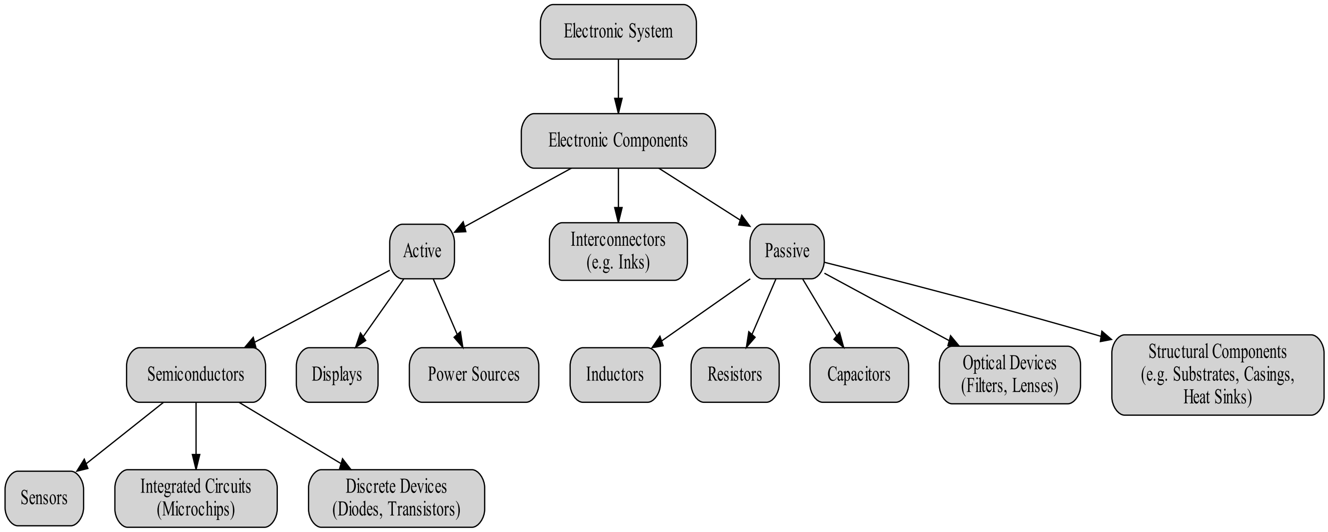

FIGURE 1. An overview of the main components of an electronic system, categorized into active and passive electronic components. Active components include semiconductors (and components further utilizing semiconductors such as sensors, integrated circuits, and discrete devices like diodes and transistors), displays, and power sources. Passive components include resistors, capacitors, inductors, structural components), and optical devices. Interconnectors, such as conductive inks, link these components to form a complete electronic system.

Life cycle assessments (LCAs), particularly those conducted in accordance with the International Organization for Standardization (ISO) 14040/14044 standards, remain the cornerstone of environmental assessments [57], [58]. They can evaluate a product's lifecycle from raw material sourcing to EoL.

In addition to LCA, non-LCA evaluational frameworks are being developed to ensure sustainability is integrated into product development. Recent advances include combining LCAs with biodegradability and toxicity studies to provide a more comprehensive understanding of environmental impact, utilizing multi-criteria decision analysis (MCDA) to assess potential ecodesign actions across technical, regulatory, economic, and environmental dimensions, or using Sustainability Readiness Levels (SRLs)-focused analyses to emphasize sustainability in technology and product development, complementing Technology Readiness Levels (TRLs) that track progress from concept to market [59], [60], [61].

Despite their usefulness, these tools have limitations. Variability in LCA databases, lack of specificity for novel electronic materials, and differing evaluation approaches can complicate comparisons and reduce accuracy [62]. Emerging standards like the EU Product Environmental Footprint (PEF) methodology or the SSbD framework aim to harmonize evaluations, but their implementation is still underway [34], [63]. Nevertheless, the integration of these tools advances electronics sustainability, particularly when applied by specialists working closely with engineers and manufacturers [45].

C. DESIGN PHASE

Decisions made during the design phase regarding materials and manufacturing methods can account for up to 80% of a product's overall sustainability performance [45]. To address this, the EU's Ecodesign Directive urges electronics manufacturers to prioritize three key areas during product design: i) reducing energy consumption during production and use, ii) enhancing resource efficiency, and iii) optimizing product lifespans through improved reliability and circularity features such as remanufacturing, reuse, and repair [28]. This subsection will therefore elaborate on these actions to advance greener electronics.

1) ECODESIGN AND DESIGN FOR CIRCULARITY

Rising concerns about resource depletion and e-waste, in conjunction with the EU Ecodesign Directive and new ESPR Directive, have placed ecodesign and circularity at the forefront of electronics innovation. Ecodesign seeks to create products which will minimize environmental impacts across their lifecycle, incorporating principles of circularity that extend product lifespans through reuse, repair, and recycling [64], [65]. Circularity offers an alternative to the traditional "take-make-dispose" model [44], [66], instead prioritizing resource recovery, reduced raw material demand, and waste mitigation.

A key aspect of ecodesign is the principle of design for disassembly (DfD), which ensures components can be easily accessed, repaired, or recycled [67], [68]. The underlying strategy behind the DfD approach relies on discrete functional layers that may be easily separated via mechanical, thermomechanical, or other chemical, optical, or physical debonding-on-demand (DoD) release concepts, enabling better reusability, repairability, or recyclability [69]. This approach supports the transition to circularity by enabling the replacement or upgrade of individual parts, thereby extending product lifespans and reducing waste. To exemplify this best practice in action, the EU projects Sustain-a-Print,

FIGURE 2. Dismantling sequence of a printed electronic to enable material recovery and reuse. Starting from a fully encapsulated device (1), the housing or laminate is removed (2) to access the functional printed layer (3). This layer is then separated into its key components: electronic parts/metal circuitry (4), and plastic substrate (5). These fractions can be processed and reintegrated into new materials.

HyPELignum, Circl-El Paper, and REFORM (see Table 2) promote circularity via DfD by developing adhesives or covalent adaptable network (CAN)-based coatings [70] that enable DoD, facilitating the reuse or recycling of compounds such as plastic or wood layers, conductive inks, and LEDs. Complementary efforts in ink recovery processes can further enhance circularity by enabling the reuse of conductive materials. For example, the REFORM project (Table 2) also designed a polymer matrix with a physical debonding mechanism that does not rely on additives, only increased temperature, enabling the removal of individual bonded components with a view towards repairability. Additionally, the ECOTRON project (Table 2) is focused on the circular design of printed electronics though innovative dismantling technologies like reversible adhesives and interconnects, ablation processes for dismantling and retrieval of waste streams and finally, these waste-streams are processed by chemical techniques like solvolysis and chemical recycling for the substrates and hydro/solvometallurgy for recovery and purification of metals. Five steps were imagined that make possible the dismantling of a device into its building blocks (see Figure 2 for a full description of these steps).

For PE-based devices that use overmolded plastic resins, DoD technologies focus on separating the plastic encapsulant from the functional substrate, which contains printed circuitry and discrete components [55], as researched, for example, in the SusFE project (Table 2). In applications where semiconductor components are not embedded in plastic encapsulants, DoD approaches may use combinations of reworkable adhesives and low-temperature solder, as explored in the project ECOTRON (Table 2) for lighting foils. The REFORM project (Table 2) is developing a new generation of substrates for printing electronics based on novel recyclable thermoset polymers and epoxy resin composites which preserves their high performance while also showing novel features, such as reprocessability, reparability and recyclability (3R) due to their dynamic bonds. In contrast to conventional epoxy resins that are nonreproducible, nonrepairable and nonrecyclable, this recyclable thermoset 3R epoxy resin composite can be chemically recycled and is being evaluated as a substrate for PEs which will be incorporated into resin-based products.

However, an ongoing challenge to ecodesign is the ability to design products that meet industry specifications for durability and functionality while facilitating repair and recycling.

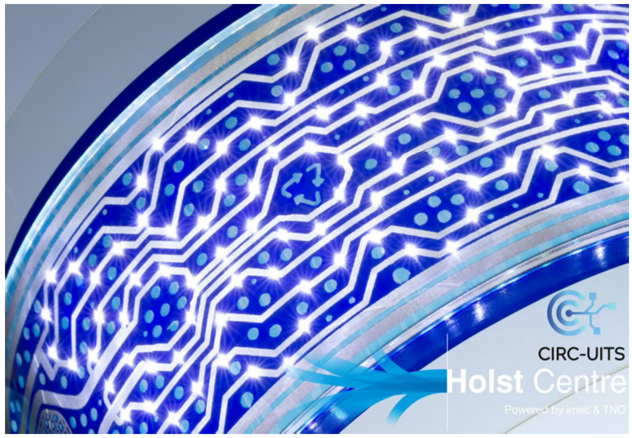

FIGURE 3. An example of a repaired In-Mold Electronics device from the project CIRC-UITS [71].

Repairability must ensure that electrical performance and performance in relation to industry specifications and standards remains comparable to the original product, as degradation in quality could result in increased power consumption and negate environmental benefits. To address this challenge, the project CIRC-UITS (Table 2), for example, explores repair strategies for in-mold electronic devices using dismantling materials optimized for recyclability (Figure 3).

Depending on performance requirements and the intended final application of an electronic, it is likely necessary to produce electronics that prioritize either circularity or durability [2]. Therefore, depending on if the targeted product is short-lived (e.g., Category 6 electronics like IT equipment - Table 4) or has a longer lifespan (e.g. long-lifespan equipment like Category 1 & 4 electronics - Table 4), recommendations may differ widely. To identify the optimal design approach, factors such as performance needs, economic viability, business models, logistics, supply chains, and waste management must be analyzed [66]. For example, in the CIRC-UITS (Table 2) project, LCA modeling is used to compare repairing with recycling, including current methods like incineration with energy recovery and advanced cradle-to-cradle recycling approaches, as investigated during project TREASURE (Table 2).

