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Research paper

Circular electronics: exploring the applicability of circularity and environmental sustainability criteria in power electronics

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ABSTRACT

The global energy transition is crucial for sustainable development, with power electronics (PE) playing a key role in this process. The design, manufacture, and life-cycle management of PE must be addressed with regard to circularity and environmental sustainability criteria. This study is novel in its comprehensive approach to integrating circularity and environmental sustainability principles into PE. The aim of this article is to define challenges and opportunities in the application of circularity and environmental sustainability principles in PE. A structured matrix of 61 criteria was developed based on relevant scientific literature and European regulation standards. The applicability of these criteria to PE design and life-cycle management was evaluated through individual interviews with industry and academic stakeholders. Key contributions include the identification of five major challenges and opportunities derived from both literature and stakeholders' perspectives. The results indicate that the PE industry primarily applies circularity and environmental sustainability criteria during the product-use stage. Likewise, 88 % of stakeholders interviewed do not consider end-of-life criteria suitable, highlighting a critical gap. The lack of holistic vision on PE life-cycle stages prevents stakeholders from fully appreciating how design decisions in one stage affect others. New partnerships, clear standards, and circular design approaches offer ways to address these gaps. Future work could involve quantitative analyses that explore how the proposed criteria could support decision-making for an improved circularity. Such efforts would help bridge the gap between academic research and industrial practices, thereby enhancing circularity and environmental sustainability in PE.

1. Introduction

Electrical and electronic equipment (EEE) poses major environmental challenges resulting from the high consumption of critical materials and energy in the manufacturing process and the generation of electronic waste. Electric and electronic equipment waste (also called electronic WEEE or e-waste) has become the fastest-growing waste stream globally [38,53]. In 2019, only 20 % of the more than 50 million tons of WEEE created worldwide was recycled [93]. By 2030, this figure is expected to reach 74.7 million tonnes (Mt), for the most part due to the continuous increase in the production of electronic equipment and its rapid obsolescence [97].

At the same time, the global consumption of materials, including rare earth elements (REEs) and heavy metals for the manufacturing of electronic products, is projected to rise exponentially in the coming years [25]. This growth stems from the increasing use of electronic equipment in key sectors, such as electric mobility or renewable energy [41]. For instance, the annual demand for aluminium and copper in the EEE sector could account for 34 % and 28 %, respectively, of current annual global aluminium and copper production by 2050. The demand for aluminium is predicted to increase from 7 Mt in 2015 to around 16 Mt in 2050. Demand for copper is anticipated to rise from 2 Mt today to about 5 Mt in 2050 [21].

The presence in these devices of critical raw materials and substances hazardous to human health and the environment is of particular concern [40]. For example, many EEE contain toxic substances such as mercury, hydrochlorofluorocarbons (HCFCs) or brominated flame retardants (BFRs) [1]. Specifically, as Adrian et al [1] says, an estimated 71kilo tonnes (kt) of plastic BFRs and 50 tonnes of mercury are collected each year in global WEEE streams, whose toxicity and perpetuation create

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serious environmental and health impacts if not properly managed.

In response to these challenges, the European Union (EU) has launched initiatives such as the European Green Deal [34] and the EU Circular Economy Action Plan (CEAP) [35], in alignment with the United Nations Sustainable Development Goals (SDGs) [95]. These initiatives aim to drive the electronics industry towards a circular economy (CE) and mitigate the environmental impact of these products [50]. For instance, the EU, through the European Green Deal [34] and CEAP [35], has made electronic products a priority to be addressed in the years to come, with the objective of reducing the growth of e-waste as well as the dependence on raw materials.

Reducing the carbon footprint of EEE is yet another significant challenge. To this end, the new EU Ecodesign for Sustainable Products Regulation (ESPR) [39] seeks to develop more sustainable energy-related products. Mentioned proposal broadens the scope of the original Ecodesign Directive (2009/125/EC) [28], to encompass not only energy efficiency, but also aspects such as durability, reparability, recyclability and the use of hazardous substances. The incorporation of the ecodesign requirements outlined in this proposal, can help increase the circularity and environmental performance of EEE [39,50].

Power electronics (PE) are understood as devices or systems that manage and control electrical energy flow using electronic components, typically to convert voltage, current, or frequency for efficient power delivery. PEs play a critical role in addressing the environmental and functional challenges posed by EEE, as their application is central to the efficient management and conversion of energy in industrial, residential, and transport sectors [9]. PE equipment, including inverters, power supplies, and converters, not only improve energy efficiency, but also reduce greenhouse gas emissions [11]. Nevertheless, while PEs do contribute to enhancing the sustainability of several sectors—such as mobility or renewable technologies—the equipment itself presents environmental challenges. Firstly, the energy consumption of PE equipment is remarkably high: producing just one silicon (Si) wafer for use in semiconductor manufacturing requires 2,127 kWh/kg [67]. Semiconductors, defined as materials exhibiting electrical conductivity that falls between conductors and insulators, are integral to modern electronic devices. Secondly, such devices require critical materials such as copper; and REE minerals including neodymium, whose extraction and processing entail high environmental costs [101]. Semiconductors also contain chemicals of concern such as lead or cadmium, as well as generating significant quantities of e-waste [1].

Improving the circularity performance and environmental sustainability of PE is thus critical to reducing their resource intensity and environmental impact, thereby facilitating sustainable energy transition [23]. Achieving this goal requires thorough analysis and the optimisation of design, manufacturing and life cycle management (LCM) processes to create circular PEs [87]. The design phase requires particular attention, given that about 80 % of the negative environmental impact originates during this stage [38,64].

Despite the significant advancements in PE technology, the existing research on PEs provides important insights, but significant gaps remain mainly regarding the circularity and environmental sustainability of PEs. Patil and Mathpati [74] investigated the impact of PEs on global warming, but did not explore CE and ecodesign strategies that could mitigate their environmental impact. Other studies have focused on the life cycle analysis (LCA) of PE devices, examining strategies to reduce environmental impact, but have not necessarily analysed the incorporation of CE and ecodesign practices into different life stages [6,67,98,104]. Similarly, Delhommais [22] and Ruthardt et al [85] presented methods to optimise the design of PE systems, highlighting the importance of energy efficiency; however, neither of them directly addressed circularity and ecodesign of equipment.

In recent years the interests on PE design and environmental sustainability has grown. For example. Sangwongwanich et al [87] analysed challenges and solutions to improving the sustainability of PE —addressing aspects such as resource efficiency and recycling in the design, use, and end-of-life (EoL) stages. Nevertheless, this work did not consider the production and logistics phases, nor presented specific ecodesign criteria to be incorporated into the product development process.Rio et al [81] proposed a method to include circular thinking in the initial design phase of electronic products. Nonetheless they only focused on the multi-use life cycle approach, leaving all other key design criteria throughout the life cycle unaddressed. Meanwhile, Freitas Lima et al [45] studied the ecodesign of a planar transformer in a dual active bridge (DAB) application, focusing on a single ecodesign approach.

Salomez et al [86] presented a comprehensive review of the progress and challenges in sustainability research in power electronics. In turn, Fang et al [42] presented a literature review where they identified the four main ecological design approaches applied to PE. Finally, Fang et al [43] analysed all the regulations and standards that influence PE. However, none of these papers proposes a specific practical approach to the integration of circularity and environmental sustainability criteria in product design. In addition, most research has focused only on academic literature, without taking into account the views of industry players in the sector.

