Journal of Cleaner Production 546 (2026) 147774

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Circularity assessment of power electronic converters: manual disassembly, bill of material, circularity indicators and actionable guidelines

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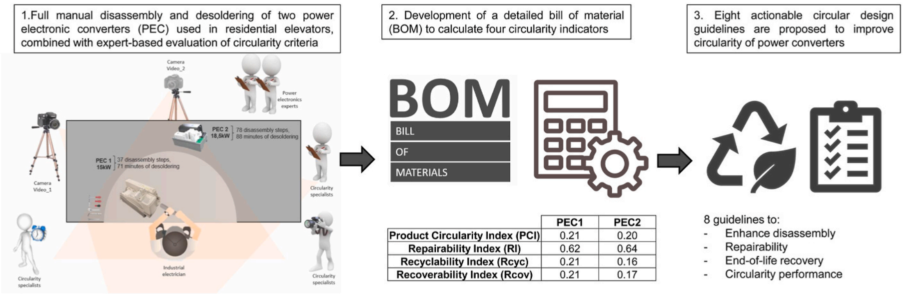
HIGHLIGHTS

- Integrated circularity assessment performed on two real power electronic converters.
- Manual disassembly and desoldering revealed major circularity barriers.
- Circularity performance of power converters remains very limited.
- Eight actionable circular design guidelines are proposed to improve sustainability.

GRAPHICAL ABSTRACT



1.Full manual disassembly and desoldering of two power electronic converters (PEC) used in residential elevators, combined with expert-based evaluation of circularity criteria

2. Development of a detailed bill of material (BOM) to calculate four circularity indicators

	PEC1	PEC2
Product Circularity Index (PCI)	0.21	0.20
Repairability Index (RI)	0.62	0.64
Recyclability Index (Rcyc)	0.21	0.16
Recoverability Index (Rcov)	0.21	0.17

3. Eight actionable circular design guidelines are proposed to improve circularity of power converters

8 guidelines to:
- Enhance disassembly
- Repairability
- End-of-life recovery
- Circularity performance

ARTICLE INFO

Keywords:
Circular electronics
Circularity indicators
Disassembly
End-of-life management
Power electronic converter

ABSTRACT

Power electronics are essential for the energy transition, supporting renewable integration, electrified transport, and efficient industrial systems. However, their growing deployment raises environmental concerns linked to the use of scarce materials, difficult-to-disassemble product architectures, and insufficient end-of-life strategies, factors which contribute to the global increase in electronic waste. As the core functional units of power electronic systems, power electronic converters (PECs) play a central role in determining these environmental outcomes. This study evaluates the circularity of two PECs. The methodology combined complete disassembly and desoldering, bill of material development, and the calculation of four indicators: Product Circularity Index (PCI), Reparability Index (RI), Recyclability (Rcyc), and Recoverability (Rcov). The results indicate that disassembly and desoldering of the two PECs, 37 and 78 steps, 71 and 88 min, respectively, require a high degree of manual effort, representing a significant barrier to practical and economically viable end-of-life recovery. Circularity was consistently low for PCI (0.21 and 0.20), Rcyc (0.21 and 0.16), and Rcov (0.21 and 0.17), while

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https://doi.org/10.1016/j.jclepro.2026.147774
Received 7 September 2025; Received in revised form 31 January 2026; Accepted 8 February 2026

RI values were moderate (0.62 and 0.64), suggesting some potential for life extension through repair. Based on these findings, eight design guidelines are proposed to improve disassembly, reparability, and recovery. This study underscores how product design directly affects circularity outcomes in PECs, reinforcing the need to integrate circular economy principles in the development and management of PECs.

1. Introduction

The global energy demand is expected to continue to grow, driven by increasing industrialisation and digitalisation (Mahmood et al., 2024). In 2024, fossil fuels accounted for approximately 60% of global primary energy, despite the accelerated deployment of renewable energy technologies (IEA, 2025). In the same year, the emissions from the energy sector reached a record 37.8 gigatons of CO_2, accounting for about 70% of all anthropogenic emissions (IEA, 2025). A large share of this growth stems from the electricity system, which is expanding as economies electricity consumption is projected to rise by about 3% per year this decade, increasing its current share from 20% to up to 36% by 2035 (IEA, 2024). These trends highlight the urgency of accelerating the decarbonisation of the global energy system.

In an effort to address climate and resource challenges the (United Nations, 2015) has called for urgent climate action (Goal 13). Similarly, the European Climate Law (European Commission, 2021) has mandated a 55% reduction in European Union (EU) greenhouse gas emissions by 2030 relative to 1990 levels. Within this framework, the Circular Economy Action Plan (CEAP) (European Commission, 2020) promotes strategies such as repair, reuse, and recycling to minimise resource extraction and waste. Complementary initiatives, including the Circular Electronics Initiative (European Commission, 2020b) and the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2024), aim to extend energy-related product longevity, enhance reparability, and foster sustainable material use across product life cycles (Spiliotopoulos and Beltran, 2025). In support of these ambitions, the Joint Research Centre (JRC) has provided an exploratory assessment highlighting the importance of electronic product categories for future reparability evaluation (Spiliotopoulos and Beltran, 2025). Taken together, these policy developments position energy-related electronic systems as priority targets for improving durability, reparability and circularity.

Among energy-related products, power electronic (PE) systems have emerged as critical enablers of the energy transition (Idoko et al., 2024). By efficiently controlling and converting electrical energy, these technologies facilitate the integration of renewable energy sources. They also improve energy conversion in electric vehicles, and reduce losses in power transmission and distribution systems (Blaabjerg et al., 2017). As demand for these functions grows, global PE deployment is projected to reach 100 TW (TW) per year by 2050, significantly contributing to net-zero targets by reducing system-level energy losses (Sangwongwanich et al., 2024).

Although PE devices contribute to greater energy efficiency, their production presents significant environmental and circularity challenges that impact EU CO2 neutrality targets. Their manufacture is highly resource- and energy-intensive, particularly in semiconductor fabrication, which requires 1.15 kW h per cm^2 wafer, substantially more than other electronic components such as printed circuit boards (PCB) (Wang et al., 2023). PE systems also incorporate critical materials, such as neodymium or dysprosium, and hazardous substances, such as lead or cadmium (Baudais et al., 2023) regulated under European laws, including RoHS (European Commission, 2011) and REACH (European Commission, 2006). Moreover, the PE sector predominantly follows a linear economy model, contributing to significant e-waste which is projected to reach 120 million tonnes annually by 2050 (Sangwongwanich et al., 2024).

Power electronic converters (PECs) are central to PE systems. They convert and control electrical energy by adapting voltage, current, or frequency to suit applications such as renewable energy integration and industrial automation (Blaabjerg et al., 2017). Their complex manufacturing and material composition reflect the broader environmental challenges linked to PEs. Enhancing PEC circularity could contribute to minimising the environmental footprint and improving resource efficiency. This requires the integration of life cycle thinking into the early stages of product design and development (Romano et al., 2023; Mendoza et al., 2017).

Despite the importance of PECs in the energy transition, the scientific literature on the circularity and environmental sustainability of PECs remains limited and fragmented. Most studies have focused on improving energy efficiency (Marati et al., 2022; Ristić, 2024; Tang et al., 2022), with little attention paid to other life cycle stages, such as material sourcing or end-of-life (EoL) management (Fang et al., 2023). This narrow focus has also been reflected in life cycle assessment (LCA) studies, which, although increasingly applied to PECs (Baudais et al., 2023; Musil et al., 2023; Vauche et al., 2024; Zimmermann, 2013) tend to concentrate mainly on energy performance or CO_2 emissions. As a result, other environmental impact categories across the full product life cycle remain understudied and the scarcity of high-quality primary life cycle inventory (LCI) data continues to constrain the development of more comprehensive and robust sustainability assessments (Fang et al., 2023). Together, these issues contribute to the fragmented understanding of the overall environmental sustainability of PECs.

Other studies have analysed circularity indicators in a broader electrical and electronic equipment (EEE), context. For example, Vanegas et al. (2018) examined the ease of disassembly of liquid crystal display (LCD) monitors to support circular strategies. Bracquené et al. (2020) proposed a framework to assess circular performance in complex supply chains, particularly relevant for electronic systems, by integrating quantitative indicators with strategic decision-making tools. Herrmann et al. (2023) reviewed recent research on measuring EEE durability but did not apply the methods to specific products. Ardente and Mathieux (2014) examined measures to improve resource efficiency in energy-consuming products such as LCD-TVs.

Despite these advances none of these studies have focused on PECs, nor have they addressed their combined environmental, functional, and material challenges. This gap is further underscored by the fact that, to the best of our knowledge, only one study has applied a circularity indicator directly to a PEC. Evaluating the ease of Disassembly Metric (eDIM) indicator (Vanegas et al., 2018), Romano et al. (2024) revealed critical limitations in the availability of disassembly data and a lack of standardised procedures. However, the scope of the study was limited to disassembly complexity and did not consider broader circularity strategies.

Taken together, these limitations demonstrate the need for comprehensive and multidimensional circularity assessments of PECs that integrate product disassembly data, bill of material (BOM), multiple indicators and design-orientated insights. While several circularity metrics have been proposed in recent years, most studies remain limited either to simplified teardown approaches or to single-indicator analyses focused on isolated life cycle stages. This restricts their ability to capture product-specific design constraints and generate actionable recommendations.

This study applies a detailed empirical methodology to assess the circularity of two real PECs. Unlike previous works based on datasheets or partial assessments, this approach combines complete manual disassembly and desoldering, material-level characterisation through primary BOM reconstruction, and the simultaneous calculation of four complementary indicators: the Product Circularity Index (PCI), Reparability Index (RI), Recyclability (Rcyc), and Recoverability (Rcov). Although these indicators have been previously defined, they are seldom applied in practice, especially in complex products like PECs, where circularity challenges are tightly linked to integration, joining techniques, and recovery feasibility.