2) ENERGY AND RESOURCE EFFICIENCY CONSIDERATIONS WITHIN ECODESIGN

The Ecodesign Directive also sets energy and resource efficiency as critical goals for electronics manufacturers [28]. Incorporating efficiency considerations into the design phase of green electronics is therefore also important to minimizing their environmental footprint while maintaining performance. Resource efficiency is particularly relevant for all those products with light sources using rare earth metals or data management (Categories 2 – Screens, 3 – Lamps, and 6 – IT Equipment), while energy efficiency can be particularly relevant to Category 1 (Temperature Exchange Equipment) and Category 4 (Large Equipment) electronics, as these are

TABLE 5. A summary of reviewed best practices and accompanying examples from the projects listed in Table 2 for the design phase of an electronic's lifecycle. The absence of a specific example from a project for a given best practice does not necessarily indicate that the project is not following the best practice. The righthand column highlights electronic types or components explicitly referenced in the reviewed best practices or project examples. While these components are directly affected by the design approaches discussed, other components may also benefit.

Best Practices in Lifecycle Phase: Design			Components/ Electronics Discussed:
	Ecodesign and Design for Circularity	*Energy and Resource Efficiency Considerations within Ecodesign*	
Sustain-a-Print	Designing for disassembly by developing adhesives that enable debonding on command; development of ink recovery processes		Plastic substrate layers, conductive inks, and LEDs
CircEl-paper	Designing for disassembly by developing vitrimers (covalent adaptable polymer networks) for debonding		PCBs, flexible substrates
HyPELignum	Designing for disassembly by developing CANs-based epoxy coatings for debonding		Woody substrates, conductive inks
ECOTRON	Designing for disassembly approaches via combinations of reworkable adhesives and interconnects, ablation processes for dismantling, and low-temperature solder	Incorporating circular materials by exploring the use of rPET for PEs	PEs, substrates, semiconductor components
SusFE	Designing for disassembly by separating plastic encapsulants from the functional substrate		Printed electronics, substrates, plastic casings, printed circuitry
UNICORN	Designing for disassembly & durability via specialized adhesives that meet durability requirements while supporting dismantling and recycling		Automotive in-mold electronics, e.g. PCBs
CIRC-UITS	Designing for durability by exploring repair strategies for in-mold electronics		In-mold electronics
REFORM	Designing for disassembly via recyclable thermoset epoxy resin composites or a polymer matrix with a physical debonding mechanism		Substrates
SUSTRONICS		Incorporating circular materials by exploring the use of rPET for PEs	Printed electronics

among the most energy-intensive appliances and often used continuously.

Optimizing the use of resources and materials during manufacturing is fundamental for improving resource efficiency [72]. Using fewer material types such as monomaterials (e.g., glass) or easily separable components simplifies recycling and reduces contamination [73]. For example, designing a device's casing from a single type of recyclable plastic or biopolymer improves recyclability and reduces the need for sorting at EoL.

Incorporating recycled materials into electronics also reduces resource consumption, emissions, and waste [50], as demonstrated in a raw-materials-focused LCA by Välimäki et al., which reported a 60% reduction in emissions from electronic substrates when recycled PET (rPET) replaced virgin PET [74]. Accordingly, the electronics using recycled materials in this study were estimated to have the lowest overall resource consumption. Recycled metals (e.g., aluminum, copper) and bioplastics can therefore replace virgin materials if they meet quality, purity, and cost requirements. For example, the EU projects SUSTRONICS and ECOTRON (Table 2) are exploring the recycling and reuse of polyethylene terephthalate (PET) for application in PEs. This strategy aligns with the principles of the circular economy by keeping materials in use for longer and reducing dependence on virgin resource extraction [22].

Finally, designing electronics with enhanced energy efficiency is also essential to greener electronics [75]. Power-saving features, such as low-power standby modes, help minimize unnecessary energy use, particularly for devices that spend extended periods in standby mode (e.g., televisions, computers, appliances). Designers can use simulations and LCA to assess component energy consumption and identify areas for optimization (although care should again be taken to avoid burden shifting).

D. SELECTION AND SOURCING OF MATERIALS AND FEEDSTOCKS PHASE

Selecting the raw materials and feedstocks that form the building blocks of electronics requires careful consideration of multiple sustainability factors. In this subsection, best practices for the selection and sourcing of feedstocks for green electronics are reviewed, emphasizing materials that pose reduced ecotoxicological and human health risks. These practices align with the principles of SSbD and consider key environmental impact indicators commonly used in LCAs, such as damage to human health, ecosystems, and resource availability.

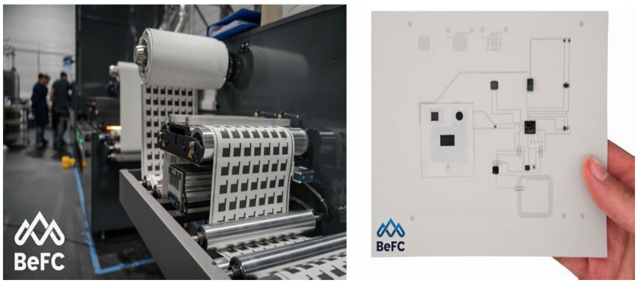

FIGURE 4. Rotary production of BeFC® printed electrodes (left) and a paper-based smart tag powered by a BeFC® biofuel cell (right).

1) BIOBASED OR BIODEGRADABLE MATERIALS

The use of biobased, renewable, bioderived, and biodegradable materials when possible can be advantageous for sustainability [12], as these feedstocks can reduce plastic waste, carbon dioxide (CO_2) emissions, and reliance on fossil fuels [45]. For example, a cradle-to-grave study by Sudheshwar et al. highlights the potential of wood-derived polymers to outperform common fossil-based polymers environmentally. The lowest carbon footprint reported for 1 kg of lignin (−2.06 kg CO2 eq.) is 10.29 kg CO2 eq. lower than the lowest footprint of polyamide (8.23 kg CO2 eq.). Compared to other fossil-based polymers, lignin's footprint is 2.53 kg CO2 eq. lower than PET. Similarly, cellulose nanofibers (−1.57 kg CO2 eq. per kg) exhibit absolute reductions of 2.04 to 9.80 kg CO2 eq. per kg relative to these fossil-based alternatives [62].

By enabling materials to break down naturally, biodegradability offers a potential solution to reducing e-waste. However, biodegradability depends on industrial processing and disposal conditions: e.g., polylactic acid (PLA) degrades efficiently only in industrial composting facilities [76]. Therefore, standardizing biodegradability and developing materials that decompose under natural conditions remain key challenges. Nevertheless, biobased feedstocks are promising for small electronics (Category 5), where low collection rates increase the likelihood of environmental loss.

Biobased materials such as PLA, silk fibroin, and wood-based cellulosic materials like paper are being explored for electronics [77]. Feedstocks used to create biobased materials are often categorized into "generations" based on their sourcing characteristics [78]. In practice, tradeoffs exist when choosing feedstocks of different generations. First-generation agricultural feedstocks (e.g., corn-derived PLA) offer high yields but compete with food production, while second-generation sources like agricultural residues or grasses reduce waste but may require energy-intensive processing [79]. On the other hand, second-generation woody feedstocks do not generally require fertilization or irrigation or much land-use change (if harvested wood is replanted or when wood is obtained from certified sustainably managed forests) but are more difficult to harvest and may have comparatively lower conversion efficiencies [62], [76].

The increasing focus on second-generation materials for electronic substrates offers new pathways for green electronics, though investment in scaling remains limited [62]. Projects like CircEl-paper, HyPELignum, REFORM, ECOTRON, and SusFE (Table 2) aim to demonstrate the potential of alternative materials to reduce environmental impact, enhance circularity, and support broader sustainability goals - reinforcing findings from studies such as that by Nassajfar et al., which used a cradle-to-grave approach to show that substituting conventional FR4-based PCBs with substrates like PET, PLA composites, or paper can reduce substrate-related environmental impacts by approximately 88%, 90%, and 98%, respectively [5]. CircEl-paper advances paper-based substrates by optimizing cellulose fibers (to address challenges such as poor thermal or moisture resistance and limited mechanical stability) for printability, recyclability, and compatibility with adhesives and passivation layers, while HyPELignum and REFORM investigate wood-derived substrates like cellulose nanofibers (CNF), plywood, and waste wood. REFORM employs green chemistry to develop low-temperature-processed wood substrates based on balsa and birch. Additionally, customized 100% cellulose-based planarization layers are being implemented toward validation as a sustainable solution for printed and hybrid electronics. In ECOTRON, existing recycled, biobased and biodegradable materials like rPET, bio-thermoplastic polyurethane or paper are being explored as flexible substrates and innovative bio-based polymers are being developed to enhance both performance and sustainability.

Biobased materials also show promise in medical electronics, where there is a goal to substitute traditional batteries (i.e., alkaline and lithium chemistries) with a biofuel cell that uses biological catalysts to convert biofuels into electricity. In this regard, the SusFE project develops eco-friendly processes for mass-producing paper-based medical devices, integrating biofuel cell technology developed by French partner BeFC and the roll-to-roll paper processing expertise of the Finnish RTO, VTT. BeFC's metal-free and compostable energy solution, made from paper, carbon, and enzymes, supports flexible, sustainable energy solutions for medical IoT (MIoT) (Figure 4) applications, demonstrating the potential for compostable energy solutions in high-demand sectors.