Thus, it can be concluded that research analysing circularity and environmental sustainability criteria for the design, manufacture, and LCM of PE remains limited. There is a clear research gap in scientific studies to guide designers in incorporating circularity and environmental sustainability criteria into the PE product design and LCM processes. This knowledge gap poses a significant barrier to implementing suitable solutions for improving the circularity and environmental performance of PEs from a life cycle perspective.

This paper, therefore, analyses key challenges and opportunities for the practical application of circularity and environmental sustainability criteria in the design, manufacture and LCM of PE products, to define best practices and guidelines for circular PE innovation. Taking into consideration the new ESPR [39], the study integrates feedback from industry stakeholders, policy recommendations, and the academic literature. The specific goals of this work are defined as follows:

- Define and characterise key circularity and environmental sustainability criteria for each life cycle stage of PE products to improve resource efficiency and environmental performance, drawing on insights from policy, industry, and the literature.
- Gather and analyse the perception of stakeholders from the PE industry as regards the application of the circularity and environmental sustainability criteria in product LCM.
- Analyse the relationship between industry perception and the academic literature on the application of ecodesign strategies. This includes evaluating the criteria of circularity and environmental sustainability to define best practices and lines for future research.

In summary, this study not only addresses and contributes to reduce the existing research gap but also provides a comprehensive framework for integrating circularity and environmental sustainability into PE and LCM processes. First, it provides an evaluation matrix of 61 circularity and environmental sustainability criteria focused on PE classified by life cycle stages, circular economy solutions and ecodesign strategies-an approach not previously explored in the PE. Second, it integrates the industrial vision with the academic one, offering challenges and opportunities posed by the transition to a CE in the PE sector. Third, this study highlights the need to develop sectoral metrics and standards more adapted to the needs of PE. Briefly, the contributions of this research not only address the existing research gap but also help PE in its transition towards a more sustainable and circular innovation.

2. Methodology

The research was carried out in four analytical steps (Figure 1). First, a three-stage literature review was conducted to identify studies on circularity and sustainability criteria for PE equipment (Section 2.1.1).

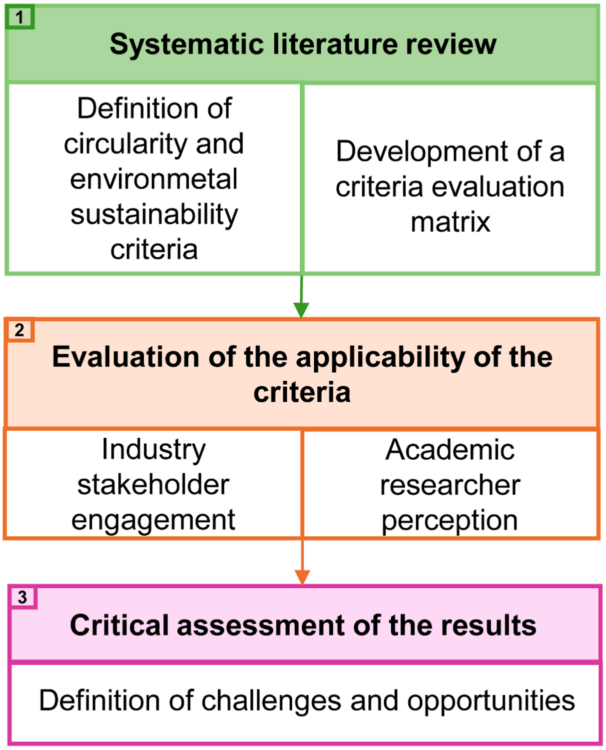

Figure 1. Methodological steps.

Secondly, all criteria obtained from the literature review were consolidated, and a design criteria evaluation matrix was created to facilitate discussion with industry stakeholders and identify insights from the academic literature (Section 2.1.2). The applicability of the circularity and environmental sustainability criteria was then evaluated using the evaluation matrix with both industrial stakeholders and the academic literature. This step was to identify the real implementation of sustainability guidelines in industry and to compare this with the literature recommendations (Section 2.2). Finally, a critical assessment of the results was carried out to define challenges and opportunities for the practical application of the circularity and environmental sustainability criteria in the PE sector (Section 2.3).

2.1. Systematic literature review

2.1.1. Definition of circularity and environmental sustainability criteria

A three-stage literature review, including the analysis of i) academic literature, ii) industrial literature and iii) normative literature, was conducted. Thirty-six documents were identified in this step for assessment to compile the circularity and environmental sustainability criteria for PE design, development, and LCM (Figure 2. illustrates the systematic literature review conducted). The Supplementary File (SF) details the complete list and combination of keywords used to identify scientific articles on the topic, using SCOPUS as search engine, together with the hits obtained in each case (see Table S1 of SF for further details).

Two searches of academic literature were conducted in May 2024, using keywords related to EEE (first search flow) that were cross-referenced with keywords related to CE and ecodesign (second search flow) and keywords related to criteria (third search flow). The first search focused specifically on the identification of circularity and environmental sustainability criteria for PE, whereas the second search had a broader scope, covering EEE in general. Only peer-reviewed journal articles and reviews written in English between 2015 and 2024 were considered, which narrowed the search to 48 results. This period was chosen because the European Commission launched the 'Circular Economy Package' in 2015, which stimulated research and implementation of this concept globally [5]. Studies working on aspects related to circular design, environmental sustainability or ecodesign applied to PE and/or EEE were considered. To this end, the pertinence of the title, keywords, and abstracts of the articles to the research topic was