The analysis generates a multidimensional profile of circularity performance and identifies specific design limitations that hinder recovery and reuse. Based on these insights, the paper proposes design and life cycle management (LCM) guidelines tailored to the functional and structural characteristics of PECs. The specific objectives of this study are:

- Analyse the PEC disassembly sequence process, identifying bottlenecks, critical steps, and design-related barriers to circularity.
- Characterise the material composition of two PECs and develop a BOM to allow calculation of circularity indicators.
- Assess the circularity of the PECs using quantitative indicators, including the Product Circularity Index (PCI), Reparability index (RI), Recyclability (Rcyc) and Recoverability (Rcov) rates, to generate a multidimensional circularity profile for each product.
- Define design and LCM guidelines to improve circularity in future generations of PECs.

2. Methodology

This study examines two industrial PECs used in elevators (rated at 15 kW and 18.5 kW) from Nidec Control Techniques (Nidec Corporation, 2025). The first converter (PEC1) belongs to the older Unidrive SP series (Control Techniques, 2011), and the second (PEC2) from the newer Unidrive M700 range (Control Techniques, 2014). Both feature a modular architecture, including PCBs, insulated-gate bipolar transistors (IGBTs), aluminium heatsinks, electrolytic capacitors, plastic housings, and integrated cooling fans. Both units were retired due to communication board failure, with other components remaining functional, and showed no external damage or visible ageing during disassembly.

These PECs were selected to comparatively assess design criteria and circularity indicators, including disassembly, reparability, recyclability, and material circularity. The comparative analysis of two commercial converters of 15 kW and 18.5 kW, manufactured in different years, makes it possible to examine how technological and architectural variability influences circularity performance and to identify potential design improvements across product generations for the same application. Although the units analysed were originally used in elevator systems, this type of medium-power converter is widely employed across industrial sectors due to its primary role in controlling three-phase alternating current (AC) motors. Approximately 380 million electric motors operate within the EU (European Commission, 2025), highlighting both the scale of the motor stock and the prevalence of the associated PECs. In this context, the units under study can be considered representative of industrial converters commonly deployed in the European market. Table 1 summarises the main technical characteristics and operational information of the two PEC.

A structured two-step methodology was applied to evaluate circularity performance (Fig. 1). First, the converters were manually disassembled and desoldered, and experts reviewed their circularity and environmental sustainability criteria (Section 2.1). Second, a detailed BOM was compiled to support the calculation of the selected circularity indicators (Section 2.2). The qualitative and quantitative information from these two stages supported an integrated interpretation of the circular design of the converters. This consolidated analysis revealed critical design limitations and circularity enablers, which in turn informed the design guidelines discussed in Section 3.3.

Table 1
Technical specifications and operational data of the analysed PECs.

Parameter	PEC 1	PEC 2
Manufacturer	Control Techniques (Emerson)	Control Techniques (Emerson)
Series	Unidrive SP	Unidrive M700
Model	SP2403	M701-064 00350 A
Production year	2011	2014
Rated power	11 kW/15 kW	15 kW/18.5 kW
Input Voltage	380–480 V AC, 3-phase	3/PE AC 380–480 V
Input Frequency	48–62 Hz	50–60 Hz
Operating Temperature	0 °C to 40 °C without derating	0 °C to 40 °C without derating
Cooling Method	Forced air cooling (internal fan)	Forced air cooling (internal fan + heatsink)
Dimensions (HxWxD)	540 × 270 × 265 mm	540 × 270 × 265 mm
Weight	8.5 kg	11.8 kg
Installation Method	Panel mounting (IP20)	Panel mounting (IP20)
Communication Options	Modbus RTU, CANopen, PROFIBUS, EtherCAT, CTNet, etc.	Modbus RTU, EtherCAT, PROFINET, Ethernet/IP (via modules)
End-of-life Condition	Failure of communication board	Failure of communication board
Estimated Years in Operation	~10–13 years (prior to disassembly)	~10 years prior to disassembly

2.1. PECs disassembly and design assessment

2.1.1. Manual disassembly and desoldering

This process was performed to both physically separate the components, and collect detailed design and operational data necessary for calculating four key circularity indicators (Section 2.2.2). The disassembly and desoldering were carried out by an industrial electrician, supported by two PE experts who ensured technical accuracy and architectural integrity. Furthermore, a team of three circularity specialists documented the process through video recordings, technical notes, and real-time logging, while gathering insights on component condition and potential for circular strategies.

The disassembly protocol was adapted from two existing methodologies: one proposed by Vanegas et al. (2018) and the other a protocol developed by the French Ministry for Ecological Transition (AGEC) (Ministry of Ecological Transition, 2022). These were combined with further operations to develop the disassembly protocol for circularity purposes. The resulting procedure was structured into sequential phases each outlining essential tasks to achieve the intended outcomes. Full details are provided in S1 of the supplementary file (SF).

The first stage of manual PEC disassembly took place in September 2024 in a controlled workshop environment. The industrial electrician followed the protocol, starting from the external casing and progressing inward. Only manual tools were used, including flat and star-tip screwdrivers, Torx (T10 and T20), Allen keys, and socket wrenches. For each component removed, the team documented the part name, type and number of fasteners, number of disassembly steps, and time required for each operation. Fig. 2 illustrates the disassembly sequence, numbered in chronological along with dismantling times, tool changes, fastener types per operation and material heterogeneity.

The second stage focused on desoldering the electronic components. Completed in March 2025 this operation aimed to recover and characterise the electronic components mounted on the PCBs for subsequent integration into BOM. The same industrial electrician who performed the disassembly conducted the desoldering process in a dedicated electronics workshop, under supervision of the research team and in consultation with PE experts.

To minimise damage and protect component integrity, desoldering was executed using specialised thermal techniques and protective measures. The workflow followed three steps: (i) preheating of all PCBs in a reflow oven to homogenise internal temperatures and reduce thermal shock; (ii) localised heating of solder joints with a hot air gun to

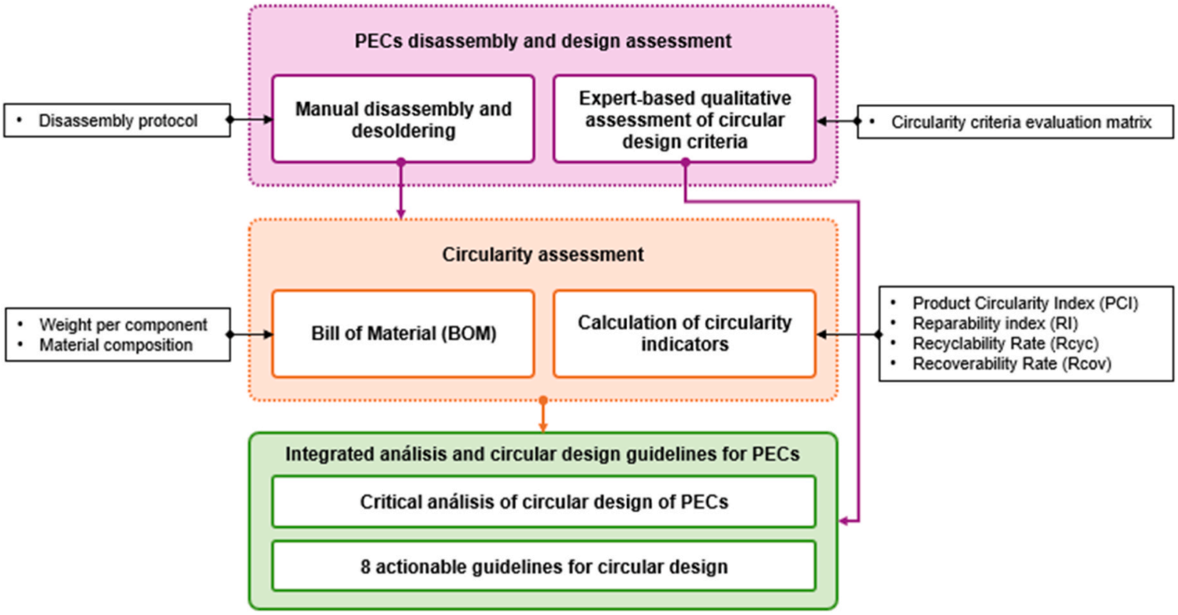

Fig. 1. Methodological steps.

allow targeted heating while preserving both board and component integrity; and (iii) manual removal of components with tweezers and controlled mechanical actions. More delicate elements, such as integrated circuits, were handled with particular care to prevent deformation or breakage.

The tools employed included a hot air gun, solder preheating station, reflow oven, and a fume extractor to reduce operator exposure to solder fumes. The operator also wore thermal gloves and safety footwear as a precautionary measure. Full details about both processes are provided in S2 of the SF. The key findings of the disassembly and desoldering process are presented in Section 3.1.

2.1.2. *Expert-based qualitative assessment of circular design criteria*

The qualitative analysis of circularity criteria was conducted during disassembly and desoldering. These hands-on sessions provided a real-world context for collaborative reflection with PEC experts and the industrial electrician. During the disassembly, technical discussions addressed component accessibility, repairability, and recyclability, as well as identifying critical components, failure-prone parts, and functional design weaknesses.

During the desoldering phase, the discussion was structured around the circularity criteria proposed by Ruiz de Azua Lahidalga et al. (2025), which served as a guiding framework for expert reflection. Rather than applying a formal scoring method, the evaluation was conducted qualitatively through open dialogue and joint interpretation among the participating experts. This process generated contextual insights into how circularity aspects were (or were not) considered in the PECs' design, and identified key barriers and opportunities for improvement. The criteria used and associated observations are presented in Table S3 of the Excel SF. The resulting insights, along with the circularity performance (Section 2.2) directly informed the design guidelines proposed in Section 3.3.

2.2. *Circularity assessment*

In this phase, each PEC component was inventoried, documenting weight, material composition, type of joints, and the presence of labels facilitating material identification, traceability, and sorting. This information supported the calculation of the four circularity indicators considered in the study (see Section 3.2).