Beyond polymers, the use of potentially bio-sorbable or bio-safe metals (e.g. copper, zinc, magnesium, or iron) is gaining attention as an alternative to non-degradable metals traditionally used in electronics [39]. These metals oxidize and degrade naturally, reducing long-lasting waste, but may require protective encapsulation for stability in electronic applications [80]. There are ongoing efforts to explore the integration of biodegradable metals into electronic components to reduce the environmental impact of metallic waste. For example, the Sustain-a-Print project (Table 2) utilizes copper-based ink in place of silver-based ink (lowering the CO_2-footprint of the ink by 96.5% and resource use by 95.1% over a cradle-to-gate production process [10]), carbon nanotubes, and non-toxic solvents due to their lower environmental footprint. Similarly, the HyPELignum project

TABLE 6. A summary of reviewed best practices and accompanying examples from the projects listed in Table 2 for the feedstock sourcing phase of an electronic's lifecycle. The absence of a specific example from a project for a given best practice does not necessarily indicate that the project is not following the best practice. The righthand column highlights electronic types or components explicitly referenced in the reviewed best practices or project examples. While these components are directly affected by the design approaches discussed, other components may also benefit.

Best Practices in Lifecycle Phase: Feedstock Sourcing				Components/ Electronics Discussed:
	Biobased or Biodegradable Materials	*Non-Biobased Materials and Substitution of High-Impact Materials*	*Feedstock Locations of Sourcing*	
CircEl-paper	Utilizing paper, biomaterials for solvents and polymers		Utilizing paper, a widely available and recyclable material and widely available metals (tin, zinc, copper) to replace silver	Substrates, solvent in inks and glues, inks
HyPELignum	Utilizing wood and wood derivatives, copper, carbon-based ink		Utilizing beech wood, a feedstock abundant throughout Europe	Substrates, conductive inks, coatings, sensors, energy storage, supercapacitors
REFORM	Utilizing wood, carbon-based fully organic, metal-free conductive inks	Advancing bio-recovery techniques for metals like silver in conductive adhesives, employing bioleaching as a low-energy, sustainable alternative to conventional metallurgical methods		Substrates, conductive inks
ECOTRON	Utilizing bio-thermoplastic polyurethane or paper, biomaterials for inks	Researching a novel chemical process, based on solvo/hydrometallurgy principles, with the aim to recover the main metal (especially silver) from conductive inks		Substrates, conductive inks
SusFE	Utilizing paper, biological catalysts			Substrates, batteries, semiconductors
Sustain-a-Print	Utilizing copper, carbon nanotubes, polylactic acid and cellulose			Conductive inks and adhesives
CIRC-UITS		Exploring circular strategies like repair and recycling to reduce petrochemical materials' footprints		Devices
TREASURE		Polycarbonate is recycled via dissolution		In-mold electronics
UNICORN		Fossil-based electronics are dismantled and recycled		In-mold electronics

(Table 2) is developing copper-based inks and the ECOTRON project (Table 2) also focuses on bio-based conductive inks compatible with various substrates and recyclability. CircEl-paper (Table 2) focuses on affordable, eco-friendly conductive inks using tin and zinc, with biodegradable encapsulation to slow oxidation. However, for applications demanding high stability and long lifetimes, these metals may still be unsuitable [45]. Additionally, while biodegradable metals are advantageous in terms of cost and resource availability, they are not without environmental and functionality considerations. Zinc, although plentiful, is listed on the U.S. critical minerals list due to concerns over lead byproducts [81].

Looking to the future, carbon-based materials may eventually replace metals in certain applications [45]. For instance, the REFORM project (Table 2) is developing fully organic, metal-free conductive inks with optimized conductivity and viscosity, ensuring stability and compatibility with various printing techniques. Similarly, the HyPELignum project (Table 2) is exploring carbon-based inks for applications such as sensors, energy storage (e.g., current collectors), and screenprintable supercapacitors and ECOTRON (Table 2) investigates the use of sp^2 carbon allotropes as conductive filler in inks.

Biobased materials also extend beyond metals and polymers to include solvents and adhesives, which are already used in other industries but face challenges when adapted to electronics. Projects like CircEl-paper (Table 2) are investigating whether these materials (e.g. bio-based solvents for inks and glues) can meet the requirements of industrial-scale electronic manufacturing, such as availability in large quantities, uniformity, reliability, and shelf life. In another example, the REFORM project is exploring the preparation of microelectronic adhesives from epoxy resins that have been synthesized from biobased feedstocks to replace commonly employed fossil-derived bisphenol glycidyl ethers. In some cases, bio-based molecules are also being developed as precursors to replace fossil-based compounds [82].

Despite their biological origin, the lower environmental impact of biobased materials is not guaranteed. Their sustainability depends on resource consumption during cultivation and manufacturing, as well as their performance and compatibility with intended applications [62].

2) NON-BIOBASED MATERIALS AND SUBSTITUTION OF HIGH-IMPACT MATERIALS

While biodegradable and biobased materials may offer environmental benefits, they cannot always meet the performance, availability, or cost requirements needed for certain electronic applications [83].

Non-biobased materials, therefore, remain essential for hybrid PEs, as well as complex electronics such as those found in Category 6 (Small IT Equipment), where advanced materials are required to ensure functionality and longevity. Non-biobased materials can still contribute to sustainability when they are low-carbon, free of critical, conflict, or toxic substances, and circular - minimizing fossil feedstock demand while enabling high recyclability with minimal quality loss [84].

A key strategy is substituting high-impact materials with recycled or less resource-intensive alternatives [85]. For example, although the devices analyzed in the CIRC-UITS project (Table 2) primarily use petrochemical materials, circular strategies like repair and recycling are integrated to reduce their footprint. Waste-derived feedstocks replace virgin plastics, such as using rPET instead of PET for substrates, or recycling metals like silver and copper for inks through established processes to maintain circularity and preserve valuable resources. When noble or high-impact metals are required, prioritizing their recyclability ensures resource conservation.

Innovative recycling processes are improving the sustainability of non-biobased materials. The TREASURE and UNICORN projects (Table 2), for example, enhance recyclability in automotive in-mold electronics (IME) by introducing dismantling layers. TREASURE has achieved 80–90% polycarbonate recovery via dissolution, with silver recycling efficiency reaching 85–95% [86] and potentially exceeding 97% through large-scale metallurgy [87]. The REFORM project (Table 2) advances bioleaching for silver recovery in conductive adhesives, while ECOTRON explores solvo/hydrometallurgical processes for recovering silver from conductive inks.

Despite these advancements, modern electronics still depend on critical raw materials (CRMs) like silicon, cobalt, graphite, and rare earth elements [88]. These materials are typically used in small quantities within complex components like chips and circuit boards, making their recovery from e-waste both technically challenging, cost-intensive, and presents ongoing significant challenges for recycling and resource recovery [45].

3) FEEDSTOCK ABUNDANCE, AVAILABILITY, AND LOCATIONS OF SOURCING

Beyond the biobased vs. non-biobased debate, the geographic availability and regional abundance of feedstocks can play a role in reducing the environmental impacts associated with electronics production. Sourcing materials locally or regionally not only supports resource sovereignty but can also lower emissions and energy use linked to transport and logistics. This is exemplified by a study by Berg and Lindholm, which found that long-distance transport of timber within the Swedish wood supply chain accounted for 54% of the total energy consumed during forest operations [89], [90].

Prioritizing locally sourced materials minimizes transportation emissions, logistical costs, and energy consumption. For example, European manufacturers can reduce their footprint by using regionally abundant materials like beech and spruce. The HyPELignum project (Table 2) seeks to validate the benefits of sourcing birch and beech wood for electronic substrates, while CircEl-paper (Table 2) integrates widely available and recyclable paper, leveraging established paper recycling infrastructure to create localized production and recycling chains. By aligning material choices with regional resource availability, manufacturers can not only shrink their environmental footprint but also potentially increase resilience to market disruptions.

Climate change further complicates material availability, as shifting climatic conditions are expected to significantly alter the distribution, growth patterns, and viability of key biomass feedstocks [91]. For instance, European forests are projected to transition from softwood species like spruce to hardwoods. This shift not only affects forest ecology but also has consequences for industrial supply chains that rely on specific wood types for their structural, processing, or chemical characteristics. Manufacturers should factor these changes into material sourcing strategies to ensure long-term sustainability.

E. PRODUCTION PHASE

This subsection examines strategies to reduce the environmental footprint of electronics manufacturing, including energy- and resource-efficient production techniques, waste minimization practices, and the adoption of more environmentally friendly production technologies.

1) RESOURCE- AND ENERGY-EFFICIENT MANUFACTURING PROCESSES

Reducing the environmental impact of electronics manufacturing requires resource-efficient processes that minimize raw material use, water consumption, energy demand, and waste. Approaches like dematerialization and process optimization are relevant across all WEEE categories but are especially relevant for energy- and material-intensive electronic products such as large equipment (Category 4) and IT equipment (Category 6).

Additive manufacturing methods such as inkjet printing, screen printing, or semi-additive lithography can reduce material waste, energy consumption, and hazardous chemical use compared to subtractive methods [92], as demonstrated in projects like HyPELignum, Sustain-a-Print, and SusFE (Table 2). According to EPoSS, additive manufacturing processes powered by renewable energy uses 90% less material and five times less energy than traditional methods, while

TABLE 7. A summary of reviewed best practices and accompanying examples from the projects listed in Table 2 for the production phase of an electronic's lifecycle. The absence of a specific example from a project for a given best practice does not necessarily indicate that the project is not following the best practice. The righthand column highlights electronic types or components explicitly referenced in the reviewed best practices or project examples. While these components are directly affected by the design approaches discussed, other components may also benefit.