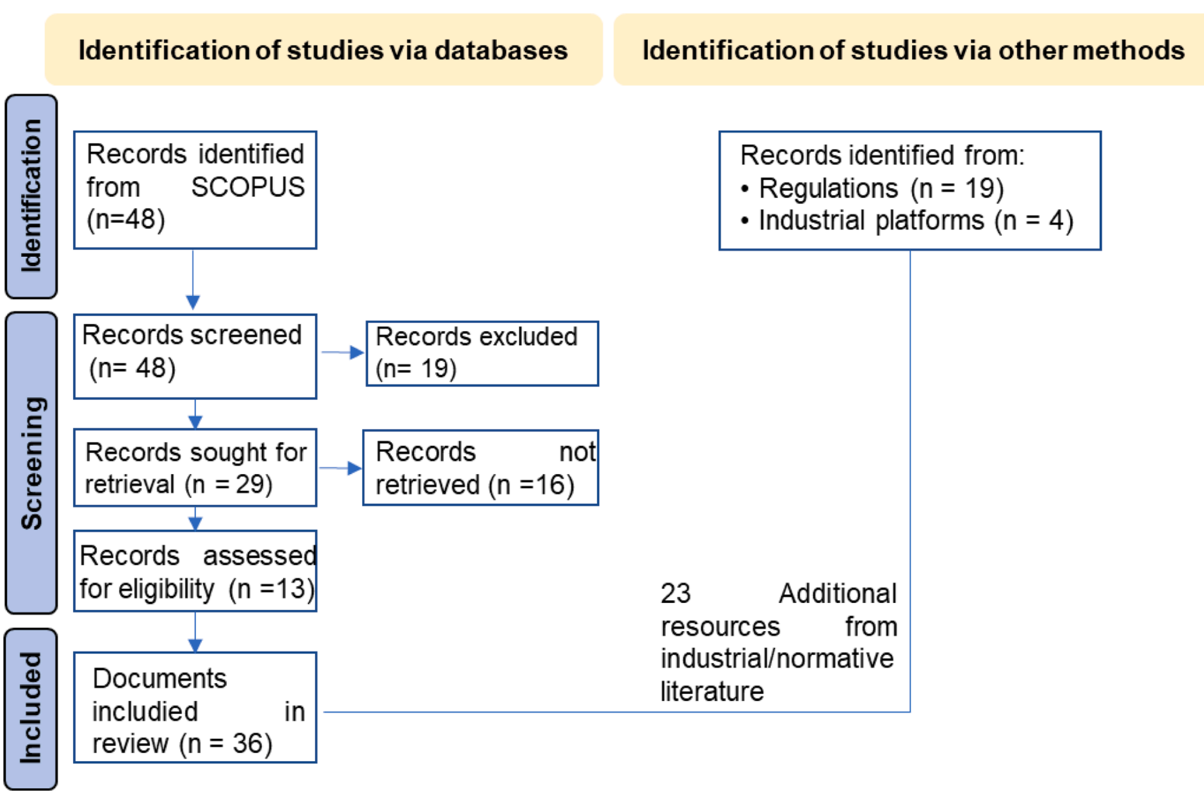

Figure 2. Systematic literature review, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram [73].

examined. Applying the aforementioned cut-off criteria, the sample of articles for comprehensive evaluation was reduced to 13 papers.

The revision of academic literature was subsequently complemented and completed with a search for relevant European regulations and industry platforms. The analysis of these regulations is fundamental for comprehending any research in the fast-growing sector of energy-related products, in particular PEs [43]. Policy sources reviewed included the REACH Regulation No 1907/2006 [30], Directive 2011/65/EU (RoHS) [31], Directive 2012/19/EU (WEEE) [32], UNE EN 45552 [3] to UNE EN 45558 [2], Ecodesign for Sustainable Products Regulation (ESPR) [39]. This regulatory analysis helped to frame the previously identified criteria and incorporate additional elements in line with the European legislative framework. It should be noted that the latest EU ESPR [39] includes all the criteria previously identified by the academic literature. Through this comprehensive approach the knowledge provided by the scientific community is aligned with the legal requirements of industry, ensuring that products are designed to reduce their environmental impact throughout their life cycle. In terms of industry documents, reports and guidelines from platforms such as the Ecosign Consortium [26] and the Platform for Accelerating the Circular Economy (PACE) [78] were included. In total, 23 references from regulatory and industry literature were reviewed. The detailed search process and the selected articles, industry reports, and legislation are described in Table SF1 of the SF.

2.1.2. Development of a criteria evaluation matrix

A total of 61 circularity and environmental sustainability criteria were identified (see Table 2 for further details), and an evaluation matrix was developed to test the practical applicability of these criteria in the PE industry. The criteria were extracted from academic literature, European regulations (including ESPR), and industrial reports. While European regulations such as the ESPR [39] provide valuable high-level guidance, they do not offer specific, design-level criteria tailored to the PE sector. In contrast, this matrix translates those general recommendations into actionable, sector-specific strategies.

To address this gap in ESPR [39], academic research has proposed frameworks with more actionable ecodesign guidance. For instance, the works of Bovea and Pérez-Belis [13], CIRCit Norden [18], Berwald et al [7] and the GreenTool by Hakola et al [50] proposed practical criteria to support circular and sustainable product development. However, these studies typically focus on general EEE or specific product categories. The literature shows that each emerging technology sector requires ad hoc adaptation of circular design frameworks. A good example is Picatoste et al [76] who customised circularity criteria for the electric vehicle battery sector. Therefore, our matrix was specifically developed to provide criteria tailored to the needs of the PE sector. The matrix was based on an adaptation of the product circularity assessment tool developed by CIRCit Norden [18], applying a similar approach to that used by Picatoste et al [75]. These works are representative examples of the broader set of references consulted. The full list of sources used to extract the 61 criteria is provided in Table SF1 of the SF.

The matrix was first adapted by integrating the 61 specific circularity and environmental sustainability criteria applicable to the design, manufacture, and LCM of EEE. For this purpose, the different life cycle stages of PE were taken into account and the 61 criteria were categorised according to the stage to which they belonged. To account for the complete life cycle of EEE, five life cycle stages have been considered: raw materials, manufacturing, transportation, use and EoL [70]. Specifically, the raw materials stage included aspects related to the choice of sustainable materials including compliance with RoHS [31] and REACH [30] regulations regarding the use of toxic materials. The manufacturing stage encompasses the manufacturing and assembly processes of the components (e.g. soldering, printed circuit board (PCB) encapsulation, etc.). The use stage refers to the operation and maintenance stage of the equipment in use by the operator. At this stage, energy efficiency aspects and ease of maintenance are essential, in order to avoid premature system failures. Finally, the EoL stage deals with all activities related to the collection, treatment and recovery or recycling of equipment at the end of its life cycle. The integrated LCM approach aims to improve the circularity and sustainability of all life cycle stages by reinforcing the design of the PEs.

These criteria were then categorised into eight ecodesign strategies defined by Ecodesign Project [26], according to their main objective and the environmental or circularity impact they aim to address. These criteria linked to different ecodesign strategies are detailed in Table 2, Section 3.

2.2. Evaluation of the applicability of the criteria

The practical applicability of the circularity and environmental sustainability criteria refers to the possibility of integrating each criteria in the current PEs design and LCM practices, to improve CE performance. The applicability was qualitatively evaluated by considering both PE industry experts' feedback and recommendations from the academic literature. As this study is qualitative in nature, based on in-depth interviews, the aim was to capture the complexity and depth of stakeholders' perceptions of real-world applicability. This approach allowed for a rich and contextual view of how these criteria can be integrated into practice. It also helped to determine the feasibility of these criteria for implementation in an industrial context, as well as identifying possible discrepancies between theory and practice as well as the strategies pursued for addressing them.

2.2.1. Industry stakeholder engagement

Multiple stakeholders from both industrial and academic backgrounds were contacted and asked to participate in a qualitative evaluation to assess the applicability of circularity and environmental sustainability criteria in the PE sector. Upon agreement, stakeholders received the evaluation matrix through email, with instructions explaining the purpose and mechanisms of the assessment. Each of the respondents was accompanied in their final evaluation through 90-minute interviews conducted both online and face-to-face between February and June 2024. These interviews elicited not only numerical evaluations of the criteria, but also qualitative assessments of the criteria. Through the discussions, questions regarding particular criteria were better addressed and the stakeholders clarified their responses in more detail. After the interviews, by iteratively incorporating their feedback, we improved both the reliability and relevance of our findings through several contact points with stakeholders. This process also enabled a validation of the numerical results, ensuring they were consistent with stakeholders' reasoning and expectations.

The study involved stakeholders from the PE industry, including both partners of the Horizon Europe SiC4GRID project [29] and additional external experts. The nine industry stakeholders that participated in the study were selected for different reasons: first, their collective expertise covered all phases of the PE life cycle, from design to EoL. They included diverse profiles of engineers, academic researchers, multinational managers and waste managers. Second, they represented different technology readiness levels (TRLs). Third, several of them were participants of the Horizon Europe SiC4GRID project [37] Finally, the participants each had more than 10 years of experience in the sector. This sample provided a comprehensive and representative approach to the reality of the sector. As highlighted by [62] small samples can yield valid insights when the participants are strategically selected to reflect key dimensions of the research context. The names of the organisations and experts interviewed cannot be displayed for confidentiality reasons; instead, they are referenced in the article as outlined Table 1.