2.2.1. *Bill of material (BOM)*

The total weight was 8.5 kg for PEC1 and 11.8 kg for PEC2. Although both share the same material categories, their mass distribution and structural configuration differ significantly. Metals dominate in both cases (84.7% PEC1, 74.7% PEC2), with aluminium, copper, and steel as the primary constituents. Aluminium was extensively used in external structures and heatsinks, particularly in PEC2 (up to 3.5 kg). Copper, present in windings, PCBs, and interconnections, was more prevalent in PEC1 relative to total weight (24.7% vs. 19.5%). Steel, used in fasteners, shielding, and transformer cores, was notably higher in PEC2 (2.9 kg vs. 1.5 kg), contributing to its greater mass.

Plastic components accounted for 10.3% of PEC1 and 16.1% of PEC2, with PEC2 more than doubling the polymer mass (1.9 kg vs. 0.9 kg) due to extended use of housing and insulation. Both devices included polycarbonate, nylon, polypropylene, and ABS. Glass fibre and composites were also higher in PEC2 (0.4 kg vs. 0.2 kg), consistent with a larger number of PCBs and double-sided configurations. Additionally, PEC2 contained more epoxy resin and mineral compounds (1.0 kg vs. 0.2 kg) used for encapsulation, coating, and potting. The BOM for the two PECs is detailed in Fig. 3, and the complete mass breakdown per material, component, and subcomponent are provided Tables S4 and S5 of the Excel SF.

2.2.2. *Calculation of circularity indicators*

The selection of the four circularity indicators was based on a two-stage literature review combining academic and normative sources. The process followed the PRISMA guidelines, as illustrated in Fig. 4.

Two structured searches were conducted in SCOPUS in February 2025, using three combined keyword streams: (i) power electronics or electrical and electronic equipment (EEE), (ii) circular economy and eco-design, and (iii) indicators and metrics (Table 2) (see Fig. 4). The first search targeted circularity and environmental sustainability indicators specifically applied to power electronics (PE), while the second search adopted a broader scope by covering EEE in general. Only peer-reviewed journal articles and reviews written in English between 2015 and 2025 were included. This period was selected because the launch of the EU Circular Economy Package in 2015 marked a turning point in research, regulation, and industrial interest in circularity (Alcalde-Calonge et al., 2022)

The two searches yielded 91 records. Studies related to circularity and environmental sustainability indicators applied to PE and/or EEE

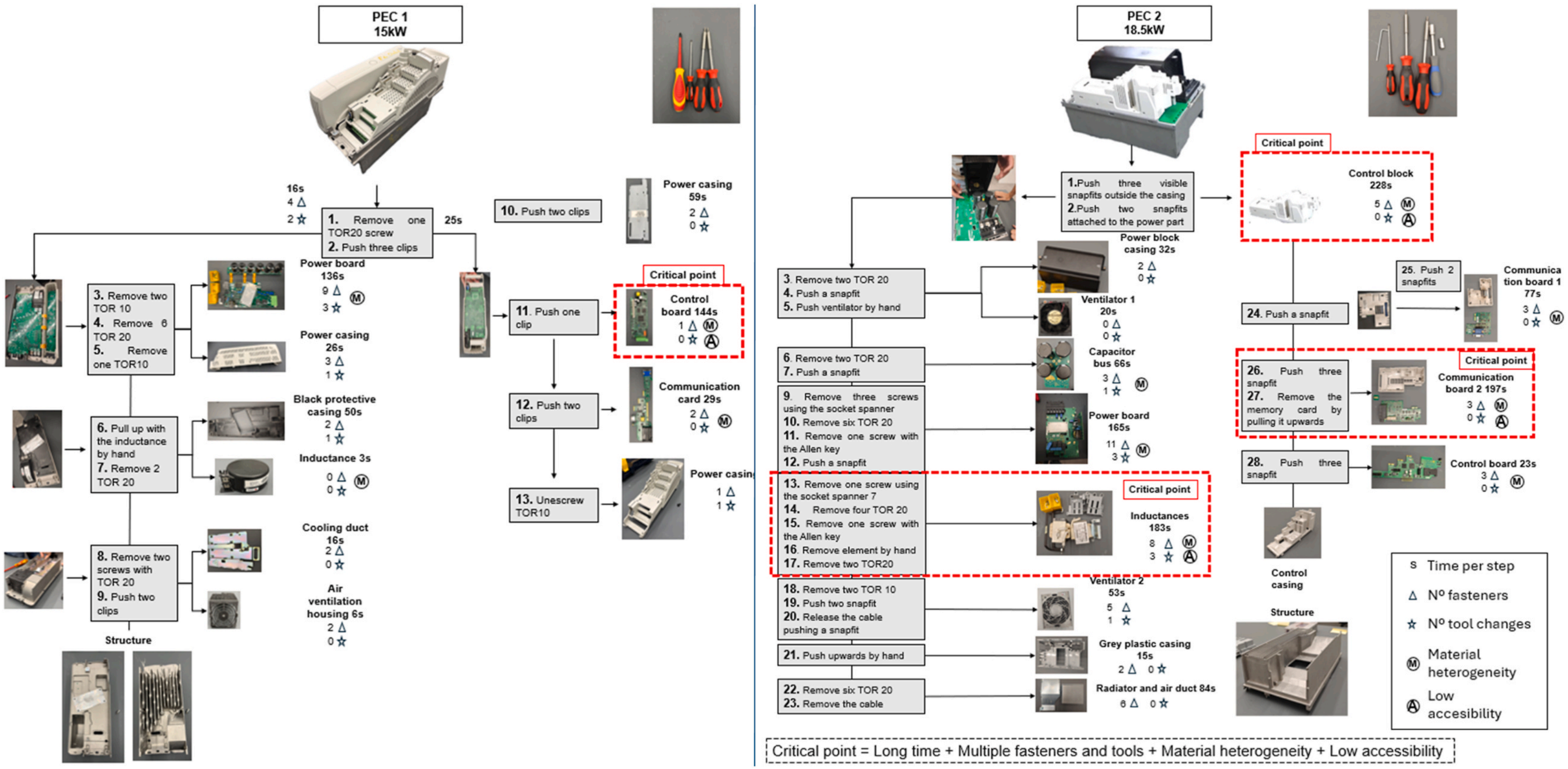

Fig. 2. Step-by-step visual workflow of both PEC disassembly process with critical point highlighted in red dotted squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

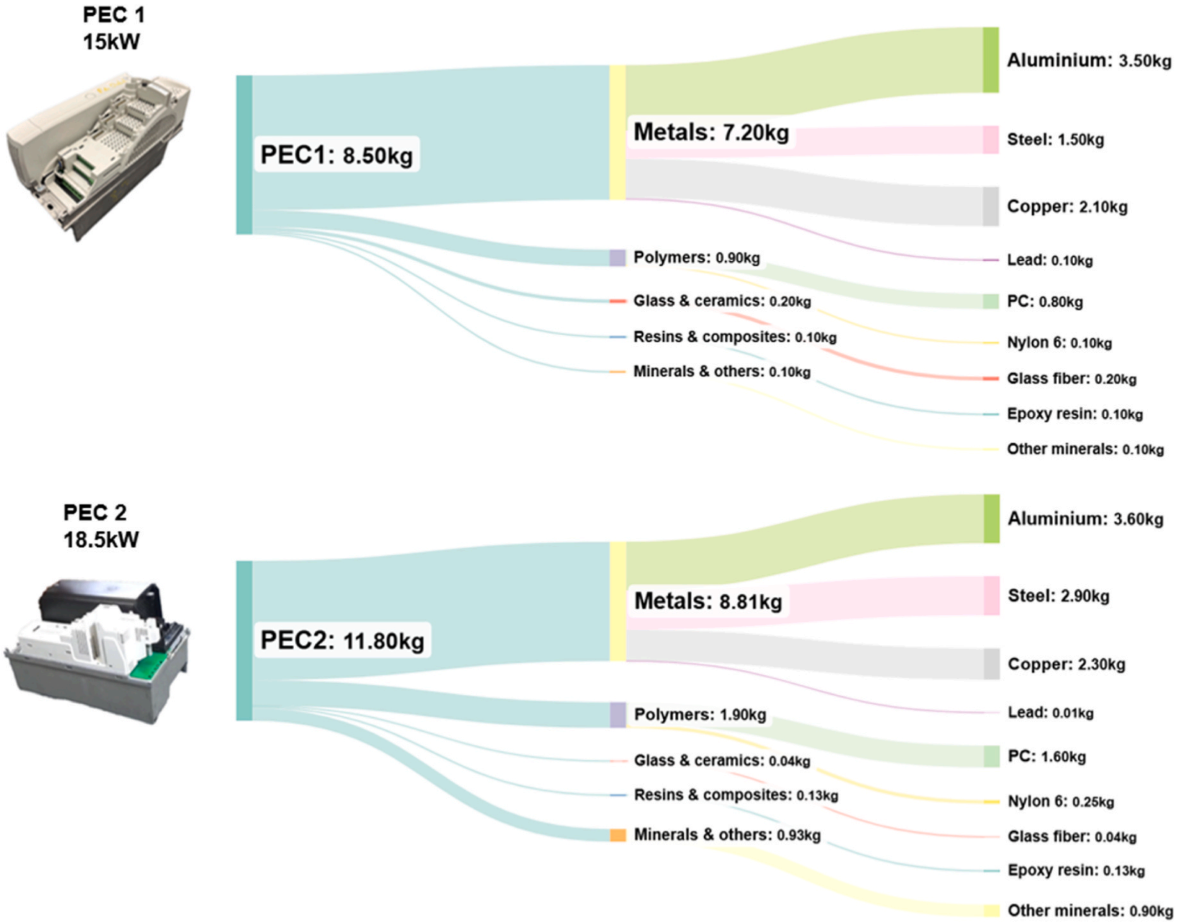

Fig. 3. Bill of Materials for the PECs. Acronyms: PEC (power electronic converter).