Best Practices in Lifecycle Phase: Production			Components/ Electronics Discussed
	Resource- and Energy- Efficient Manufacturing Processes	***Minimize Toxic and Hazardous Process Materials***	
HyPELignum	Additive manufacturing via printing; microwave-assisted synthesis for nanoparticles	Recycling process solvent; polyol process with polyols as solvents and reducing agents	Conductive inks, substrates
CircEl-paper	Lamination: UV curing in place of hot pressing	Systematically evaluates the ecotoxicity of chemicals	PCBs
Sustain-a-Print	Flow chemistry for continuous chemical reactions; photonic flash sintering	Utilizing non-toxic, bio-based solvents	Chemicals, conductive inks, PEs
REFORM	Eliminates the need for sintering altogether		Conductive inks
SusFE	Roll-to-roll manufacturing: semi-additive lithography; laser ablation; cold atmospheric plasma		Conductive inks, sensors, adhesives, chemicals, substrates
ECOTRON	Additive manufacturing via printing		Conductive elements

also producing lighter electronics that can be more easily separated for reuse or recycling [45].

However, a key challenge of additive (printed) circuit manufacturing is ensuring multi-layer circuit performance, particularly in printed dielectric layers and the construction of vias that connect conductive traces through the dielectric or substrate. Misalignment when printing conductive traces over dielectric regions can cause defects like pinholes, requiring multiple passes that slow production and introduce inconsistencies. Via plating is also difficult, often resulting in incomplete traces and higher electrical resistance. Currently, dispensing and stencil printing are the most reliable methods, though research continues to improve inkjet and screen-printing processes.

Other resource-efficient production methods like laser ablation, used to pattern precise designs for pH sensors, further reduces energy and water consumption through fewer processing steps compared to conventional lithography [93], while cold atmospheric plasma for system integration reduces the need for traditional adhesives and chemical processing, achieving a 100% reduction in both water and toxic chemical use through its dry, non-toxic approach [94]. For example, the SusFE project (Table 2) integrates sustainable roll-to-roll (R2R) manufacturing for medical electronics, with a goal of reducing environmental impact via project partners VTT (Finland) and Fraunhofer (Germany), who have developed and utilize semi-additive lithography, laser ablation, and cold atmospheric plasma methods for medical applications. The ECOTRON project (Table 2) explores high-resolution, chemical-free printing methods, including reverse offset and transfer foil techniques.

Energy optimization throughout the production process is another important factor in relation to reducing the impacts of electronic production [75]. Incorporating renewable energy, reusing captured process energy, and adopting low-temperature or energy-efficient technologies can lower emissions. For instance, in the HyPELignum project (Table 2), microwave-assisted synthesis methods for conductive nanoparticle fillers for conductive inks reduce energy demands compared to conventional equipment, offering potentially 30% higher efficiency due to uniform heating, shorter reaction times, and improved control of process parameters, with potential for scale-up via semi-automated batch or continuous flow systems [95]. Similarly, the Sustain-a-Print (Table 2) project investigates flow chemistry as a preferred process action, as chemical reactions that occur in continuous streams rather than batch processes improve efficiency, reduce energy consumption, and minimize waste, as illustrated by a cradle-to-gate LCA of continuous hydrothermal synthesis of silver sulfide nanoparticles, which showed 46.4% and 87.4% lower greenhouse gas emissions compared to batch processes [96]. CircEl-paper (Table 2) tackles energy consumption in one of the hotspots in PCB manufacturing: lamination. By using vitrimers, ultraviolet (UV) curing of a few minutes can replace energy-intensive hot pressing, helping to reduce the overall carbon footprint of PCBs. A study by Zhang et al., supports the broader sustainability potential of vitrimers in electronics, showing that vitrimer-based PCBs can reduce global warming potential by 20% compared to conventional counterparts [97], [98].

Sintering, a high-temperature process commonly used in printed electronics, can be energy-intensive and incompatible with heat-sensitive paper- or biopolymer-based substrates [99]. Eliminating or finding alternatives to this process step for PEs with biobased substrates can make manufacturing more energy-efficient, while allowing for the use of greener substrates [100]. For example, the Sustain-a-Print project (Table 2) utilizes photonic flash sintering to reduce required curing times by a reported 20% compared to conventional methods (a separate study by Altay et al. also demonstrated that one-step photonic curing can achieve effective results in as little as 1.6 milliseconds compared to 5 minutes with conventional thermal heating, reinforcing the potential of this approach to significantly reduce processing

TABLE 8. A summary of reviewed best practices and accompanying examples from the projects listed in Table 2 for the use phase of an electroni's lifecycle. The absence of a specific example from a project for a given best practice does not necessarily indicate that the project is not following the best practice. The righthand column highlights electronic types or components explicitly referenced in the reviewed best practices or project examples. While these components are directly affected by the design approaches discussed, other components may also benefit.

Best Practices in the Lifecycle Phase: Use			Components/ Electronics Discussed
	Reduce Energy Consumption/Increase Energy Efficiency during Use	***Lifetime Optimization***	
HyPELignum	Developing energy and power management capabilities such as low-power operation, a power comparator for voltage monitoring, reverse supply prevention, and RFID wake-up functionality		Microchips
SUSTRONICS	Optimizing standby-to-active power alternation		Medical electronics
SusFE	Developing ultra-low power printed sensors and FlexICs		Medical electronics
Sustain-a-Print		Designing electronic equipment with greater longevity	Printed electronics

time [101]), while the REFORM project (Table 2) eliminates sintering entirely with metal-free conductive inks.

Silicon-based electronics, known for high carbon footprints, are also seeing sustainability innovations. Flexible semiconductors, based on thin-film technology, present a more sustainable alternative, reducing energy, water, and harmful chemical consumption - as shown in a review by Maalouf et al. of multiple thin-film LCAs, which found that emerging thin-film technologies for solar cells have median greenhouse gas emissions of only 5-10 kg CO2 per m^2, respectively, compared to 295-326 kg CO2 per m^2 for conventional silicon-based technologies [102]. For example, Pragmatic Semiconductor, a partner in the SusFE project (Table 2), uses this streamlined fabrication process to produce flexible integrated circuits (FlexICs) for medical applications utilizing a smaller physical footprint, further minimizing resource consumption. This method employs spin coating on polymeric films and additive manufacturing processes at a single site of production, with the expected benefits of minimizing waste, energy use, and the physical production footprint.

Finally, as greener manufacturing processes transition from lab-scale to industrial production, continued optimization will enhance sustainability and cost-effectiveness [103]. While small-scale processes may initially appear inefficient compared to mature, traditional manufacturing methods, continuous refinement during upscaling can significantly improve sustainability and competitiveness.

2) MINIMIZE TOXIC AND HAZARDOUS PROCESS MATERIALS

Reinforced by RoHS [31], reducing the use of toxic and hazardous materials in electronics manufacturing is also important for greener production processes [45]. This effort is particularly relevant to Categories 1 (Temperature Exchange Equipment), 2 (Screens and Monitors), and 6 (Small IT Equipment), which often rely on flame retardants, rare metals, or complex manufacturing processes involving solvents and acids.

Solvent use in electronics production contributes to chemical waste and air pollution, making reduction and reuse important sustainability strategies [39]. For example, the HyPELignum project (Table 2) recycles process solvent (acetone) during the extraction process to produce cellulose and lignin from wood, reducing the amount of new solvent needed for subsequent extraction processes (a study by Smit et al. on the same extraction process reported acetone self-condensation solvent loss of only 0.7 wt% in an optimal extraction scenario for straw) [104]. Alternatively, switching to green solvents, such as water-based solvents or biodegradable alternatives, can potentially reduce toxicity. HyPELignum also explores the polyol process for metal nanoparticle synthesis, replacing hazardous chemicals with polyols that serve as both solvents and reducing agents, with a goal of lowering environmental impact. Similarly, Sustain-a-Print (Table 2) develops non-toxic, bio-based solvents for ink formulations, working toward environmentally friendly production.

Designing green electronics requires considering toxicity in material selection and manufacturing. The CircEl-paper project (Table 2) exemplifies this by using quantitative structure–activity relationship (QSAR) models to assess the ecotoxicity of raw materials and chemicals, allowing for the early identification of less toxic alternatives [105]. These assessments are validated through LCA and experimental data, ensuring compliance with eco-toxicity standards and broader sustainability goals.

3) LOCATIONS OF PRODUCTION

When selecting production locations for greener electronics, it can be valuable to consider factors that minimize environmental impact, such as transportation distances and the local availability of renewable energy. Locating facilities closer to raw material suppliers, components manufacturers, and key consumer markets can reduce the carbon emissions associated with transport, as demonstrated by a study by Sarioğlu on a manufacturer that cut its inbound transportation emissions by 30% through a nearshoring strategy that brought part of its material supply closer to its production facility [106]. Rail-mediated freight transport, particularly in regions with electrified networks powered by renewables, is another energy-efficient alternative that can further lower GHG emissions, depending on specific transportation routes and freight origin and destination [107].

In addition to logistics considerations, the choice of production location should prioritize access to clean energy grids with a high percentage of renewable sources such as wind, solar, and hydropower. Countries that incorporate significant renewables in their electricity mix can reduce the carbon footprint of manufacturing processes, as demonstrated in an LCA study by Rödger et al. where transitioning from a conventional German grid mix to scenarios with higher shares of renewable energy reduced process-related global warming potential from 65% down to approximately 22% per product [108].

F. USE PHASE

The sustainability of electronics during their use phase is often influenced by consumer behavior, which can be challenging to control directly. However, opportunities exist to improve environmental outcomes through optimized energy efficiency and extended product lifespans.