The stakeholders were asked to: i) define whether they already implemented each specific criteria, and ii) evaluate the importance and feasibility of implementing each design criterion in business practice. The scales used for the evaluation were based on Picatoste et al [75] as follows: importance, scoring 0 for not important, 1 for low importance, 3

Table 1
Organisations involved in the research. Acronyms: CE (Circular Economy), R&D (Research and Development), SiC (Silicon Carbide), WEEE (Waste from Electrical and Electronic Equipment.

Organisations	Economic activity	Components	Participant
University (U1)	Research and development of advanced power electronics systems, and electrical machines, applied to energy generation, storage, distribution and transmission, as well as traction, renewable energies, and industrial electronics.	Power converters and electrical machines	Researcher
University (U2)	Research and development of advanced electrical energy conversion and control systems, with applications in renewable energies, electric mobility, and industrial energy efficiency.	Power converters, electrical machines and energy storage systems	Researcher
Technology Centre (TC)	Centre for applied research and technological development in energy transition: Development of solutions for competitive renewable energy generation and CO_2-free mobility.	Embedded systems and power converters	Researcher
Multinational company (MC1)	Design and manufacture of electric traction systems, energy storage, and control and communication systems for the railway sector.	Power converters for the railway industry	Head of CE department and head of technical office
Multinational company (MC2)	Development and supply of power semiconductors, offering applications in key sectors of the global energy economy.	Semiconductors	R&D Engineer SiC
Multinational company (MC3)	Design and production of semiconductor materials.	Semiconductor materials	Technician
Multinational company (MC4)	Design and manufacture of gate drivers for high power and high availability applications.	Gate drivers	Technical director
Multinational company (MC5)	Power conversion solutions for industrial and marine applications, including frequency converters and energy storage systems.	Power converters	Technician
Recycling Company (RC)	Industrial waste management and recycling solutions.	WEEE	Recycling expert

for moderately important, and 9 for very important; and feasibility scoring 0 for totally unfeasible, 1 for probably unfeasible, 2 for low viability, 3 for moderately viable, 4 for fairly feasible, and 5 for absolutely feasible). The multiplication of both variables determined the suitability level of each criterion (Equation 1). S2 of the SF provides the evaluation matrix of the circularity and environmental sustainability criteria used with each stakeholder.

Equation 1. Formula for prioritising circularity and environmental sustainability criteria

$$\text{Suitability} = \text{Importance x Feasibility}$$

The suitability score was obtained as the average product of the responses from industrial stakeholders to the questions: *"How important this criterion for the sustainability of power electronics equipment is (scale 0-1-3-9)?"* and *"How techno-economically feasible the application of this criterion for PE equipment is (scale 0-5)?"* The different scales were selected as a means to provide weight to more important criterion over the techno-economical feasibility. The suitability of each circularity and environmental sustainability criterion was then expressed as a percentage of the maximum possible score, this value being at most 45 (the result of multiplying the maximum 9 for importance by the maximum 5 for feasibility). For example, a criterion scoring high in both importance (9) and in feasibility (4) would yield a 72 % suitability score (36 points out of 45), while a criterion with moderate importance (3) and high feasibility (5) would score 33 % (15 points out of 45). This approach ensured that the most suitable criteria to ensure the circularity and environmental sustainability of the PE sector were identified and prioritized in the short term. S2 of the SF provides the evaluation matrix of the circularity and environmental sustainability criteria used with each stakeholder.

2.2.2. Academic researcher perception

The artificial intelligence (AI) tools SciSpace [89] and Elicit [27] were used as support to identify and analyse literature focused on evaluation and/or discussion of the applicability of the defined criteria. A set of prompts were developed based on the themes (8 ecodesign strategies) and sub-themes (61 circularity and environmental sustainability criteria) described in Table 2. Examples of these prompts include "*What are the main challenges and benefits of using recyclable materials in the design and development of power electronics?*" "*What are the most relevant trade-offs when implementing lightweighting technologies in power electronics manufacturing?*". A full list of these specific questions is provided in S3 of SF.

This search yielded 39 documents, which were further analysed for insights into the feasibility, challenges, and opportunities of applying the identified criteria. The key findings highlighted discrepancies between the industry view and the literature while confirming PE trends, such as the miniaturisation of equipment. This process ensured a robust and representative selection of academic contributions. The process also identified previous studies, current trends, and expert opinions that address both the benefits and the technical and economic challenges of the adoption of ecodesign strategies in the sector.

2.3. Critical assessment of the results

The results were examined holistically in order to define and discuss the key challenges and opportunities for the practical application of circularity and environmental sustainability criteria in the design and LCM of PE products.

2.3.1. Definition of challenges and opportunities

The main challenges and opportunities were identified by assessing industry stakeholders and supporting scientific research focused on the application of circularity and sustainability in the sector. The results of this study can be used as a reference and guide for PE professionals and stakeholders to improve circularity and environmental sustainability of

Table 2
Suitability score according to the stakeholders of the circularity and environmental sustainability criteria classified by ecodesign strategies grouped into life cycle stages and CE strategies. Acronyms: CE (Circular Economy), EoL (End-of-Life).

			Life cycle stages					CE strategies											Suitability score (%)
								Narrowing	e (%)Slowing					Closing		Regenerating			
Ecodesign strategies	**N°**	**Circularity and environmental sustainability criteria**	Raw materials	Manufacturing	Transportation	Use	End-of-life	Rethink	Reduce	Reuse	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover	Renewable inputs	Low-toxicity	
I. Use of low-impact materials	**1**	Select and/or increase the use of renewable, reused, recovered, and recycled materials	**X**				**X**			**X**					**X**	**X**	**X**		**5 %**
	2	Substitute and/or reduce the use of hazardous substances	**X**				**X**		**X**						**X**	**X**		**X**	**90 %**
	3	Avoid and/or reduce the use of energy-intensive raw materials and components	**X**						**X**										**82 %**
	4	Reduce the use of different types of materials	**X**				**X**								**X**	**X**			**36 %**
	5	Use of materials that allow easy separation	**X**				**X**								**X**	**X**			**20 %**
	6	Ensure responsible, stable and local material sourcing	**X**		**X**				**X**										**11 %**
	7	Specify materials that emit low or zero volatile organic compounds	**X**															**X**	**6 %**
II. Reduction of material use	**8**	Reduce the weight and size of materials, components, and products	**X**		**X**				**X**										**71 %**
	9	Increase the use of durable and robust materials	**X**			**X**			**X**	**X**									**88 %**
III. Optimisation of manufacturing processes	**10**	Ensure easy component assembly		**X**		**X**				**X**	**X**	**X**	**X**						**78 %**
	11	Decrease the need for consumables		**X**					**X**										**24 %**
	12	Reduce production waste		**X**					**X**										**75 %**
	13	Reduce the number of processes and components		**X**					**X**										**74 %**
	14	Optimise production techniques to increase the efficient use of energy, water, and material resources		**X**					**X**										**23 %**

(*continued on next page*)

Table 2 (*continued*)