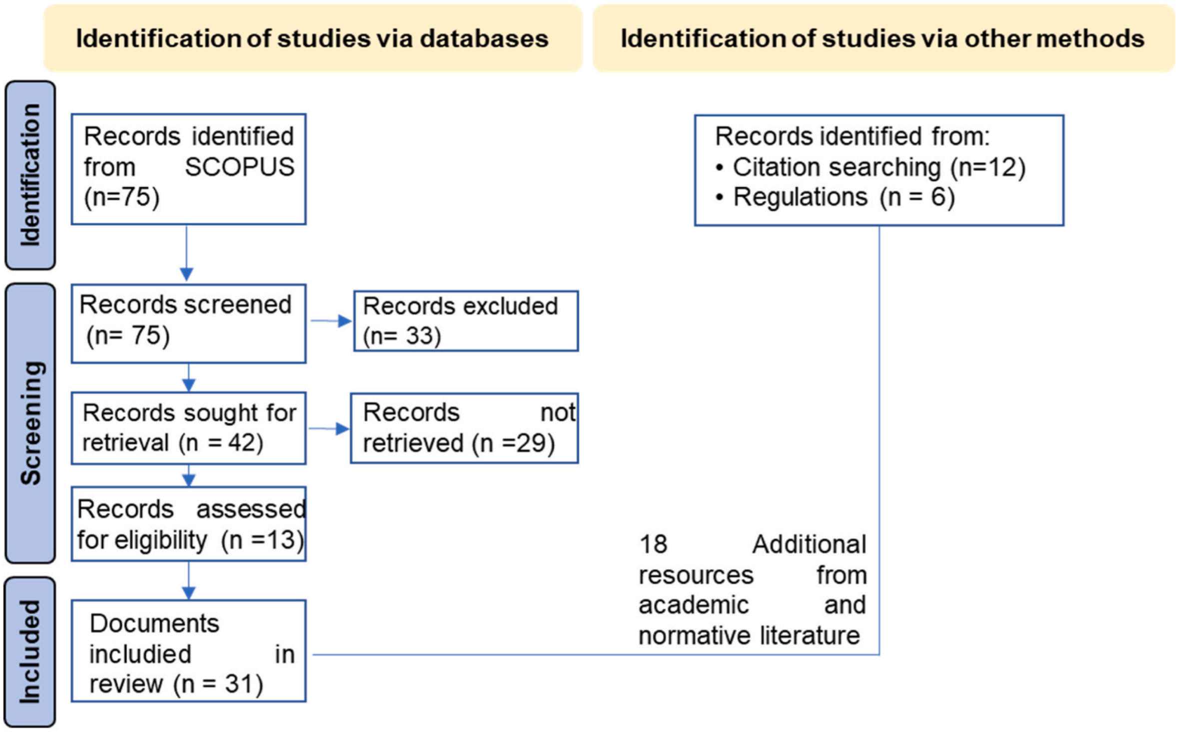

Fig. 4. Systematic literature review, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al., 2021).

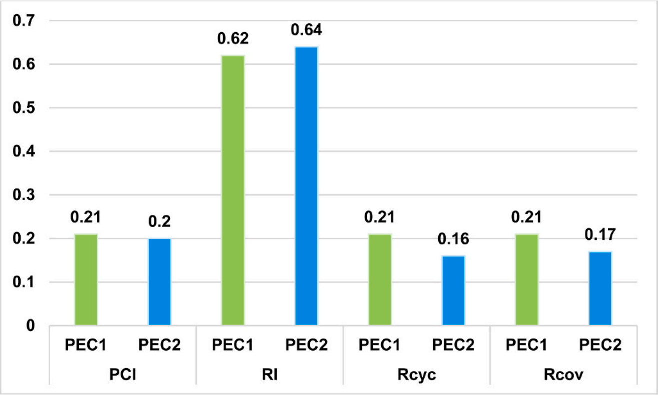

Fig. 5. Circularity performance of PEC1 and PEC2 against four indicators. Acronyms: PEC (Power Electronic Converter), PCI (Product Circularity Index), RI (Reparability Index), Rcyc (Recyclability Index), Rcov (Recoverability Index).

Table 2
Literature searches to identify relevant journal papers. Acronyms: CE – circular economy, EEE – electric and electronic equipment.

Literature searches	Search streams	Keywords	Hits
1	Stream 1	“Power electronic*" OR “Power converter” OR “electronic power switch*" OR Semiconductor*	18
	Stream 2	“Circular economy” OR CE OR circularity OR “circular design” OR eco-design OR ecodesign OR “design for environment” OR “design for sustainability” OR “sustainable design” OR circularity-by-design OR “circularity by design	
	Stream 3	indicator OR index OR metric* OR scor*	
2	Stream 1	“Electrical equipment” OR “Electronic equipment” OR “Electronics product*" OR “Electric appliance*" OR “electrical and electronics industry” OR “electric and electronic equipment” OR “electric and electronic sector” OR EEE OR “Power electronic*" OR “Power converter” OR “electronic power switch*" OR Semiconductor*	75
	Stream 2	Same as above	
	Stream 3	Same as above	

were considered. To this end, the pertinence of the title, keywords, and abstracts of the articles to the research topic was examined. Applying the aforementioned cut-off criteria, the sample of articles for the exhaustive evaluation was reduced to 14 papers in relation to the circularity indicators for EEE. In addition, the search for indicators was supplemented by a further 11 papers identified by snowballing, giving a total of 25 papers.

The academic review was complemented with relevant European regulations, the analysis of which is fundamental for comprehending research in the fast-growing sector of energy-related products, in particular PEs (Fang et al., 2024). Policy sources reviewed included the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2024), UNE EN 45552 (AENOR, 2021), and UNE EN 45558 (AENOR, 2019). Six references from regulatory and industry literature were reviewed.

In total, 31 documents (25 academic and six normative) formed the basis for identifying the circularity and environmental sustainability indicators considered in this study. The complete list of included works is provided in Table S6 of the Excel SF. From this review, indicators were selected based on three criteria:

i) Proven applicability to EEE products, validated through case studies and prior scientific literature (Saidani et al., 2019);
ii) Methodological robustness and institutional endorsement, particularly by the European Commission and its Joint Research Centre (JRC) (Joint Research Centre, 2025), which guarantees alignment with regulatory frameworks such as the ESPR (European Commission, 2024) and CEAP objectives (European Commission, 2020a);
iii) Coverage of the three core CE strategies: Narrowing (reducing resource use), Slowing (extending product life), and Closing (reincorporating materials into the economic cycle) (Mendoza et al., 2022). By combining resource efficiency, durability, and EoL valorisation perspectives, the selected indicators ensure a holistic assessment of circular performance.

Finally, the following four indicators were considered:

- Product Circularity Indicator (PCI) (Bracquené et al., 2020): Measures the overall circularity of a product by quantifying the share of circular versus virgin material flows throughout its life cycle. It integrates three key variables: (i) the proportion of secondary materials used, (ii) the potential for component reuse, and (iii) the recoverability of materials at EoL. The PCI formulation combines these variables into a single linear flow index (LFI), which is subsequently adjusted by a utility factor that reflects product lifetime relative to sectoral use patterns. This yields a dimensionless value between 0 and 1, where higher scores indicate lower dependence on virgin resources and greater capacity to retain material value throughout the product life cycle. These aspects correspond to the circular economy strategies of narrowing, slowing, and closing loops. The final expression applied in this study is given in Eq. (1).

$$\mathrm{PCI} = 1 - \frac{\mathrm{LFI}}{\mathrm{X}} \tag{1}$$

- Reparability Index (RI): Measures the level of repairability of a product based on the specifications of Wandji et al. (2023) and the recommendations of standard EN 45554 (AENOR, 2020a). It combines qualitative and quantitative criteria, organised into nine analytical blocks: i) disassembly, ii) support, iii) spare parts, iv) working condition, v) product design, vi) product reconditioning, vii) documentation, vii) after-sales strategy, and ix) product identification.

Each block includes specific evaluation parameters, such as fastener type and accessibility, availability of repair guides, or provision of spare parts. The calculation of the final score follows a hierarchical weighted-aggregation structure. First, a partial score S_k is obtained for each category k as the weighted average of its criterion-level scores, as expressed in Eq. (2):

$$\mathrm{S_k} = \frac{\sum (\mathrm{S_i} \cdot \omega_\mathrm{i})}{\sum \omega_\mathrm{i}} \tag{2}$$

where S_i represents the score of criterion i within category k, and ω_i is the weight assigned to that criterion. The overall Reparability Index is then computed as a weighted combination of the category-level scores following Eq. (3):

$$\mathrm{RI} = \frac{\sum \mathrm{S_K}\ \mathrm{W_K}}{\sum \mathrm{W_K}} \tag{3}$$

with W_k denoting the weight of each category k. This formulation makes explicit that the RI is a weighted average across all analytical blocks, integrating both the hierarchical structure of the method and the relative importance of its components. The indicator reflects the circular-economy strategy of slowing resource loops, as it supports product lifetime extension through repair-oriented design.

- Recoverability and Recoverability Rates (Rcyc and Rcov): Measures the proportion (by weight) of a product that can be technically recycled (Rcyc) or valorised (Rcov) through either material recycling or energy recovery, based on established industrial processes. While Rcyc reflects the material fraction compatible with current recycling technologies, Rcov accounts for additional non-recyclable but energetically recoverable fractions, offering a more comprehensive measure of EoL valorisation potential (AENOR, 2020b). Both indicators are calculated by weighting each material stream according to its mass (m_k) and its recyclability or recoverability factor ($Rcyc_k$ or $Rcov_k$), relative to the total product mass (m_{tot}), as shown in Eq. (4) and Eq. (5). These factors represent the proportion of each material that can be recycled or recovered under current industrial treatment conditions. Both indicators are aligned with the closing strategy of the circular economy and are defined under the EN 45555 standard (AENOR, 2020b).

$$\mathrm{Rcyc} = \frac{\sum_{k=1}^{n} m_k \cdot \mathrm{Rcyc}_k}{m_{tot}} \text{ x } 100 \tag{4}$$

$$\mathrm{Rcov} = \frac{\sum_{k=1}^{n} m_k \cdot \mathrm{Rcov}_k}{m_{tot}} \text{ x } 100 \tag{5}$$

Together, these indicators provide a multidimensional evaluation of the product circularity performance: PCI offers an integrated perspective, RI focuses on life extension, and Rcyc and Rcov quantify the material recirculation at EoL.