1) REDUCE ENERGY CONSUMPTION/INCREASE ENERGY EFFICIENCY DURING USE

Energy consumption during the use phase of electronics can be minimized through energy-efficient design and power-saving modes [109]. Energy efficiency is particularly important for WEEE categories with high or continuous energy demands, such as Category 1 (Temperature Exchange Equipment), Category 2 (Screens and Monitors), and Category 4 (Large Equipment).

Incorporating automatic power-saving modes into electronic devices can significantly reduce energy consumption during inactivity - for example, enabling such a feature in monitors can cut annual waste power use from 46.89 kWh to 1.04 kWh, saving over 45 kWh per device, as demonstrated by Kim et al. [109]. Features such as sleep modes, auto-dimming screens, and low-power standby settings allow devices to conserve energy during periods of inactivity without compromising user experience. Innovations in energy management are exemplified by projects like HyPELignum (Table 2), which is working to advance energy management with microchips featuring low-power operation, voltage monitoring, and RFID wake-up functionality. Similarly, SUSTRONICS (Table 2) aims to enhance energy efficiency in medical electronics by optimizing standby-to-active power transitions for imaging devices, while SusFE (Table 2) develops ultra-low-power printed sensors and FlexICs.

Beyond optimizing electronics themselves, intelligent and printed electronics can improve the sustainability of non-electronic products by embedding smart features that save energy and materials during use. For example, SUSTRONICS' (Table 2) smart wound dressing monitors healing and alerts healthcare providers only when needed, leading to possibilities for reduced material use, transportation for patient visits, and overall energy consumption.

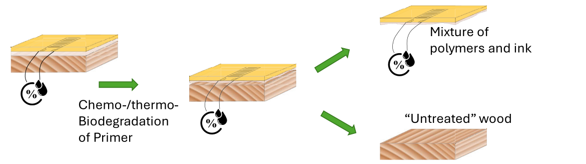

FIGURE 5. The CANs-based reversible coating concept that can aid in the recycling of metal-based inks and wood-based substrates.

2) LIFETIME OPTIMIZATION

Manufacturers can influence longevity through product design and support for repairability [110]. This principle applies to all WEEE categories but is particularly valuable for long-lasting, resource-intensive products like temperature exchange devices (Category 1) and large equipment (Category 4), as emphasized by Sustain-a-Print project partners (Table 2).

Lifetime optimization begins with prioritizing durability and repairability during the design phase. Products designed to withstand wear and tear, alongside features that allow for easy repair and refurbishment, are essential to prolonging their use. Right to Repair laws, which ensure the availability of repair documentation, spare parts, and accessible service options, are key in supporting this goal [111]. However, for applications with high energy and material consumption, such as certain large appliances, the decision to repair versus recycle must be carefully evaluated [92]. In cases where continued operation leads to excessive energy or material use, immediate recycling of defective parts may be the more sustainable choice [112].

Educating consumers on proper device maintenance, such as battery care, software updates, and avoiding overcharging, can further extend product life [110]. Encouraging longer use, resisting frequent upgrades, and prioritizing repairs over replacements also contribute to reducing electronic waste [110].

G. END OF LIFE PHASE

The EoL stage, like the initial design phase, can greatly influence the overall environmental impacts of an electronic [92]. Here, the varied EoL options for green electronics are reviewed. When electronics reach the end of their use phase, several pathways can be pursued, including reuse, refurbishment, recycling, or energy recovery through incineration. In some cases, a combination of these approaches may be feasible. However, the worst outcome remains landfill disposal, where electronics contribute to long-term environmental harm, especially when embedded in other products or packaging [113]. Furthermore, when mechanical wear occurs - an almost inevitable process - non-biodegradable components can generate microplastics that persist indefinitely, posing additional threats to ecosystems [114]. To mitigate these issues, materials with properties such as recyclability, biodegradability, and/or low toxicity should be prioritized.

1) REUSE, REPAIRABILITY, RECYCLING, AND CIRCULARITY

An ideal EoL management system for green electronics might resemble a closed-loop system, cascading devices from primary use to lower-performance applications before recycling and material recovery [66]. From an environmental point of view, reuse is usually the best option, as it minimizes waste and conserves resources more effectively than recycling [115]. Achieving material circularity therefore involves a tiered approach: remanufacturing, where components are refurbished for reuse in similar products; repurposing, where recovered materials are used in alternative applications; and finally, recycling, where materials are processed into raw forms for new manufacturing. The feasibility of reuse, repairability, and recycling varies by WEEE category. Categories 2 (Screens/Monitors), 3 (Lamps), and 4 (Large Equipment) offer strong circularity potential due to valuable materials and easier disassembly. Category 6 (Small IT Equipment) contains high-value materials but suffers from low collection rates (~5% globally), complicating recovery. Medical devices (Category 5) pose challenges due to small size and regulatory constraints.

However, electronic scrap recycling is challenging due to the material heterogeneity and complexity [116]. Traditional e-waste processing involves dismantling, material separation, recovery, and pollutant treatment [117]. The primary incentive for recycling e-waste is the recovery of valuable metals, which relies on mechanical, pyrometallurgical, and hydrometallurgical processes, though these can be energy-intensive and produce hazardous emissions [117] [118]. To mitigate these environmental impacts, alternative recovery technologies are being developed. Alternative metal recovery technologies based on biotechnology [119] or chemical processes with reduced reagent use [120] are being developed to achieve eco-friendly extraction of metals, alleviating the impact of metal recycling on the environment. These advancements aim to reduce the environmental footprint of e-waste recycling, paving the way for more sustainable EoL solutions. Efficient separation of targeted materials remains key to the success of these recycling processes, emphasizing the importance of robust collection systems and deposit schemes. For instance, the SUSTRONICS project (Table 2) explores improved e-waste processing for various consumer products to enhance material recovery and recycling rates.

To further facilitate the reuse, repairability, recycling, and circularity of electronics, the design for disassembly approach becomes essential, as first discussed in the Design Phase subsection above. This strategy facilitates the separation and recycling of discrete functional layers at EoL, enabling the recovery of valuable materials, such as metals or rare earth elements, from e-waste (see Figure 5 for an example from the HyPELignum project).

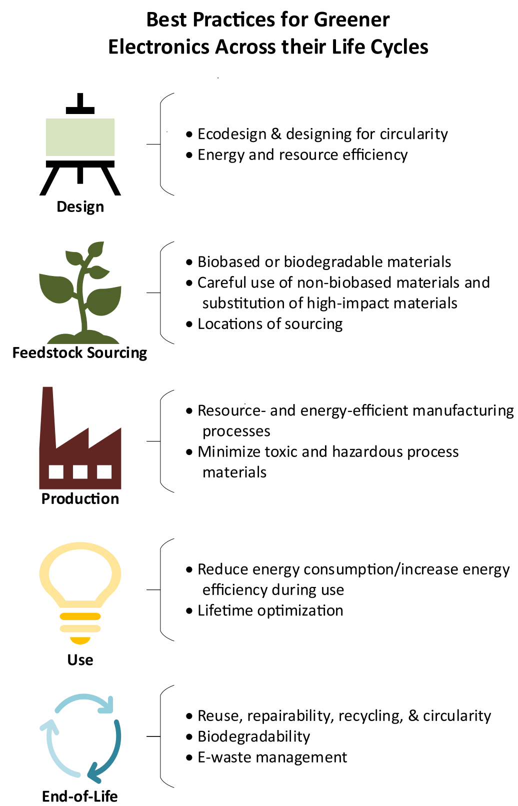

FIGURE 6. A summary of the best practices reviewed and recommended for each lifecycle stage of an electronic.

However, low-cost, disposable PEs pose challenges, as reuse is often impractical, and economic factors may favor new production over recovery. Establishing reverse logistics and manufacturer-supported e-waste collection can improve recycling for such devices [121]. CircEl-paper (Table 2) exemplifies this approach by designing PCBs compatible with established paper recycling systems, leveraging Europe's well-established paper recycling infrastructure (~70.5% recycling rate, targeting 76% by 2030 [122]) and strong market for secondary raw pulp material. Moreover, the collection, recovery and sorting systems are capillary, efficient and cost-efficient, because they manage large quantities of material. By ensuring that all materials and processes in the CircEl-paper project are compatible with the paper recycling stream, the project safeguards both the recyclability of paper substrates and the recovery of metals at the EoL stage. The quality of recycled materials is assessed using international standards, and their suitability for reuse in printed electronics is experimentally validated. Alternatively, ECOTRON (Table 2) develops a conceptual blueprint for printed electronics recycling plant, integrating multiple dismantling and recycling technologies applicable to various use cases (consumer, wearable, smart packaging, and medical).

2) BIODEGRADABILITY

Biodegradability offers a viable EoL solution for certain electronics, particularly short-lifespan, low-value,

TABLE 9. A summary of reviewed best practices and accompanying examples from the projects listed in Table 2 for the EoL phase of an electroni's lifecycle. The absence of a specific example from a project for a given best practice does not necessarily indicate that the project is not following the best practice. The righthand column highlights electronic types or components explicitly referenced in the reviewed best practices or project examples. While these components are directly affected by the design approaches discussed, other components may also benefit.

Best Practices in the Lifecycle Phase: EoL				Components/ Electronics Discussed
	Reuse, Repairability, Recycling, & Circularity	*Biodegradability*	*E-Waste Management*	
SUSTRONICS	Explores improved e-waste processing to improve material recovery and recycling rates	Exploring the impact of electronic components on biodegradable substrates		Electronics (general), substrates
CircEl-paper	Designs PCBs compatible with established paper recycling systems		Exploiting existing material streams like paper recycling	PCBs
ECOTRON	Develops a conceptual engineering and upscaling blueprint of a printed electronic recycling plant	Setting up an evaluation protocol for compostable electronics		Electronics (general), substrates

or non-recyclable devices, such as those in Category 5 (Small Devices, including medical and low-cost disposable electronics) [123]. By aligning the decomposition time of materials with the comparatively short lifespan of modern electronics, biodegradable materials can help reduce e-waste and plastic pollution while addressing the mismatch between conventional long-lived plastics and increasingly short electronic use durations. For materials prone to forming microparticles, biodegradability, even at slower rates, can mitigate the long-term environmental damage caused by persistent particles.