			Life cycle stages			CE strategies				Suitability score (%)
						Narrowing	e (%)Slowing	Closing	Regenerating	
	15	Increase use of repaired and/or remanufactured parts	X				X			**3 %**
	16	Reduce use of hazardous process chemicals (e.g., volatile solvents)	X						X	**95 %**
	17	Reduce emissions to air, water, and soil and anticipated pollution	X						X	**30 %**
	18	Ensure safe environmental and operational conditions while minimizing harmful processes	X						X	**60 %**
	19	Comply with CE marking and declaration of conformity	X							**41 %**
IV. Optimisation of distribution systems	**20**	Reduce the number of locations in which product parts are produced		X		X				**40 %**
	21	Reduce energy consumption and emissions from transportation and logistics		X		X				**17 %**
	22	Forward and reverse logistics		X		X				**20 %**
	23	Optimise cargo (in trucks, containers, etc.) and the road routes		X		X				**64 %**
	24	Optimise shape and volume for maximum packaging density, reducing (over) packaging and waste		X		X				**60 %**
	25	Ensure the use of fair-trade models		X						**22 %**
V. Reduction of environmental impact during operation	**26**	Maximise material and energy efficiency during use			X	X				**92 %**
	27	Reduce waste generation during product use			X	X				**58 %**
	28	Avoid single-use components as part of the product during the use phase			X		X			**15 %**

(*continued on next page*)

Table 2 (*continued*)

			Life cycle stages			CE strategies							Suitability score (%)
						Narrowing	e (%)Slowing				Closing	Regenerating	
	29	Ensure compliance with energy labelling requirements	X	X		X							**38 %**
VI. Optimisation of product lifetime	**30**	Ensure user safety and security		X									**69 %**
	31	Ensure reliability and durability		X			X	X	X	X	X		**76 %**
	32	Minimise aging, fatigue, and wear-out of the components or products		X			X	X					**85 %**
	33	Extend product lifetime		X			X	X	X	X			**64 %**
	34	Maximise compatibility with electromagnetic fields to ensure effective performance and reduce interference		X		X							**88 %**
	35	Provide extended warranty periods and customer support services		X			X	X	X	X			**29 %**
	36	Deliver updates/ upgrades packages for products		X					X	X			**24 %**
	37	Forward and backward compatibility and use of standardized parts	X	X		X	X	X					**19 %**
	38	Reduce maintenance requirements		X		X		X					**75 %**
	39	Ensure easy and non-destructive disassembly			X			X	X	X			**29 %**
	40	Ensure modularity	X	X	X			X	X	X			**78 %**
	41	Reduce and/or standardize tools, fasteners, and connectors	X	X				X	X	X			**49 %**
	42	Facilitate inspection and accessibility of joints and components, for easy removal	X	X	X			X	X	X			**52 %**
	43	Maximise the availability and delivery of spare parts		X				X	X	X			**72 %**
	44	Use interfaces for diagnostic support, failure detection, etc.		X				X	X	X			**74 %**
	45	Facilitate cleaning: ability to clean, sterilize and restore aesthetic state		X			X	X	X	X			**52 %**

(*continued on next page*)

Table 2 (*continued*)

			Life cycle stages					CE strategies											Suitability score (%)
								Narrowing	e (%)Slowing					Closing		Regenerating			
	46	Maximise repairability and refurbishment rate				X	X				X	X							**11 %**
VII. Optimisation of end-of-life management systems	**47**	Maximise reusability rate					X			X									**45 %**
	48	Maximise remanufacturability rate					X						X						**9 %**
	49	Maximise product recyclability rate					X								X				**11 %**
	50	Maximise material recoverability rate					X									X			**16 %**
	51	Use digital product passport		X			X			X	X	X	X	X	X	X			**18 %**
	52	Increase the use of traceability/ circularity labels		X			X			X	X	X	X	X	X	X			**27 %**
	53	Set up effective collection systems					X			X			X		X	X			**7 %**
	54	Avoid technical solutions detrimental to reuse, upgrading, repair, maintenance, refurbishment, remanufacturing, and recycling of products and components					X			X	X	X	X	X	X	X			**6 %**
	55	Maximise material-specific and process efficiency of EoL treatments: reusability, remanufacturing, recyclability, and recoverability processes.					X			X	X	X	X	X	X	X			**1 %**
	56	Identify and facilitate the extraction of substances, mixtures, and components					X								X	X			**13 %**
	57	Avoid microplastics release					X								X	X		X	**2 %**
	58	Minimise anticipated emissions in disposal processes					X											X	**1 %**
	59	Minimise the amount of non-recoverable waste		X			X									X			**5 %**
VIII. Optimisation of function (new product ideas)	**60**	Transform physical solutions (hardware, software, or services) into digital solutions				X		X											**5 %**
	61	Maximise product use intensity. Ex: leasing, renting, or sharing				X		X											**2 %**
TOTAL			**9**	**18**	**8**	**24**	**21**	**2**	**20**	**17**	**19**	**17**	**18**	**5**	**12**	**13**	**1**	**7**	-

the sector, providing criteria to incorporate in the design and LCM of PE products.

3. Results and discussion

Table 2 presents the average suitability score of the 61 circularity and environmental sustainability criteria for PEs identified in the literature review (Section 2.1), grouped into eight ecodesign strategies [26] to simplify analysis of the applicability of the criteria to the sector. The criteria were further classified according to the life cycle phase [79] and the CE solutions [58] and strategies [10] which they influence and/or target. Therefore, this matrix provides detailed, design-level criteria that have been specifically adapted to the power electronics sector. In addition to being tailored to the technical and organisational realities of PE products, the matrix incorporates the perspective of stakeholders from across the value chain and integrates multiple circular economy strategies and life cycle stages. These features make the matrix not only sector-specific, but also a practical and operational tool for identifying opportunities for circularity in PE design and LCM. The specific definitions used for this analysis can be found in S4 of the SF.

Table 2 presents the circularity and environmental sustainability criteria classified according to the life cycle stages and CE strategies they influence. The results show that most of the criteria are concentrated in the use stage (24 out of 61 criteria). In turn, among the most outstanding results, the strategies associated with the resource loops 'Narrowing' and 'Slowing' obtain the highest percentages of criteria with 32 % and 35 %, respectively. The first refers to optimising the use of resources (materials, energy, components), while the second seeks to extend the useful life of products through durability, maintenance and reuse. In contrast, the strategies of 'Closing', associated with the reintegration of waste into the economic cycle, and 'Regenerating', related to ecosystem management and the use of renewable inputs, are less represented with 21 % and 12 % of the criteria, respectively [63]. This aligns with stakeholders' prioritisation of the use phase through strategies that seek to reduce resource consumption and prolong the life of products.

Moreover, Table 2 shows the suitability scores obtained in the stakeholder interviews for each of the criteria. It is important to clarify that the percentages presented in this analysis do not represent a total of 100 %, as they reflect average values obtained from the opinions of the different stakeholders consulted. Among the criteria with the best score, the criterion '*Maximise material and energy efficiency during use*' stands out with an average score of 92 %. In contrast, the criterion '*Minimise anticipated emissions in disposal processes*' barely achieved 1 % suitability. The characterisation of the content of this table will be done in the following subsections.

3.1. Analysis of the scope of circularity and environmental sustainability criteria for application to the PE industry

3.1.1. Scope of circularity and environmental sustainability criteria classified by life cycle stages

Figure 3 shows that the circularity and environmental sustainability criteria are primarily focused on the use phase of PE (36 %). This is aligned with the trend in the scientific literature, in which the use phase is the most studied phase of the product life cycle [42]. This is likely because the greatest impacts are generated during this stage, such as high energy consumption, energy losses, and associated greenhouse gas emissions [98], as well as the need for PE developers to ensure the products perform well during their lifetime.