The calculations drew from primary data obtained from the physical disassembly and BOM of each PEC (Section 2.2.1), and secondary data from academic sources. Each indicator was calculated using a custom Excel-based tool developed for this study, which integrates official methodologies and formulas. The tool, input data, and calculation sheets are available in S3 of the SF.

Table 3

Summary of disassembly and component-related parameters for PEC1 and PEC2. Acronyms: PEC (Power Electronic Converter), PCB (printed circuit board).

Parameter	PEC1 (15 kW)	PEC2 (18.5 kW)
Disassembly process		
Disassembly time	10min 36s	22min 35s
N° disassembly steps	37	78
N° fasteners	19 screw and 10 clips	47 screw and 17 clips
N° of different fastener types	3 (TOR (10,20), clips)	4 (TOR (10,20), Allen, clips)
N° tools	4	5
N° distinct elements (modules)	13	15
N° distinct components	29	67
N° PCB	4	5
Desoldering process		
Desoldering time	71min	88min
N° different electronic component	17	17
N° electrolytic capacitors	19	14
N° capacitors	221	490
N° resistors	335	926
N° transistors	127	91
N° diodes	50	51
N° inductors	6	12
N° sensors	2	3
N° relays	4	4
N° varistors	6	1
N° integrated circuit	77	190
N° connectors	14	16
N° power modules	1	1

3. Results and discussion

3.1. PECs structural configuration and disassembly process

Key quantitative metrics collected during the manual disassembly and desoldering of both PECs are presented in Table 3. The values include total operation times, number and types of fasteners, tools employed, components extracted, and electronic components identified. Full procedural details are provided in S2 of the SF.

Disassembly performance varied significantly between the devices. The modular architecture and intuitive layout of PEC1 allowed disassembly in 10 min and 37 steps, involving 29 fasteners and 4 tools. Snap fits dominated, with minimal tool variation and straightforward access to key components. In contrast, PEC2 required 78 steps, 22 min, 64 fasteners, and 5 separate tools, reflecting a denser internal configuration and greater mechanical complexity.

The disassembly sequence in Fig. 2 (Section 2.1) reveals that PEC1 followed a relatively linear and intuitive dismantling sequence, with minimal obstruction between modules. In contrast, there were several critical points in PEC2 (highlighted in red), where component extraction was delayed by dense architecture and complex fastening strategies. For instance, the control block required over 220 s (s) and five snapfit interactions; the inductance block involved socket, Torx, and Allen tools across a multi-step sequence totalling more than 180 s; and the communication board zone included tightly packed, interconnected PCBs with hidden snapfits that required two operators for safe removal. These factors (time, fasteners, tool diversity, material composition, and accessibility) emerged as the principal dimensions conditioning dismantlability, providing concrete guidelines for improving circular design.

These structural differences were also reflected in desoldering times: 71 min for PEC1 versus 88 min for PEC2. PEC2 contained more identified components (67 vs. 29), more distinct modules (15 vs. 13), and higher electronic density. This was evident in the desoldering metrics: PEC2 included 490 capacitors, 926 resistors, and 190 integrated circuits, nearly triple the number in PEC1, all of which increase processing time and hinder manual recovery. Although both PECs featured high-value elements such as inductors and power modules, their accessibility and separability differed considerably. The higher density of components, use of double-sided PCBs, and presence of high thermal mass areas made PEC2 more demanding to process. These barriers hinder not only recycling operations but also repair and upgrade interventions during the use phase, limiting circular strategies.

In addition, material heterogeneity, particularly in PEC2, further limited circular potential. Multi-material joints, such as encapsulated inductors or resin-sealed power modules, extended processing time and complicated EoL separation. These design choices compromise recyclability and hinder interventions for repair or reuse during the use phase.

These disassembly patterns are consistent with findings reported in recent literature. Vanegas et al. (2018) show that disassembly time in electronic products is often dominated by tasks such as identification, positioning and tool changes—rather than by the detachment itself—particularly when accessibility is limited or fasteners are heterogeneous. This behaviour mirrors the critical points observed in PEC2, where hidden snap-fits, obstructed access and multiple tool changes substantially extended operation times. Similar constraints are reported by Romano et al., 2024, who demonstrate that power electronic systems combine dense PCB integration, encapsulated components and diverse fastening strategies that hinder both disassembly and desoldering operations. Finally, Fang et al. (2023) highlight that design decisions in PECs are frequently driven by functional compactness rather than circularity, which results in architectures that challenge EoL interventions.

Moreover, the critical disassembly bottlenecks identified in this analysis have direct economic implications that help explain current end-of-life treatment practices for PECs. In most industrial recycling schemes, complex and highly integrated electronic products are not manually dismantled, but instead processed through shredding-based routes, as manual disassembly is generally constrained by high labour costs and limited economic viability (Choux et al., 2024). This is particularly the case for power electronic equipment, where resin encapsulation, dense component integration and irreversible joining techniques substantially increase disassembly effort while reducing the recoverable value of individual components.

As a result, prevailing recycling practices prioritise bulk material recovery over component-level reuse, often leading to losses in material quality and functional value (Goyal and Gupta, 2024). In this context, the disassembly times and bottlenecks identified in this study should be interpreted not only as technical indicators of dismantlability, but also as proxies for the economic barriers that currently limit the implementation of higher-value circular strategies for PECs.

3.2. PECs circularity performance

Fig. 4 summarises the circularity results, enabling a comparative interpretation of the PECs in terms of material circularity, reparability, and recovery potential (Section 2.2.2). Results are presented normalized on a scale from 0 to 1. Full disaggregated results for each indicator are provided in S3 of the SF.

3.2.1. Product circularity index

Both PECs reported similarly low PCI values: 0.21 (PEC1) and 0.2 (PEC2). This indicates that less than a quarter of the material value is retained throughout the product lifecycle. These values are far from the ideal performance (PCI = 1). As a recirculation-related indicator, they fall significantly below the minimum material recovery (55%) and overall recovery (75%) rates required by the WEEE Directive (European Commission, 2012) for small electronic equipment, specifically for those classified as equipment for the generation of electric currents. This clearly reflects the low circularity of the products.

In both cases, the proportion of materials flowing circularly in the product system is limited, resulting in high dependence on virgin resources and restricted EoL material recovery capability. The root causes of this limited circularity can be better understood by analysing the three key variables that define the PCI, as described in Section 2.2.2.

The first PCI variable concerns the use of secondary materials. Both devices incorporate recycled materials, such as aluminium and copper, used in structural components like chassis, heatsinks, and inductors. However, the proportion of recycled content is moderate (32% in PEC1, 40% in PEC2), and their integration limits recovery. For example, the copper in inductors is coated, encapsulated, and bonded to the core, while aluminium heatsinks are mechanically integrated with other parts. Without design strategies for recovery, these recycled materials contribute little to the PCI.

The second variable, component reuse, scored near zero for both devices. Although passive components could theoretically be reused, the lack of modularity, standard connectors, and accessible interfaces prevents their extraction without damage. This effectively eliminates reuse opportunities, significantly penalising the PCI score.

The third variable, material recoverability at EoL, is also severely restricted by the design. Valuable materials like copper can only be accessed through destructive processes such as cutting or shredding, which are inefficient and unfeasible at scale. This limitation mirrors broader issues in e-waste management, where high theoretical recyclability is rarely realised under real operating and industrial recovery conditions (European Commission, 2012).

Hence, the low PCI values reflect a significant dependence on virgin materials and architectures that hinder circularity. These findings reinforce the need for ecodesign strategies that prioritise both the use of quality secondary materials and their incorporation into easily disassembled and recoverable configurations. These PCI results are consistent with previous studies on product-level circularity. Bracquené et al. (2020) emphasise that the PCI is particularly sensitive to component reuse and to the ability of a product system to return high-quality materials to the supply chain, two conditions that rarely hold in complex electronic equipment. Their analysis shows that even when recycled metals are present, their contribution to circularity remains limited if recovery requires destructive processes or if materials are embedded in multi-material assemblies. This was precisely the case for inductors and aluminium heatsinks in the PECs analysed in the present paper. Furthermore, the restricted recoverability observed here mirrors the broader gap between theoretical recyclability and real material recovery documented for WEEE systems, where only a fraction of valuable metals is actually recovered due to material losses during separation and recycling inefficiencies (European Commission, 2012). These findings confirm that low PCI values in PECs arise from both limited secondary material content and design configurations that hinder reuse and prevent effective end-of-life valorisation.

Furthermore, these results show that the low PCI values are mainly driven by limitations in upstream material sourcing and reuse potential, rather than by improvements in end-of-life recycling efficiencies. A scenario-based sensitivity analysis (SA) confirmed this trend: increasing the recycled content of the main structural metals raised the PCI to 0.61 and 0.55, while improving the potential for component reuse led to a PCI of 0.43 and 0.40. In contrast, enhancing the end-of-life recycling efficiency produced only a marginal increase (PCI = 0.25 and 0.23). These findings reinforce the importance of prioritising design strategies that facilitate material reuse and integration of high-quality secondary materials as the most effective levers for improving product circularity. Table 4 summarises the PCI sensitivity results; detailed scenario calculations are available in S3 of the SF.

3.2.2. Reparability Index

The results show a score of 0.62 for PEC1 and 0.64 for PEC2, both falling within the “good” repairability range [0.61–0.8], as defined by the AGEC (Ministry of Ecological Transition, 2022). These scores reflect the capacity of the two PECs to be repaired at the assembly level, replacing entire PCBs, rather than at the level of individual PCB components.