However, biodegradability introduces challenges and is not universally preferable for green electronics [62]. Biodegradable materials often require specific environmental conditions such as industrial composting facilities with controlled temperature, humidity, and microbial activity for effective degradation [76]. These conditions are frequently unavailable, and the presence of coatings or embedded electronic components can further impede biodegradation [62]. Additionally, certain materials, such as silver and copper used in electronic tracks or adhesives, can inhibit biodegradability due to their antimicrobial properties [124]. Projects like SUSTRONICS (Table 2) are exploring these interactions in greater detail to better understand the impact of electronic components on biodegradable substrates. ECOTRON (Table 2) is also focused on compostability as an EoL option by setting up an evaluation protocol for compostable electronics including the design consideration and testing procedures.

In some cases, prioritizing biodegradability is neither environmentally nor economically viable. Durable, high-performance applications, such as automotive in-mold systems, benefit more from reuse or recycling strategies. Additionally, some recycling processes are so efficient that even petrochemical-based materials, like rPET, can have a lower emissions footprint than biobased alternatives. For example, Shen et al. reported that the global warming potential (GWP100a) of 1 kg rPET (amorphous granulate, cradle-to-factory gate) was 1.01 kg CO2-eq./kg, compared to 1.36 kg CO2-eq./kg for maize-based bio-PET, 1.03 kg CO2-eq./kg for sugarcane-based bio-PET, and 1.30 kg CO2-eq./kg for one form of PLA [125]. Large-scale composting also raises concerns about resource efficiency if valuable metals in electronic components are lost. While biodegradability helps mitigate e-waste, it can introduce trade-offs in different environments. In landfills, anaerobic degradation of biomaterials generates methane (CH4), a potent greenhouse gas, whereas incineration produces only CO2, which has a lower global warming potential. In such cases, recycling may be the more sustainable option [62].

Biodegradability is a useful strategy for select applications. However, for electronics containing critical metals like silver or copper that are not separated before disposal, recycling remains the most effective solution for minimizing environmental impact and ensuring resource recovery.

3) E-WASTE MANAGEMENT

Managing e-waste effectively remains a challenge as electronics become more diverse and increasingly integrated into non-traditional products [12]. Many emerging technologies do not align with existing recycling models, complicating waste processing. While reuse and recycling are critical to reducing environmental impact, centralized systems for collection, processing, and recycling require coordination beyond designers and manufacturers. For non-industrial applications like consumer electronics, successful e-waste management therefore depends heavily on consumer participation and political commitment to develop and optimize recycling infrastructure [126].

In Europe, current waste processing schemes may need adaptation to accommodate emerging technologies like hybrid PEs, particularly in non-traditional applications such as smart packaging and clothing. These products often fall outside or across multiple regulatory frameworks, like the WEEE Directive [7], [12], and their unique material compositions and embedded functionalities may complicate sorting, disassembly, and recovery processes. Established recycling systems may struggle to handle these innovations efficiently, necessitating advancements in collection methods, processing technologies, and regulatory clarity to ensure proper material recovery and environmental safety.

For products using commonly recycled materials, such as paper-based PEs, existing material streams may be leveraged, as explored in the CircEl-paper project (Table 2). However, ensuring valuable materials, such as silver from conductive tracks, are recovered and redirected into appropriate recycling loops again remains a challenge. Without proper adaptation, integrating electronics into traditional waste streams could lead to inefficiencies and economic losses.

VII. CONCLUSION

The primary goal of this work was to review and discuss best practices for developing greener electronics (Figure 6) that align with a newly defined concept of the same.

The best practices presented in this work highlight the multifaceted challenges and opportunities associated with advancing greener electronics. The following conclusions and recommendations outline pathways for stakeholders (including researchers, manufacturers, and policymakers) to drive progress toward this goal.

A. RECOMMENDATIONS FOR RESEARCH AND INDUSTRY

- Prioritize circularity in design and EoL management: Focus on electronics that integrate into existing recycling streams (paper, metal, plastic) by using design-for-disassembly and design-for-recycling principles.
- Develop biodegradable and compostable solutions: While biodegradable electronics are not universally suitable, their role in addressing disposable applications warrants further investigation. Research should focus on creating materials capable of readily degrading under ordinary/standard environmental conditions, while still retaining electronic functionality during the use phase.
- Improve recycling technologies: Develop improved recycling methods through industry-academia collaboration.

B. POLICY RECOMMENDATIONS

Translating these best practices into policy requires the expansion and harmonization of e-waste regulations to accommodate emerging technologies like hybrid PEs and electronics embedded in unconventional applications. Suggested policy actions include:

- Expand the scope of e-waste regulations to emerging technologies: Broaden and harmonize policies to include emerging technologies like hybrid PEs and electronics in smart packaging and clothing, ensuring proper classification and processing under directives like WEEE.
- Support R&D for enhanced recycling systems: Provide financial and regulatory backing for innovations that improve recycling systems and critical material recovery rates.
- Incentivize ecodesign adoption: Offering tax breaks, subsidies, or other incentives for manufacturers implementing ecodesign principles or producing recyclable and repairable electronics can encourage sustainable practices across the industry.
- Promote sufficiency in electronics production and use: Consider policies that promote the creation and utilization of novel applications for electronics only when they offer significant social or environmental benefits, reducing unnecessary production and consumption.

C. BALANCING SUSTAINABILITY AND ECONOMIC CONSIDERATIONS

Economic feasibility remains a significant barrier to widespread adoption of greener technologies. Competition in pricing for both bio-based and recycled plastics versus petrochemical materials is challenging and requires volume scaling, efficient production, marketing, and legislation to realistically link the costs of climate change to petrochemical materials [127]. Achieving balance requires:

- Scale production to lower costs: Scaling up the production of biobased and novel materials can help reduce their costs, making them more accessible and competitive with conventional materials.
- Internalize environmental costs of conventional electronics: Legislative frameworks should aim to internalize the environmental costs of conventional electronics, for example, by imposing carbon taxes or requiring companies and consumers to pay for e-waste recycling.

D. LIMITATIONS

Sustainability in electronics is a shared responsibility. It requires coordinated efforts between researchers to innovate, manufacturers to adopt greener practices, and policymakers to create an enabling environment for sustainable transitions. Assessing sustainability is also complex, as optimal solutions vary by application, function, and supply chain. Rather than a one-size-fits-all approach, this work emphasizes tailored strategies. While primarily focused on environmental sustainability, it also acknowledges the social benefits of greener electronics, such as healthcare applications that reduce energy consumption and improve patient outcomes through smarter monitoring.

While this work is grounded in EU policy, regulatory structures, and research initiatives, the framework for greener electronics presented here is relevant beyond the European context. The core principles, such as circularity, material safety, energy efficiency, and designing for EoL, can serve as a foundation for similar efforts globally. Translating this framework to other regions requires adapting to local regulatory landscapes, infrastructure capabilities, and supply chain realities. In lower- and middle-income countries, for example, integration with informal e-waste sectors and investment in safe recycling infrastructure may be essential. In regions with strong manufacturing capacity, focus could be placed on ecodesign, green supply chains, and material standardization.

International collaboration and alignment of sustainability criteria across borders could further accelerate progress, helping to shape cohesive global strategies for greener electronics development.

Additionally, while the best practices discussed in this work are highly relevant for electronic components like substrates, they do not necessarily apply to areas such as optical equipment or all active components. These aspects are not the primary focus of the projects involved in this work, not due to a lack of interest but rather due to differing research priorities. As a collective, these projects offer valuable insights within their areas of research but do not represent every sector of electronics. Identifying these research area gaps is important for future EU initiatives, as a more detailed exploration of these areas could help shape more comprehensive sustainability strategies for electronics.

Finally, while the unified definition of green electronics proposed in this work addresses a critical terminological gap, it also contributes to the development of a broader conceptual framework for sustainable electronics. Specifically, this definition is grounded in and made actionable through a structured set of best practices that span the entire electronics lifecycle. These best practices reflect core principles of established sustainability frameworks such as circular economy, green chemistry, and sustainable supply chain management. As such, they collectively serve not only as practical guidance, but as a form of applied framework that operationalizes the definition of green electronics in line with life cycle thinking. In doing so, this work supports the integration of green electronics into larger theoretical constructs, such as circular electronics systems or sustainable value chains, and provides a foundation for future research that aims to further formalize these links.

ACKNOWLEDGMENT

This publication reflects only the authors' views, and the European Union is not liable for any use that may be made of the information contained therein. They acknowledge EPoSS for their previous work on this topic, Dr. Vincent Hickl of the Biointerfaces, X-ray Analytics, and Biomimetic Membranes and Textiles laboratories at Empa for the valuable feedback, and their respective project consortiums for their valuable review and feedback.

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KEALIE VOGEL received the B.S. and M.S. degrees in natural resources and environmental sciences from the University of Illinois Urbana–Champaign, in 2019 and 2021, respectively. From 2020 to 2021, she was a Policy Advisor with the Illinois Commerce Commission, Chicago, IL, USA. From 2021 to 2023, she was a Senior Scientific Specialist in sustainability with the Illinois Sustainable Technology Center, Champaign, IL. Since 2023, she has been a Scientist with the Technology and Society Laboratory, Empa—Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland, and the Environmental Risk Assessment and Management (ERAM) Group. Her research interests include life cycle assessment, sustainable materials, and the environmental impacts of hybrid printed electronics on wood-based substrates.