PE are pivotal in this context, as they are dedicated to the efficient conversion, control, and conditioning of electrical energy. This contributes to maximising energy efficiency, thereby reducing both energy consumption and environmental impact [51]. The ESPR approach [39] underlines the need to optimise the performance of equipment throughout its lifetime, to mitigate environmental impact and address the environmental, economic, and energy security issues facing Europe. Improving the energy efficiency of PE products is expected to save 20 % of the overall energy demand [12].

The second most widely addressed life cycle stage by the circularity and environmental sustainability criteria is the EoL stage (32 %). This largely due to the growing volume of e-waste and the significant challenges this presents. In this regard, the ESPR advocates design for circularity, promoting measures to extend the useful life and prepare products for reuse or repurpose such as easy disassembly and repair. Moreover, it highlights the need for strategies that maximise the recovery of valuable materials and components through recycling, thereby reducing the amount of waste sent to landfill [39].

As environmental regulations tighten, especially within the EU, compliance with regulations including the WEEE Directive [32] becomes increasingly critical. For PE in particular, the anticipated

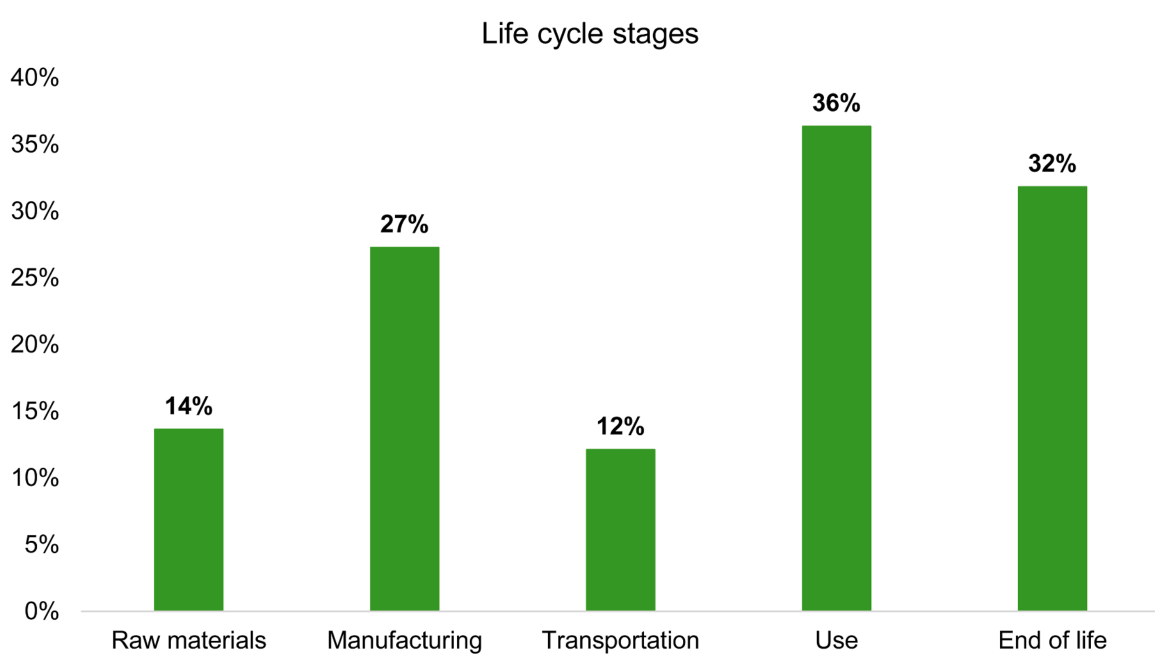

Figure 3. Distribution of Circularity and Environmental Sustainability Criteria According to Life Cycle Stages of PE Products. Acronyms: PE (Power Electronics).

generation of additional e-waste could correspond to the equivalent of 5000 gigawatt of installed power converter capacity annually by 2050 [52]. This underscores the need to address waste management challenges and policies such as WEEE have prompted further research into improving component recyclability and energy recovery.

The manufacturing stage occupies third place, accounting for 27 % of the circularity and environmental sustainability criteria (Figure 3). This is considered a critical phase owing to its high economic and environmental impact [71]. Manufacturing PE components, such as semiconductors and inverters, is particularly resource-intensive, requiring high-precision, energy-intensive processes, that involve high-temperatures, chemical treatments, and highly specialized machinery [67]. In addition, these devices use scarce materials such as silicon, copper, and heavy metals, whose treatment is also energy-intensive [101]. Applying optimised production techniques to address these challenges is critical. Such practices help reduce waste and its associated costs, lower the environmental footprint of the product, while complying with European regulations on critical materials and energy efficiency.

Ranked fourth is the extraction and processing of raw materials (14 %), in which the focus is on the origin of materials and their criticality. In this regard, PEs contain scarce or difficult to recycle materials such as REEs, which are operationally essential [65]. The need to reduce dependence on these resources has encouraged investigation into more sustainable alternatives and the miniaturisation of devices [23]. This approach seeks not only to optimise the use of resources, but also to reduce dependence on critical materials—namely rare earth materials—which are difficult to obtain and recycle (S [103].).

Finally, the logistics stage received the least attention (12 %) in the reviewed studies (Figure 3). In the context of PEs, this indicates that the management of transport and distribution of materials and final products has not been prioritised in circularity research. Although logistics does have an impact on the carbon footprint, the literature to date indicates that the potential for improvement in terms of CE lies mostly in the design, use, and EoL phases [87].

The trends emerging from the academic and normative literature highlight the significance of the use and EoL phases for PE, while the logistics phase remains comparatively overlooked. This shows that the ESPR does not address all life cycle stages with equal depth [39]. Such an omission could be considered a limitation, as the directive fails to capture the full picture of the cumulative environmental impacts of products. For example, transporting PEs such as high-voltage converters, requires significant energy and material for packaging. Inefficient practices in this stage could lead to carbon emissions that counteract gains in other life cycle phases, such as EoL [8]. In other words, neglecting circular decisions during logistics can negatively influence other life stages, making the transition to a true circular economy impossible.

3.1.2. Scope of circularity and environmental sustainability criteria classified by CE solutions

Figure 4 shows the classification of circularity and environmental sustainability criteria according to the strategies associated with the resource loops and their respective CE solutions. The strategies and solutions are listed in the text below, ordered from highest to lowest percentage, highlighting their relevance within the analysis.

3.1.2.1. Narrowing resource loops. One of the most widely implemented CE strategies in academic, regulatory and industrial literature is narrowing resource loops, mainly because its objective is to reduce the use of material and energy resources over the entire product lifetime. This approach holds particular significance for PEs, as efficient use of resources is a key priority for electronic equipment manufacturers [42]. The current trend in the PE sector is towards miniaturisation, hence reducing weight and volume is key [84]. Optimising equipment in these terms lowers production costs and decreases the energy required for manufacturing. Moreover, minimising the number and amount of materials and components reduces reliance on valuable materials, thus complying with European regulations, such asRoHS [31].