In PEC1, the components with the longest disassembly times, the power board and the horizontal control PCB, also exhibited the lowest repairability scores (5.95 and 6.07). This stems from poor performance in the “disassembly & reassembly”, “spare parts” and “product reconditioning” criteria. Together, these components account for nearly half of the total disassembly time, mainly because of obstructive fasteners, limited accessibility, and component fragility. This correlation between disassembly complexity and repair challenges supports the RI score obtained for PEC1.

In contrast, PEC2 presented a more nuanced situation. As shown in Fig. 3, the control block (228s), communication board 2 (197s), and inductances (183s) required the most time to disassemble. However, these were not the main contributors to the RI score. Instead, the capacitor bus (5.96) and the electronic power board (6.07) were the most penalising components. Their mechanical and functional interdependence means that one must be disassembled to repair or replace the other, preventing selective interventions and increasing the likelihood of unnecessary part replacements.

These results indicate that the RI captures several product-level

Table 4
Scenario-based sensitivity analysis of the PCI for PEC1 and PEC2.

PCI Scenario	PEC 1	PEC 2
Baseline	0.21	0.20
SA1: Higher recycled content in structural metals	0.61	0.55
SA2: Higher reuse fraction of key components	0.43	0.40
SA3: Improved recycling efficiency at EoL	0.25	0.23

criteria beyond disassembly alone. In both PECs, several categories scored in the moderate-to-low range, highlighting systemic areas for improvement. Notably, the “product reconditioning” category scored the lowest in both cases (0.4), indicating limited potential to reuse or improve internal components. Similarly, the “product design” and “after-sales strategy” categories revealed design flaws such as the use of non-standard fasteners, lack of repair documentation, or limited availability of spare parts. These limitations were more pronounced in PEC1, contributing to its lower overall score.

These RI outcomes are in agreement with broader repairability patterns described in recent research. Current studies emphasise that repair potential in electronic equipment is primarily limited by architectural complexity, internal interdependencies and insufficient diagnostic or repair information, rather than by isolated component features (Ruiz-Pastor and Mesa, 2023; Romano et al., 2023; Formentini et al., 2025). This aligns with the multi-criteria perspective adopted in emerging EU frameworks such as the ESPR (European Commission, 2024) and the recent JRC proposal (Spiliotopoulos and Beltran, 2025), which highlight that repairability depends on how product architecture enables (or restricts) selective interventions throughout the lifecycle. Both PECs achieved “good” repairability scores, yet they still exhibit several structural barriers. This illustrates a wider trend identified in the literature: products can be repairable in principle at the subsystem level but remain constrained by design choices that limit modular upgrades, component-level access and the availability of technical support.

3.2.3. Recycling and recoverability index

The results obtained reveal modest differences in the EoL circularity potential between the two PECs. The PEC1 achieved 0.21 in both indicators, while PEC2 scored lower: 0.16 and 0.17, respectively.

These results show limited potential to close the material cycle in both products, although PEC1 performs comparatively better. This gap stems partly from the differences observed during disassembly. PEC1 presents a simpler, more accessible architecture, with modular connections and a higher proportion of easily separable metals. These features allowed a higher fraction of its total mass to be recovered through conventional recycling or energy recovery routes.

In contrast, PEC2 prioritises compactness of design, incorporating for example double-sided printed circuit boards, which complicates the separation of components and materials and increases the complexity of material streams. As a result, both the effective input of recycled materials and the possibility of recovering their EoL value are reduced.

Ultimately, these findings show that maximising recoverable circular value requires not only technically recyclable materials but also product architecture that allows access, separation, and sorting without loss of quality or functionality. Hence, the complementarity between robust initial design and effective EoL measures is key to improving levels of real circularity (Romano et al., 2023).

These low Rcyc values and only moderate Rcov levels reflect recent evidence on the technical recyclability of EEE. Hämmer and Wambach (2024) show that, at each treatment stage, products with high electronic density and complex architectures tend to generate substantial “lost” fractions, even when they contain high-value materials such as copper or aluminium. This occurs because separation without degradation or dispersion is often impossible. Similarly, Charles et al. (2020) demonstrate that, although many electronic components contain valuable metals such as gold, their real recovery potential is limited. Existing industrial infrastructure can efficiently recover only a small share of these materials, while the remainder is either permanently dissipated in pyrometallurgical processes or diluted into heterogeneous low-value fractions. This evidence aligns closely with the behaviour observed in both converters, where dense PCBs, encapsulated inductors and multi-material joints restrict both recyclability (Rcyc) and the potential to retain value at end-of-life (Rcov), despite the presence of recoverable metals.

3.3. Integrated analysis and circular design guidelines for PECs

Neither PEC1 nor PEC2 was conceived with circularity as a design priority. The marginal differences between their circularity indicators suggest no substantial evolution in design strategy between generations. This continuity reflects a design logic driven by functionality and performance, with little consideration of resource efficiency or EoL strategies (Fang et al., 2023).

This misalignment exemplifies a broader disconnection between product functionality and resource recovery potential, a recurring issue in PEs (Ruiz de Azua Lahidalga et al., 2025). This gap contributes to the environmental impacts of EEE, notably through the irreversible loss of critical materials (Köpman and Majava, 2024)

The disassembly and desoldering processes confirmed that current design practices, such as resin encapsulation, permanent bonding, and complex material assemblies, limit component reuse and material recovery, while also compromising the quality of secondary raw materials.

Furthermore, the applied circularity indicators capture only partial dimensions: PCI quantifies material circular flows, Rcyc and Rcov address EoL recovery potential, and RI reflects reparability. Yet none offers a systemic view of circularity (Picatoste et al., 2024). This highlights the need for integrated assessment frameworks that connect life cycle stages with value retention, a gap particularly evident in PE.

Advancing the circularity of PECs therefore requires a systemic rethinking of design logic, embedding circular principles from product architecture and material selection through to EoL strategies. When the design limitations identified at product level are extrapolated to the scale of the European PEC market, the urgency of this shift becomes evident. This is especially urgent considering the European PEC market reached 17.535 billion dollar in 2024 (over 30% of global revenues) and is projected to grow at 7.3% annually until 2031 (Kalyani Raje, 2025). Without a shift towards circular design approaches, the environmental footprint of this sector will continue to escalate.

Although the limited number of case studies represents a constraint in terms of statistical generalisation, the challenges identified in the analysed power electronic converters extend beyond these specific products and reflect broader limitations affecting complex EEE. In particular, the high material density and architecture observed in the analysed PECs highlight the systemic relevance of certain critical materials. PECs and other complex EEE rely on material-intensive designs that combine power semiconductors, printed circuit boards, passive components, and metallic structural elements, resulting in high material density and complex assembly configurations. Among these materials, copper plays a fundamental role in power tracks and planes, windings, transformers, and busbars, making it one of the main contributors to both the material footprint and the end-of-life value of such equipment. Current projections indicate that final copper demand could increase by a factor of 2.5 between 2015 and 2050, reaching approximately 62 million tonnes, while life-cycle-related copper emissions could rise from 0.3% to 2.7% of the global carbon budget by 2050 (Watari et al., 2022). These trends highlight that improving material efficiency, recoverability, and circularity in electrical and electronic equipment (including PECs) is not a marginal design optimisation, but a systemic requirement. Consequently, the circularity-related design challenges identified in this study are not only relevant for the PECs, but are also significant for other categories of high-power and material-intensive EEE, reinforcing the relevance and transferability of the results beyond the specific case studies considered.

The qualitative analysis conducted with experts is directly corroborated by the results of the quantitative indicators. During the disassembly and desoldering processes, experts identified structural barriers that hinder circularity, such as the absence of secondary materials, high material heterogeneity, irreversible joining techniques, extreme design compactness, and limited accessibility to critical components. These issues were consistently reflected in the PCI, RI, Rcyc and Rcov values. As explained by the experts, the wide variety of materials and the use of double-sided PCBs complicate separation and sorting operations, which aligns with the low recyclability and recoverability scores. Likewise, the lack of modularity, the high component density, and the presence of hidden fasteners penalise practical repairability, as also captured in the RI results. The PCI further confirms the near-absence of component reuse and the minimal incorporation of secondary materials. This was consistent with the expert assessments, indicating that in semiconductors, magnetics and capacitors, current design practices do not allow meaningful recovery or reuse. Hence, the alignment between qualitative observations and quantitative results both validates the diagnostic and clearly indicates which design dimensions must be transformed to achieve higher levels of circularity.

Building on this convergence, the study proposes a set of eight circular design guidelines specifically tailored to PECs. These guidelines directly address the design limitations identified through our integrated analysis and are grounded in expert knowledge gathered during the disassembly and desoldering processes, following the criteria established by Ruiz de Azua Lahidalga et al. (2025). They offer operational, evidence-based recommendations aimed at embedding circularity principles from the earliest stages of product development.

To operationalise these guidelines, it is essential first to define the circular strategies to be prioritised, such as extending product lifespan, enhancing reparability, or improving material recovery. Clear specifications must then be established to translate these strategies into concrete design requirements, ensuring that circularity is integrated holistically throughout the product life cycle.