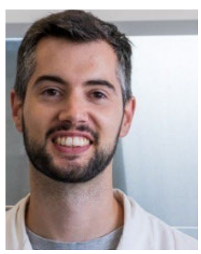
SARA CARNIELLO received the degree in materials engineering and nanotechnologies in Italy, and the M.B.A. degree in generic management from Montanuniversität Leoben (MUL), Leoben, Austria. She worked for many years as a Project and Team Manager in the electronics industry, gaining extensive experience in technology and product development. Following her is an Entrepreneur and a Freelance Consultant. She joined Joanneum Research, in 2022, to focus on the sustainability of electronics and advanced materials. She is currently the Coordinator of the Business Area "Environment and Sustainability" within the Institute for Climate, Energy Systems, and Society at Joanneum. She is also an Advisor with the Circular Economy Forum Austria, a Lecturer with the University of Applied Sciences in Wiener Neustadt, and a Guest Lecturer with various European universities. Her research interests include sustainable electronics, circular economy strategies, and advanced material sustainability assessment.

VALERIO BENI received the degree in chemistry from the Università degli Studi di Firenze, Florence, Italy, in 1999, and the Ph.D. degree in chemistry from University College Cork, Cork, Ireland, in 2005. He was a Postdoctoral Researcher with the Tyndall National Institute, Ireland, from 2005 to 2007, and a Marie Curie Fellow with Universitat Rovira i Virgili, from 2008 to 2011. From 2011 to 2014, he was an Assistant Professor with Linköping University, Sweden. Since 2015, he has been a Senior Scientist and a Project Manager with RISE Research Institutes of Sweden AB, Norrköping, Sweden. His current research activities are focused on the development of formulations and processes for the sustainable manufacturing of hybrid-printed electronics on unconventional substrates, including articles and wood. Besides this, he is also engaged in the design and development of printed sensors and hybrid-printed sensing platforms for environmental and med tech applications.

AKSHAT SUDHESHWAR received the B.S. degree in environmental engineering technology from Delhi Technological University, in 2017, and the M.S. degree in environmental engineering from ETH Zürich. He is currently pursuing the Ph.D. degree with the Technology and Society Laboratory, Empa—Swiss Federal Laboratories for Material Science and Technology, St. Gallen, Switzerland, working on the development of methods for safe and sustainable by design.

NADIA MALINVERNO received the bachelor's and master's degrees in environmental sciences from ETH Zürich, Zurich, Switzerland, in 2019 and 2021, respectively, with a specialization in human–environment systems and environmental policy analysis. Since 2021, she has been a Scientist with the Technology and Society Laboratory, Empa—Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland, and the Environmental Risk Assessment and Management (ERAM) Group. Her research focuses on the cascading use of wood and biomass strategies, biobased development, circular economy strategies, and negative emission technologies, contributing to more sustainable resource management and climate mitigation.

YOLANDA ALESANCO received the degree in chemistry from the Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain, in 2011, and the M.S. degree in applied chemistry and polymeric materials sciences and the Ph.D. degree in chemical sciences from the University of the Basque Country (UPV/EHU), Donostia-San Sebastián, Spain, in 2014 and 2017, respectively. Since 2011, she has been with CIDETEC, Donostia-San Sebastián, where she is currently a Senior Researcher and a Project Manager with the Smart and Functional Surfaces Unit. Her current scientific activity involves the development of functional materials and formulations and their implementation in printed electronics by different techniques, particularly in the area of nanosurfaces. She has participated in various scientific conferences and more than 20 national, regional, and European research projects related to this topic, being the Consortium Leader of the European REFORFM project (Grant Agreement: 101070255). She is the co-author of 17 peer-reviewed articles, four patents, and more than ten communications in international conferences. Her awards and distinctions include the Extraordinary Doctorate Prize for her Ph.D. Thesis on molecular design and synthesis of new electrochromic molecules and development of optoelectronic devices, in 2018, the two Extraordinary Prizes awarded during her degree, namely the Extraordinary End-of-Degree Award, from 2010 to 2011, and the Best Academic Record in science, from 2009 to 2010.



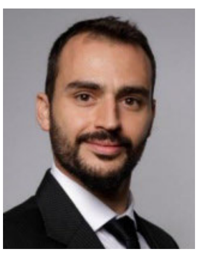
MAX TORRELLAS was born in 1991. He received the B.S. degree in biotechnology from the University of Valencia, Valencia, Spain, in 2013, the M.S. degree in plant biotechnology from the Polytechnic University of Valencia, Valencia, in 2015, and the Ph.D. degree in biotechnology from the University of Valencia, in 2020. From 2020 to 2022, he was a Researcher with the Valencian Institute of Microbiology, Valencia. Since 2023, he has been a Biotechnology Researcher with AIMPLAS, Valencia, where his interest has focused on the biorecovery of metals using microorganisms and the use of biotechnological processes for organic waste valorisation and plastic recycling.

STEPHAN HARKEMA received the Ph.D. degree in polymer chemistry from the University of Groningen, Groningen, The Netherlands, in 2006, with a dissertation titled "Capillary instabilities in thin polymer films: mechanism of structure formation and pattern replication."

Since 2005, he has been with TNO, The Netherlands, and studied blue light-emitting polymers for use in organic light-emitting diodes. Hereafter, he joined the development of flexible organic light-emitting diodes for lighting and signage applications at Holst Centre, The Netherlands. In 2017, his focus shifted to In-Mold Electronics, particularly to human–machine interfacing using hybrid and printed electronics and light management. Since early 2021, he has been managing the sustainable electronics program that leverages TNO's broad range of expertise to develop novel sustainable solutions for hybrid and printed electronics. His research interests include decarbonization, material circularity, and lifetime extension of hybrid and printed electronics, and providing supporting lifecycle assessments.

MARGREET DE KOK was born in Eindhoven, The Netherlands, in 1970. She received the M.S. degree in organic chemistry from the Radboud University of Nijmegen, Nijmegen, The Netherlands, and the Ph.D. degree in the synthesis of electroluminescent polymers from the University of Hasselt, Hasselt, Belgium, in 1999. She began her career as a Senior Scientist with Philips Research, in 1999, where she worked on materials and applications for OLED technologies. She has worked on displays, lighting, and health-related projects. She joined TNO, in 2008, to work at TNO/Holst Centre, The Netherlands, on conformable, stretchable and thermoformable electronics for textile, automotive, and health applications. She is responsible for funded and bilateral projects. She is the co-author of more than 40 publications and holds more than 60 patents.

CORNÉ RENTROP is currently a Project Leader with the TNO at Holst Centre. He has more than 12 years of experience in hybrid printed electronics (HPE) and in that time coordinated various (EU-funded) projects on the topic. Lately, sustainability is an important topic to allow the responsible production of (printed) electronics. He is also the Co-Founder of TracXon b.v. (a spin-off company of TNO at Holst Centre). TracXon is commercializing printed electronics solutions for the medical and automotive markets, focusing on sustainable production of PE in Europe.



IGNACIO ZURANO VILLASUSO was born in Montevideo, Uruguay, in January 1992. He received the bachelor's degree in chemical engineering from Universidad de la República, Montevideo, Uruguay, in 2019, and the M.S. degree in chemical engineering and bioprocesses from Universidade de Santiago de Compostela, Santiago de Compostela, Spain, in 2022. He has a solid and specialized career in technical, environmental, and sustainability fields. He began his professional career with two years as a commercial technician for chemical supplies in the food industry, where he gained expertise in chemical products and their applications in the food sector. Following this, he spent five years as a Process Engineering Assistant with the Environmental Department of a waste treatment company. In this role, he developed skills in process management and waste treatment, with a strong focus on sustainability and environmental care. For the past two years, he has been a Sustainability Technician with LOMARTOV S. L., Valencia, Spain, where he focuses on developing European projects and providing environmental advisory services. His work is centered on advanced methodologies, such as life cycle assessment (LCA), cost analysis, and social life cycle assessment (SLCA), demonstrating his ability to integrate environmental, economic, and social aspects into decision-making processes.

LOU BERNARD received the bachelor's and M.S. degrees in biotechnology engineering from Bordeaux Graduate School of Biomolecule Technology, Bordeaux, France, in 2023. She did various work placements in startups on environmental microbiology and molecular biology, where she was investigating bioplastic synthesis from organic waste and air depollution using bacteria. She is currently a Sustainability Engineer with LOMARTOV S. L., Valencia, Spain, where she focuses on sustainability assessment of emerging technologies. Her work includes conducting life cycle assessments (LCA), economic evaluations, and using eco-design methodology, among other tasks, to evaluate the impacts of innovative technologies.

ENRIQUE MOLINER was born in Castellón, Spain, in December 1981. He received the Ph.D. degree in industrial engineering from Universitat Jaume I, Castellón, Spain. He has 18 years of experience in R&D&I in the fields of sustainability and circular economy. He started his research career with Universitat Jaume I, working on eco-design, life cycle assessment (LCA), and waste management, while developing his Ph.D. thesis on the environmental assessment of road transport. Then, he worked for seven years at AIMPLAS, the Plastics Technology Centre, Valencia, Spain. His work there was focused on the sustainability of materials, technologies, processes, and products associated with the plastics industry, including waste recovery and recycling. He gained experience in technical and legal advice on the environmental issues to be considered for the development or improvement of products and processes, using tools, such as eco-design and life cycle sustainability assessment, including environmental LCA, life cycle costing (LCC), and social LCA. He participated in numerous EU-funded projects on the recovery and recycling of plastic waste, and in projects on the development and application of bioplastics. Since 2021, he has been a Sustainability Technical Officer with LOMARTOV S. L., an environmental engineering consultancy SME located, Valencia. He provides high-qualified consultancy services to companies and organizations, helping them to develop innovative and circular solutions. He also participates in industrial and technological projects, contributing to improving their sustainability. He has been a speaker in more than 60 conferences and seminars and the author of more than 20 technical articles for scientific journals (including some indexed journals). He also has teaching experience on eco-design, LCA, carbon footprint, environmental labelling, plastics recycling, and circular economy. His current research interests include innovation and business development, eco-design, life cycle sustainability assessment, circular economy modeling, environmental communications, regulatory compliance, and certification and standardization processes.