In contrast, the rethinking strategy (understood as increasing product and material value by developing sustainable business models [10]) plays a smaller role in the PE sector. This is largely because the sector focuses on improving energy efficiency and ensuring the durability and reliability of products, and this can be achieved through repair, remanufacturing, and maintenance strategies [39]. Hence, the industry prioritises meeting market demands for efficiency and reliability rather

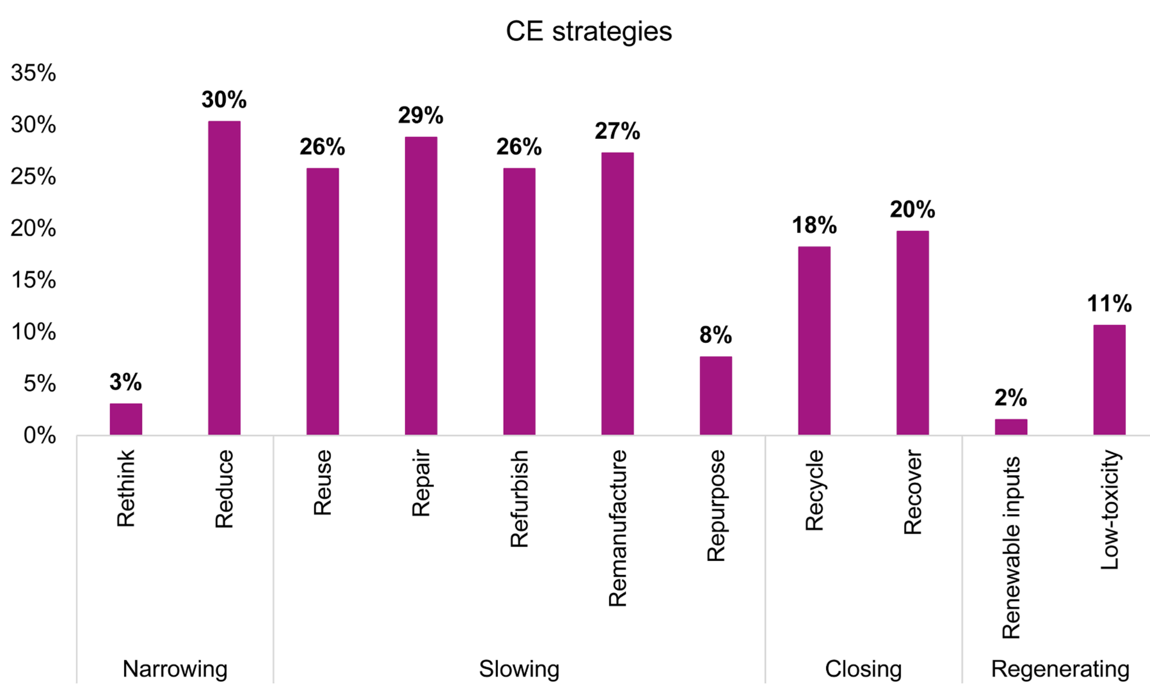

Figure 4. Classification of Circularity and Environmental Sustainability Criteria According to CE Strategies. Acronyms: CE (Circular Economy).Narrowing resource loops.

than rethinking business and design models. Nonetheless, some authors (e.g. Suppipat et al [93] and Salomez et al [86]) have studied the application of circularity in product-service systems, have identified seven innovative business models for EEE circularity: circular supplies, resource recovery, product life extension, sharing platforms, product as a service, product transformation y circular design. These business models help to improve the sustainability of EEE, facilitating the transition to a CE in the sector.

3.1.2.2. Slowing resource loops. The second most prominent CE solution to emerge from the analysis (Figure 4) is repair which can be facilitated through modularity, ease of assembly and disassembly, or the use of standardised parts [20]. As PEs are used in sectors with long life cycles (e.g. 25 years for power converters). This means that this equipment is designed to operate for long periods, where unscheduled downtime can have significant consequences [61]. Simplifying maintenance and repair is advantageous both economically and environmentally, because repair minimises the production of new equipment. For this reason, the ESPR [39] focuses its efforts on maximising the durability and repairability of equipment.

This strategy is closely followed by remanufacturing, reuse, and refurbishing, all of which play an important role in extending the lifetime of PE products [44]. Some parts of PE products, such as passive components, can be reused, which reduces the consumption of new resources [86]. For instance, Kouloumpis et al [59] highlights that CE strategies, such as repair and reuse, can reduce material consumption and environmental impacts by 25 % per electronic device. These savings might also apply for PEs, although this requires further investigation through the development of empirical CE case studies. However, it should be noted that PE equipment is often employed in applications with very demanding performance requirements and that during use the electronic components suffer significant wear and tear [86,100]. In such cases, applying these CE strategies to products may lead to non-compliance with these requirements, making them an impractical option for the industry [90].

3.1.2.3. Closing resource loops. Closing resource loops received considerably less attention than the narrowing and slowing (Figure 4). Adopting criteria related to the closure of the material cycles presents considerable challenges due to the high complexity of the design of PE equipment [87]. As noted above, the trend in PE is towards miniaturisation, and this is achieved through compact designs that reduce size without altering functionality and performance. However, these designs complicate disassembly and separation of materials for recovery, critical steps for EoL strategies that promote circularity of materials and components [90]. Added to this, there are no appropriate disassembly channels for these products and the cost of these processes is high [86]. In addition, PE products contain a variety of key materials to achieve the demanding performance requirements of their applications. These materials include rare earth metals (such as neodymium), hazardous substances (such as brominated flame retardants), and other valuable metals (such as copper) that are not easily substituted by renewable or recycled alternatives further complicating the recovery and recycling process [1,88]. Moreover, many materials and components suffer from wear and tear during use, which complicates their reintegration into the power electronics production cycle.

3.1.2.4. Regenerating resource loops. Finally, the least valued CE strategy regenerates resource loops. PE uses non-renewable materials (such as tantalum or gallium nitride (GaN)) that do not regenerate biologically. These materials are used in semiconductor and control circuits, which require specific performance properties such as high thermal resistance. These technical requirements clash with the properties of sustainable materials (e.g. renewable, recycled) that often fail to effectively provide product functionality and lifetime, which runs counter to the PE objectives of reliability and energy efficiency (aligned with the narrowing and slowing down strategies [80]). However, the development of these new materials is crucial to limit the use of hazardous and environmentally toxic components, especially in compliance with REACH [30]. To fill this gap, it is imperative to engage industry in the research and development of sustainable alternative materials that meet PE specifications. Sustainable materials are not yet standardised for PE, and their adoption requires significant changes in the design and supply chain of companies, which complicates the adoption of these practices by industry.

3.2. Industry and academic perception of the application of circularity and environmental sustainability criteria in the design and LCM of PEs

Figure 5 shows a bar chart representing the circularity and industrial sustainability criteria categorised in ecodesign strategies and their level of adoption by PE stakeholders, expressed in percentages. Each bar reflects the percentage of application of these specific criteria by industry, highlighting which are the most used compared to the least implemented. There is a clear preference of the PE industry for the criteria focused on reduction of material use (miniaturisation of equipment) and efficient use of equipment (optimisation of lifetime and reduction of environmental impact), while the least prioritised is optimisation of function through new product ideas. Each strategy is listed below in order of highest to lowest relevance, according to the percentages presented.