1. Facilitate selective and non-destructive disassembly:
   a. Avoid irreversible joining techniques such as potting with silicone or adhesives.
   b. Ensure that fixing points are clearly visible and marked on the internal structure.
   c. Relocate failure-prone components, such as capacitors and power modules, to peripheral areas or easily removable subassemblies to facilitate access and replacement
2. Enhance modularity and standardisation to enhance repairability
   a. Separate control and power boards with detachable, testable interfaces.
   b. Design control units with standard protocols and voltages for reuse across PEC power classes.
3. Enable reuse and refurbishment of durable components
   a. Design inductors and heatsinks with mounting systems for safe extraction and reconditioning.
   b. Avoid tight integration of components (e.g. fused SMDs on both PCB sides) that hinders testing and reuse.
4. Prioritise thermomechanical compatibility in material selection
   a. Use materials with similar coefficients of thermal expansion in multilayer assemblies.
   b. Apply sintering and advanced interconnections to reduce failures and enhance durability.
5. Improve component traceability and monitoring
   a. Embed identification codes or digital twins on priority components for lifecycle monitoring.
   b. Use sensorised fuses, solid-state relays, or thermal monitors to support preventive maintenance.
6. Reduce functional over-integration to enable recovery
   a. Minimise double-sided PCBs or isolate recoverable materials in accessible zones.
   b. Avoid full-function integration (e.g., AC/DC + DC/AC stages in a single silicon module).
7. Reduce material heterogeneity and enhance recoverability
   a. Use metals with higher proportion of recycled content in structural parts; avoid mixed-material.
   b. Replace low-value resins or plastics with recyclable polymers.
8. Integrate circularity indicators and expert feedback into design
   a. Apply tools such as PCI, RI, Rcyc, Rcov, at the design stage to guide improvements.
   b. Validate circularity design via disassembly trials and expert reviews, incorporating feedback loops.

The analysis confirms that the limited circularity of PECs stems from a functionality-driven design approach that overlooks resource efficiency and EoL strategies. Addressing this challenge requires a systemic approach encompassing the full product lifecycle, from material sourcing and architectural design to reparability, recyclability, recoverability, and reintegration. The guidelines proposed in this study target these gaps by enhancing modularity, disassemblability, traceability, and material recoverability. Implementing such strategies will be key to aligning PEC development with CE principles, especially in a market poised for rapid growth.

4. Limitations and future lines

Five major limitations were identified: first, the disassembly and desoldering times may be overestimated, since the operators were not previously familiar with the optimal sequence for intervening in each converter. Therefore, these values should not be interpreted as standardised operational times but rather as empirical references useful for identifying bottlenecks and design-related barriers. Second, both the measured times and weights exhibit the variability inherent to experimental processes based on manual operations and the handling of complex subassemblies. Third, although the BOM was based on primary data extracted directly from the units, some assumptions were needed to calculate the circularity indicators, as no manufacturer-specific information or consolidated sectoral data were available. The fourth limitation concerns the indicators themselves: the circularity metrics applied in this study were not conceived specifically for power electronic converters, which could lead to a lack of completeness in the analysis. However, this limitation was partially overcome with the use of 4 different circularity indicators in the analysis. Finally, the indicators applied capture relevant dimensions of circularity but do not constitute a comprehensive environmental assessment of the converters, as trade-offs involving energy efficiency, manufacturing impacts, or use-phase emissions are not addressed.

These limitations highlight four complementary research directions that should guide future work. First, the development of a sector-specific circularity indicator for the PE industry, capable of addressing the unique design and end-of-life challenges associated with this type of product.

Second, advancing the integration of circularity indicators with LCA is essential to capture the environmental trade-offs associated with design changes, material flows and energy efficiency. While CE–LCA integration has been explored in other sectors (Khadim et al., 2025), no equivalent methodological development exists for PECs. Establishing such a framework would establish a more holistic evaluation of circular design interventions.

Third, developing decision-support tools tailored to the PEC sector that integrate design-for-circularity principles, circularity metrics, and LCA outcomes. These tools will be essential to guide sustainable innovation, helping PECs align with EU sustainability objectives and reach the circularity maturity already seen in sectors like rail and wind power. Without this progress, the PEC market risks regulatory penalties and resource inefficiencies that threaten the industrial resilience of Europe.

Finally, future research should extend this empirical approach to new generations of PECs, including converters explicitly developed with circularity principles or more recent architectures. Applying the same disassembly-based analytical framework to these products will be crucial to assess whether emerging circular design practices effectively overcome the structural barriers identified in current mainstream PECs.

5. Conclusions

This study addressed a critical gap in circularity assessment approaches applied to PECs, namely the lack of integrated, multidimensional evaluations based on real products. Through the complete disassembly and desoldering of two PECs, a detailed BOM was developed, enabling precise material characterisation and the calculation of four quantitative indicators (PCI, RI, Rcyc, Rcov). Combined with a qualitative, expert-informed analysis, this approach identified design practices that hinder circularity in PECs and proposed specific design and LCM strategies for improvement.

Disassembly revealed critical barriers, including irreversible joints, tight component interdependencies, and compact layouts. These aspects contradict key CE principles, such as design for disassembly and material separability, and limit environmental sustainability goals like reducing hazardous material dispersion or enabling component reuse. The circularity assessment confirmed these limitations: both PECs scored low in PCI (<0.21), recyclability and recoverability rates (<0.21), and moderate reparability (~ 0.63). These findings align with broader challenges in the EEE sector, where circularity assessments are often limited to theoretical approaches, with fewer studies validating these insights through comprehensive physical product analysis. While sectors like consumer electronics have made progress, empirical studies on complex products such as PECs remain notably scarce.

However, these constraints are not intrinsic to PE but stem from historical design choices. Our results highlight pathways to reconcile functional performance with circularity: enhanced modularity and material standardisation. Such strategies align with ongoing European efforts to standardise reparability and circularity metrics under the ESPR framework.

CRediT authorship contribution statement

Irati Ruiz de Azua Lahidalga: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Christian Wandji:** Writing – original draft, Investigation, Formal analysis. **Aitor Picatoste:** Supervision, Formal analysis, Conceptualization. **Daniel Justel:** Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Iosu Aizpuru:** Validation, Formal analysis. **Andreas Riel:** Writing – review & editing, Validation, Supervision. **Helmi Ben Rejeb:** Writing – review & editing, Validation, Supervision. **Joan Manuel F. Mendoza:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to improve language and readability. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received financial support from the European Union#8217; s Horizon Europe Research and Innovation programme under Grant Agreement No.101075496 (next generation modular SiC-based advanced power electronics converters for enhanced renewables integration into the GRID (SiC4GRID) project). The document reflects only the view of authors'; the Agency is not responsible for any use that may be made of the information it contains.

This work has received financial support from BASQUE CIRCULAR HUB, the public environmental management company of the Basque Government (IHOBE), through the HIREKIN centre in Arrasate.

The authors of this research would like to thank all the participants involved in this study for their involvement and help during the interviews. Special thanks are extended to Ibon Ajuria for conducting the desoldering and disassembly processes, and to Jose Maria Canales for sharing his expertise in power electronics.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147774.

Data availability

Data will be made available on request.

References

AENOR, 2021. UNE-EN 45552 - general method for the assessment of the durability of energy-related products [WWW Document]. URL. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0065602, 5.28.24.

AENOR, 2020a. UNE-EN 45554 - general methods for the assessment of the ability to repair, reuse and upgrade energy-related products [WWW Document]. URL. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0064909, 5.28.24.

AENOR, 2020b. UNE-EN 45555 - general methods for assessing the recyclability and recoverability of energy-related products [WWW Document]. URL. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0063786, 5.28.24.

AENOR, 2019. UNE-EN 45558 - General method to declare the use of critical raw materials in energy-related products [WWW Document]. URL. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0062616, 5.28.24.

Alcalde-Calonge, A., Sáez-Martínez, F.J., Ruiz-Palomino, P., 2022. Evolution of research on circular economy and related trends and topics. A thirteen-year review. Ecol. Inform. 70, 101716. https://doi.org/10.1016/J.ECOINF.2022.101716.

Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: method and application. J. Clean. Prod. 74, 62–73. https://doi.org/10.1016/J.JCLEPRO.2014.03.049.

Baudais, B., Ben Ahmed, H., Jodin, G., Degrenne, N., Lefebvre, S., 2023. Life cycle assessment of a 150 kW electronic power inverter. Energies 16. https://doi.org/10.3390/EN16052192, 2023 Page 2192 16, 2192.

Blaabjerg, F., Wang, H., Davari, P., Qu, X., Zare, F., 2017. Energy saving and efficient energy use by power electronic systems. Lect. Notes Eng. 37, 1–14. https://doi.org/10.1007/978-3-319-49875-1_1.

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resour. Conserv. Recycl. 154, 104608. https://doi.org/10.1016/J.RESCONREC.2019.104608.

Charles, R.G., Douglas, P., Dowling, M., Liversage, G., Davies, M.L., 2020. Towards Increased Recovery of Critical Raw Materials from WEEE– evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. Resour. Conserv. Recycl. 161, 104923. https://doi.org/10.1016/J.RESCONREC.2020.104923.

Choux, M., Pripp, S.W., Kvalnes, F., Hellström, M., 2024. To shred or to disassemble – a techno-economic assessment of automated disassembly vs. shredding in lithium-ion battery module recycling. Resour. Conserv. Recycl. 203, 107430. https://doi.org/10.1016/J.RESCONREC.2024.107430.

Control Techniques, 2014. Unidrive M700 [WWW Document. https://acim.nidec.com/es-ES/drives/control-techniques/Products/High-Performance-Drives/Unidrive-M700, 6.20.25.

Control Techniques, 2011. Unidrive SP [WWW Document. https://acim.nidec.com/es-ES/drives/control-techniques/Downloads/User-Guides-and-Software/Unidrive-SP-Freestanding, 6.20.25.

European Commission, 2025. Electric motors - European commission [WWW Document]. URL. https://energy-efficient-products.ec.europa.eu/product-list/electric-motors_en, 11.21.25.

European Commission, 2024. Ecodesign for sustainable products regulation - european commission [WWW Document]. URL. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en, 10.7.24.

European Commission, 2021. Regulation - 2021/1119 - EN - eur-lex [WWW Document]. URL. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119, 7.3.25.

European Commission, 2020a. Circular economy action plan - european commission [WWW Document]. URL. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en, 3.19.24.

European Commission, 2020b. Circular Electronics Initiative [WWW Document]. URL. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-circular-electronics, 3.18.25.