CHRISTIAN REIN received the M.Sc. degree in nanotechnology and the Ph.D. degree in chemistry (biomimetic) from Copenhagen University, Copenhagen, Denmark. He is currently a Senior Specialist, a Product Manager, and an upscaling Expert with the Printed Electronics Section, Danish Technological Institute (DTI), Taastrup, Denmark, where he participates in multiple EU projects, including LEE-BED, BioMAC, and DIAGONAL. He is also the Coordinator of the Horizon EU ''Sustain-a-Print'' Project, which focuses on sustainable electronics, and the Danish Coordinator of the ''EECONE'' (CHIPS JU) Project. From 2016 to 2018, he was an Industrial Postdoctoral Researcher with DTU Energy, where he worked on research and development of third-generation solar cells and nanomaterials for roll-to-roll (R2R) production. His responsibilities included chemistry, materials characterization, solar cell design, and project development. He has published 13 peer-reviewed articles, including collaborative work in click chemistry with Nobel laureate M. Meldal. He has received awards for his contributions to project management and cross-disciplinary innovation. He is an expert in sustainable electronics, safety compliance, and guiding the development of next-generation technologies for electronic applications. His research interests include printed electronics, sustainable materials, and the development of innovative, scalable solutions for electronic technologies.

YVES BAYON received the M.S. degree in biochemical engineering from INSA Lyon, France, in 1989, the degree in pharmacology from University Paris Descartes, Paris, France, in 1990, the Ph.D. degree in biochemistry from INSA Lyon, in 1993, and the M.B.A. degree from IAE Lyon, France, in 2006. Since 2000, he has been with Sofradim Production, Trévoux, France, now part of Medtronic. He is the co-author of more than 85 publications and the co-inventor of more than 40 families of patents. In his current position as a Distinguished Scientist, his research interests include the commercial development of medical devices, mainly for general surgery applications, including electronics-based devices. He is a fellow of the Biomaterials Science and Engineering (FBSE), a status awarded by the International Union of Societies for Biomaterials Science and Engineering (IUSBSE).

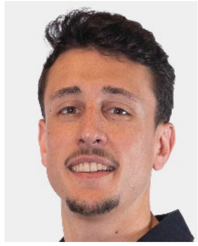
ZULFIQUR ALI received the B.Sc. degree (Hons.) in applied chemistry from the University of Greenwich, in 1986, and the Ph.D. degree in instrumentation and analytical science from The University of Manchester, U.K., in 1989. He is currently the Pro Vice Chancellor of Research and Knowledge Exchange, University of Cumbria, U.K. His research interests include microfabrication, microfluidics, and transducer development, particularly electrochemical and optical sensing, and AI for sensor data.

CAROLIN ZACHÄUS received the master's degree in applied physics and the Ph.D. degree in electrochemistry from Technical University Berlin, with research focused on semiconductor physics for energy applications. Since 2017, she has been actively involved in European research and innovation with VDI/VDE Innovation + Technik GmbH, a national innovation agency based in Berlin. As a Senior Consultant with the European and International Business Development department, she specializes in circular approaches for the automotive sector, shaping strategies, and roadmaps to enhance sustainability. Her work bridges automotive innovation (electrification, automation), circular economy, and renewable energies, with a strong focus on the twin transition towards digitalization and sustainability. She is a Leading Contributor with the UNICORN project, an EU-funded research and innovation action supporting the development of circular functional electronics in the automotive sector. She leads the creation of a strategic vision, roadmap, and policy recommendations to promote decarbonisation, material recycling, utilization improvement, and product lifetime optimization. Her work emphasizes flexible and printed electronics as enablers for sustainable automotive electronics. Her research interests include electronics for sustainable mobility, automated driving, circular economy strategies, and international cooperation in European research and innovation. She is particularly engaged in exploring how emerging technologies and policy frameworks can accelerate the transition toward a sustainable and connected automotive ecosystem. She is an active member of key European networks and partnerships, including the Connected, Cooperative, and Automated Mobility (CCAM) Partnership, the European Association on Smart Systems Integration (EPoSS), and the European Association of Automotive Suppliers (CLEPA). She engages in stakeholder dialogues, policy development, and strategic initiatives to drive European research and innovation forward.

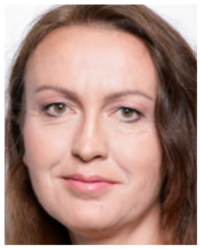
NICOLAS GOUZE received the Engineering degree in optronics from the University of Paris XI (now the University of Paris-Saclay) and the degree in innovation management from the University of Valenciennes, France. Since 2004, he has been actively involved in European research and innovation activities with VDI/VDE Innovation + Technik GmbH, Berlin. He plays a key role in the strategic activities of EPoSS, the European Technology Platform for Smart Systems Integration, contributing to the development of strategic articles and roadmaps, and integrating end-user requirements into research and innovation priorities. He is involved in several EU-funded projects focused on digitalization across various application sectors. Currently, he is the Coordinator of the UNICORN project, an EU-funded research and innovation action supporting the green and digital twin transition. His UNICORN promotes circularity in automotive electronics through decarbonisation, material recycling, utilization improvement, and lifetime optimization. The project emphasizes the development and testing of innovative solutions, particularly in flexible and printed electronic systems, to drive a greener digital future. His publications include the ECS Sustainability and Environmental Footprint, EPoSS White Paper, in July 2023, Net Zero–Strategies for a Sustainable Digital Future (VDI/VDE-IT), in August 2024, and the A Model for a Life-Long Personalized Continuum of Integrated Care Revolutionizing Healthcare Delivery: Description of Technological Impact (Institute for Innovation and Technology), in November 2020. His research interests include electronics and optronics, European innovation and research policy, circular economy, health technologies, and international cooperation. He is an active member of professional networks in the field of European research and innovation. His contributions to strategic policy development and technology integration have been widely recognized.

MARIE BERTHUEL received the M.Sc. degree in chemistry from the University of Oregon, Eugene, OR, USA, in 2015, the master's degree in formulation and industrial chemistry from Université Claude Bernard Lyon 1, Lyon, France, in 2016, and the Ph.D. degree from University Grenoble Alpes, Grenoble, France, in 2020, for the development of biosensors based on micro-structured electrodes and physically microencapsulated biomolecules with a focus on glucose detection and vector-borne diseases early-stage detection. In completing her Ph.D., she has developed a strong knowledge of electrochemistry, enzymatic reactions, and affinity biosensors by working on a multidisciplinary subject gathering chemistry, material sciences, and biology. In 2020, she became the Co-Founder of a deeptech startup BeFC©in Grenoble, France, where she started as a Senior Scientist, taking the responsibility of managing the development laboratory and the supply chain. Over the course of five years, she grew to become the Product Director, focused on defining the product vision, ensuring the product aligns with customer needs. Overseeing product strategy and development, she also provides extensive customer project management, product engineering, and product marketing experience.

CRISTINA GONZÁLEZ BUCH received the degree in chemical engineering from Polytechnic University of Valencia, Spain, in 2010, and the Ph.D. degree in engineering and industrial production, in 2016. She started her work as a Researcher with the Polytechnic University of Valencia, in 2011. Since 2016, she has been a Project Manager in recycling technologies and waste management area with ITENE, Valencia, Spain, with eight years of experience participating in national and EU level projects on packaging sustainability, and in new technologies for valorization of plastic and organic waste developing the life cycle assessment of product and processes, life cycle costing, carbon footprint, sustainability, and eco-efficiency. She is a member of the Spanish network of LCA.



FRUELA PÉREZ SÁNCHEZ received the B.S. degree in industrial chemical engineering and the M.S. degree in environmental engineering from Universitat Politècnica de València (UPV), Valencia, Spain. He is currently a Researcher in the field of sustainability assessment with ITENE, Valencia, with a focus on life cycle assessment (LCA), organizational carbon footprinting, life cycle costing (LCC), and social life cycle assessment (s-LCA). He is an Active Member of the Spanish Life Cycle Assessment Network, contributing to the advancement of life cycle thinking in scientific and industrial contexts.''



CLAUDIA SOM received the master's degree in biology from the Department of Ecology, University of Zurich, Zurich, Switzerland. She is currently a Senior Scientist with Empa—Swiss Federal Laboratories for Materials Science and Technology. She has been an active in the fields of life cycle thinking, industrial ecology, and sustainable innovation for more than 25 years. During her early career, she led technology cooperation focused on cleaner production with countries in transition. She was also part of the SETAC LCA Working Group ''LCA and Conceptually Related Programs.'' She is a member of the Technology Assessment Network (NTA) and develops integrated methods for prospective life cycle assessments, meta-analyses, and material flow assessments. She serves as a work package leader in several Horizon projects, collaborating with industry partners with a particular emphasis on nano-, polymeric, and bio-based materials in electronics and other sectors. She also publishes guidelines and peer-reviewed articles aimed at supporting decision-making in materials science and industry, promoting safe, and sustainable-by-design approaches.