European Commission, 2012. Directive 2012/19/EU WEEE [WWW Document]. URL. https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=celex%3A32012L0019, 5.16.24.

European Commission, 2006. REACH regulation - no 1907/2006 [WWW Document]. URL. https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en, 3.15.24.

Fang, L., Lefranc, P., Rio, M., 2023. Barriers for eco-designing circular Power Electronics Converters. Procedia CIRP 116, 287–292. In: https://doi.org/10.1016/J.PROCIR.2023.02.049.

Fang, L., Romano, T.T., Rio, M., Mélot, J., Crébier, J.C., 2024. Enhancing sustainability in power electronics through regulations and standards: a literature review. Sustainability 16. https://doi.org/10.3390/SU16031042, 2024 Page 1042 16, 1042.

Formentini, G., Prioli, J.P., Ko, J., Hapuwatte, B., Ferrero, V., Badurdeen, F., Rickli, J.L., Ramanujan, D., 2025. A review of disassembly systems for circular product design. J. Clean. Prod. 506, 145459. https://doi.org/10.1016/J.JCLEPRO.2025.145459.

Goyal, S., Gupta, S., 2024. A comprehensive review of current techniques, issues, and technological advancements in sustainable E-waste management. E-Prime - Advances in Electrical Engineering, Electronics and Energy 9, 100702. https://doi.org/10.1016/J.PRIME.2024.100702.

Hämmer, M., Wambach, K., 2024. Methodology and Database for the Quantification of the Technical Recyclability of Electrical and Electronical Equipment Demonstrated on a Smartphone Case Study. Sustainability (Switzerland) 16, 8726. https://doi.org/10.3390/SU16198726/S1.

Herrmann, H., Modarres, J.W., Habibollahi, H., Abadi, N., Herrmann, J.W., Modarres, M., 2023. Measuring and indexing the durability of electrical and electronic equipment. Sustainability 15 (14386 15), 14386. https://doi.org/10.3390/SU151914386, 2023.

Idoko, Idoko Peter, Ijiga, Onuh Matthew, Akoh, Omachile, Agbo, Daniel Obekpa, Ugbane, Solomon Ileanaju, Umama, Esther Ene, 2024. Empowering sustainable power generation: the vital role of power electronics in California's renewable energy transformation. World Journal of Advanced Engineering Technology and Sciences 11, 274–293. https://doi.org/10.30574/WJAETS.2024.11.1.0058.

IEA, 2025. International energy agency (IEA). CO2 Emissions – Global Energy Review 2025 – Analysis - IEA [WWW Document]. URL. https://www.iea.org/reports/global-energy-review-2025/co2-emissions?utm_source=chatgpt.com, 6.12.25.

Joint Research Centre, 2025. Joint Research Centre [WWW Document]. URL. https://commission.europa.eu/about/departments-and-executive-agencies/joint-research-centre_en, 7.2.25.

Kalyani Raje, 2025. Europe power converters and inverters industry report 2025 [WWW Document]. URL. https://www.cognitivemarketresearch.com/regional-analysis/europe-power-converters-and-inverters-market-report?utm_source=chatgpt.com, 5.5.25.

Khadim, N., Agliata, R., Han, Q., Mollo, L., 2025. From circularity to sustainability: advancing the whole building circularity indicator with life cycle assessment (WBCI-LCA). Build. Environ. 269, 112413. https://doi.org/10.1016/J.BUILDENV.2024.112413.

Köpman, J., Majava, J., 2024. The role of product design in advancing the circular economy of electric and electronic equipment. Resources, Conservation & Recycling Advances 21, 200207. https://doi.org/10.1016/J.RCRADV.2024.200207.

Mahmood, M., Chowdhury, P., Yeassin, R., Hasan, M., Ahmad, T., Chowdhury, N.U.R., 2024. Impacts of digitalization on smart grids, renewable energy, and demand response: an updated review of current applications. Energy Convers. Manag. X 24. https://doi.org/10.1016/J.ECMX.2024.100790.

Marati, N., Ahammed, S., Karuppazaghi, K., Vaithilingam, B., Biswal, G.R., Bobba, P.B., Padmanaban, S., Chenniappan, S., 2022. Recent advancements in power electronics for modern power systems-comprehensive review on DC-link capacitors concerning power density maximization in power converters. Artificial Intelligence-based Smart Power Systems 65–98. https://doi.org/10.1002/9781119893998.CH4.

Mendoza, J.M.F., Gallego-Schmid, A., Velenturf, A.P.M., Jensen, P.D., Ibarra, D., 2022. Circular economy business models and technology management strategies in the wind industry: sustainability potential, industrial challenges and opportunities. Renew. Sustain. Energy Rev. 163, 112523. https://doi.org/10.1016/J.RSER.2022.112523.

Mendoza, J.M.F., Sharmina, M., Gallego-Schmid, A., Heyes, G., Azapagic, A., 2017. Integrating Backcasting and Eco-Design for the Circular Economy: The BECE Framework. J. Ind. Ecol. 21, 526–544. https://doi.org/10.1111/JIEC.12590.

Ministry of Ecological Transition, 2022. Instructions Manual for the Display and the Calculation of the Repairability Index of Electrical and Electronic Equipments. France.

Musil, F., Harringer, C., Hiesmayr, A., Schönmayr, D., 2023. How life cycle analyses are influencing power electronics converter design. PCIM Europe Conference Proceedings, pp. 1–9. https://doi.org/10.30420/566091368.

Nidec Corporation, 2025. Control techniques | nidec drives [WWW Document]. URL. https://acim.nidec.com/en-US/drives/control-techniques, 7.1.25.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372. https://doi.org/10.1136/BMJ.N71.

Picatoste, A., Schulz-Mönninghoff, M., Niero, M., Justel, D., Mendoza, J.M.F., 2024. Comparing the circularity and life cycle environmental performance of batteries for electric vehicles. Resour. Conserv. Recycl. 210. https://doi.org/10.1016/J.RESCONREC.2024.107833.

Ristić, L., 2024. Energy optimization of industrial processes through advanced use of controlled electrical drives and power electronics. IEEP2024 : zbornik radova 340–370. https://doi.org/10.46793/IEEP24.340R.

Romano, T.T., Alix, T., Lembeye, Y., Perry, N., Crebier, J.C., 2023. Towards circular power electronics in the perspective of modularity. In: Procedia CIRP. Elsevier B.V, pp. 588–593. https://doi.org/10.1016/j.procir.2023.02.099.

Romano, T.T., Fang, L., Alix, T., Rio, M., Mélot, J., Serrano, F., Lefranc, P., Lembeye, Y., Perry, N., Crébier, J.C., 2024. Disassemblability assessment of power electronic converters for improved circularity. Sustainability 16. https://doi.org/10.3390/su16114712.

Ruiz de Azua Lahidalga, I., Mendiburu-Valor, E., Justel, D., Mendoza, J.M.F., 2025. Circular electronics: exploring the applicability of circularity and environmental sustainability criteria in power electronics. Results in Engineering 26. https://doi.org/10.1016/J.RINENG.2025.105199.

Ruiz-Pastor, L., Mesa, J.A., 2023. Proposing an integrated indicator to measure product repairability. J. Clean. Prod. 395, 136434. https://doi.org/10.1016/J.JCLEPRO.2023.136434.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/J.JCLEPRO.2018.10.014.

Sangwongwanich, A., Stroe, D.I., Mi, C., Blaabjerg, F., 2024. Sustainability of power electronics and batteries: a circular economy approach. IEEE Power Electronics Magazine 11, 39–46. https://doi.org/10.1109/MPEL.2024.3356248.

Spiliotopoulos, C., Beltran, B., 2025. Reparability scoring system-product relevance scoping study. https://doi.org/10.2760/4556439.

Tang, Z., Yang, Y., Blaabjerg, F., 2022. Power electronics: the enabling technology for renewable energy integration. CSEE J. Power Energy Syst. 8, 39–52. https://doi.org/10.17775/CSEEJPES.2021.02850.

United Nations, 2015. The 17 goals. Sustain. Dev. [WWW Document]. URL https://sdgs.un.org/goals 4.29.24.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. 135, 323–334. https://doi.org/10.1016/J.RESCONREC.2017.06.022.

Vauche, L., Guillemaud, G., Lopes Barbosa, J.C., Di Cioccio, L., 2024. Cradle-to-Gate life cycle assessment (LCA) of GaN power semiconductor device. Sustainability 16. https://doi.org/10.3390/su16020901.

Wandji, C., Rejeb, H. Ben, Riel, A., Zwolinski, P., Zuanna, C.D., 2023. Leveraging circularity through repair standards: a comparison of methods for assessing product reparability for extended use on mechanical products. Proced. CIRP 120, 273–278. https://doi.org/10.1016/J.PROCIR.2023.08.049.

Wang, Q., Huang, N., Chen, Z., Chen, X., Cai, H., Wu, Y., 2023. Environmental data and facts in the semiconductor manufacturing industry: an unexpected high water and energy consumption situation. Water Cycle 4, 47–54. https://doi.org/10.1016/J.WATCYC.2023.01.004.

Watari, T., Northey, S., Giurco, D., Hata, S., Yokoi, R., Nansai, K., Nakajima, K., 2022. Global copper cycles and greenhouse gas emissions in a 1.5 °C world. Resour. Conserv. Recycl. 179, 106118. https://doi.org/10.1016/J.RESCONREC.2021.106118.

Zimmermann, T., 2013. Parameterized tool for site specific LCAs of wind energy converters. Int. J. Life Cycle Assess. 18, 49–60. https://doi.org/10.1007/s11367-012-0467-y.

IEA, 2024. International Energy Agency (IEA)Pathways for the energy mix – world energy outlook 2024 – analysis - IEA[WWW Document]. URL7.16.25https://www.iea.org/reports/world-energy-outlook-2024/pathways-for-the-energy-mix.

European Commission, 2011. Directive 2011/65/EU of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). Official Journal of the European Union L 174, 1 July 2011, pp. 88–110. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0065.