3.2.1. Reduction of material use

As Figure 5 shows, the ecodesign strategy of reducing the use of materials was prioritised in the design and LCM of PE equipment, with a score close to 80 %. In particular, the criterion '*Reduce the weight and size of the materials, components, and products*' received a suitability score of about 71 % (Table 2). In the words of UR (Table 1), 'M*iniaturisation is a clear trend in the PE industry*'. Optimising the size delivers significant advantages, such as savings in manufacturing, packaging and transport costs; reduction of the energy needed to operate the equipment; and compliance with market requirements. Similarly, the criterion '*Increase the use of durable and robust materials*' scored 88 %. In PE, equipment often operates at high temperatures and in high load environments, making robustness key to preventing unnecessary failures.

These findings are supported by the published scientific literature (section 2.2.2). According to Stala et al [92], the use of new materials, such as GaN and silicon carbide (SiC), makes it possible to miniaturise equipment and reduce the number of components. Dhameliya [23] highlighted the advantages of these components, pointing out that the thermal conductivity of SiC surpasses that of Si, which simplifies thermal systems and makes the equipment smaller and lighter. However, this miniaturisation also presents challenges, particularly in relation to equipment reliability. For instance, overheating and high currents can affect the performance and lifetime of the equipment [102].

Hence, both industry and the academic literature highlight the importance of reducing material usage, driven by the miniaturisation trend. Innovations are moving towards developing compact equipment, which optimises the use of resources and improves the sustainability of the equipment.

3.2.2. Optimisation of product lifetime

Optimising the lifetime of products is essential and was the second most prioritised strategy for the industry due to the importance of durability, reliability and efficiency aspects of PE. As can be seen in Table 2, the most highly rated aspects were: reducing electromagnetic interference problems (88 %), minimising aging, fatigue, and wear-out of the components or products (85 %), and minimising operational damage by ensuring correct operation without frequent maintenance (75 %). These factors are essential for the proper operation of the equipment. Achieving good electromagnetic compatibility is especially

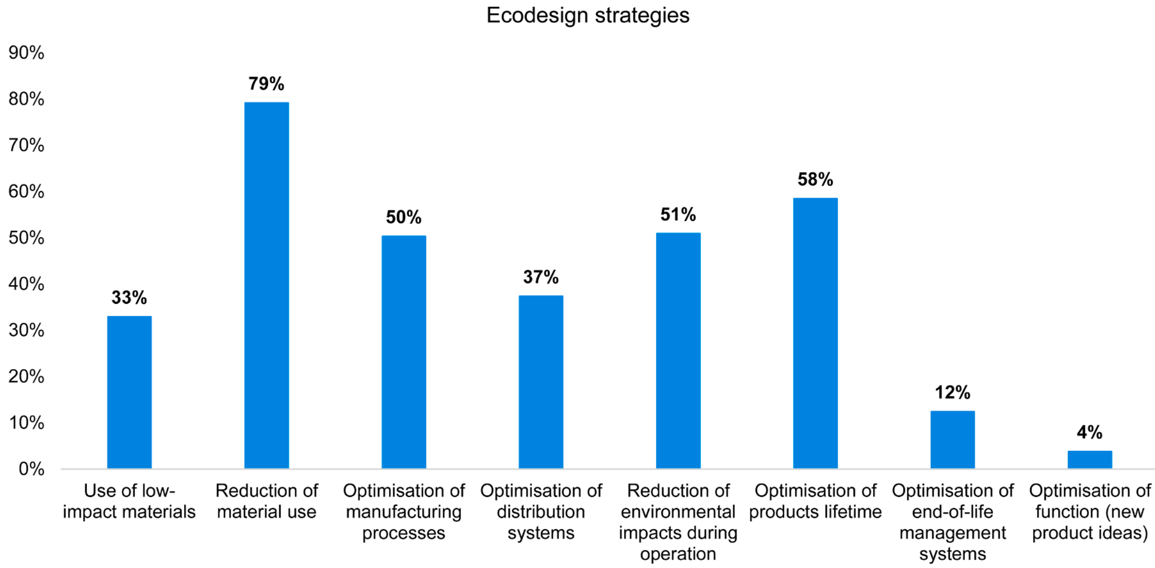

Figure 5. Ecodesign Strategies Implemented in the PE Industry.

important to avoid failures in critical systems. MC1 (Table 1) noted that '*Electromagnetic interference can damage not only the equipment components, but also the surrounding equipment, calling into question the reliability of our equipment*'. The maintenance and repairability of equipment is another aspect that all organisations agreed on: MC1 addedd that '*It is one of our key activities in the organisation, which is addressed from the early stages of design, involving different departments in the company. We have a committee of experts*'.

Many of the scientific studies developed in the field of PE aim to improve the reliability of equipment. Wang et al [99] presented a methodology of design for reliability of PE equipment based on the analysis of mission profile, thermal profile, failure mechanisms, and associated lifetime estimation. The LETSCOPE (Lifecycle Extensions through Software-Defined Predictive Control of PE) framework for extending the lifetime of equipment through predictive modelling was developed by Chu et al [17]. Ruthardt [85] proposed a closed-loop control system based on junction temperature, with the aim of minimising temperature fluctuations to reduce damage and extend the lifetime of equipment. Furthermore, Turkbay Romano et al [94] described the advantages of modularity to extend the lifetime of products through CE solutions such as reuse, repair, and recycling.

Lifetime optimisation is a crucial strategy for the PE industry and the academic literature, with both emphasising the importance of equipment reliability and durability to improve competitiveness and sustainability. This strategy seeks to extend the lifetime of equipment through reliable designs, effective maintenance, and ease of repairs and upgrades, which is a key objective of the ESPR [39]. By optimising the useful life of products, the manufacture of new products is minimised, thus reducing the consumption of new resources and the generation of new waste. Specifically, optimising the lifetime of a corroded reel by early detection and timely removal could lead to a theoretical total reduction of 188.8 tonnes of CO_2 emissions and significant savings in e-waste from a single defective coil [100]. The fact that both sectors agree on their vision for this strategy highlights the importance of optimising the lifetime of equipment as a means of improving the circularity of the sector.

3.2.3. *Reduction of environmental impacts during operation*

Reducing the environmental impact while in operation is a priority for the PE sector, as one of the key objectives is to improve efficiency by controlling the losses associated with drive and switchgear equipment [23,49]. According to MC2 (Table 1), '*Energy efficiency is at the core of PE, all our efforts are focused on reducing losses to the minimum possible.*'

Regulatory mandates (e.g. Regulation (EU) 2017/1369 [33], Directive (EU) 2023/1791 [29]) also require that manufacturers meet minimum energy efficiency requirements. PEs play a crucial role in processing energy from sustainable sources with optimal efficiency, however reducing their environmental impact during use is also key to achieving climate neutrality by 2050. During the in-use phase, durable and efficient designs can help reduce the environmental footprint of the equipment. Energy efficiency is key aspect of the environmental performance of PEs. For example, Musil et al [67] points out that energy losses of a standard solar inverter during 20 years of operation with 97 % of energy efficiency represent 187 kg of CO_2e, which is 19.6 % of the total carbon footprint. The importance of operational efficiency during the lifetime of these products is clear, prompting industry to develop innovative new wide-bandgap semiconductor materials that will facilitate further advances in this domain [23].

The alignment between stakeholder priorities and scientific research highlights the importance of creating more efficient PE equipment that minimises energy consumption and reduces the emissions generated during use. This convergence reflects the commitment of both sectors to energy improvement and the sustainability of the PE sector.

3.2.4. *Optimisation of manufacturing processes*

Experts place great importance on equipment manufacturing due to its high economic and environmental impact. Circularity and environmental sustainability criteria related to the manufacturing of EEE are well established and relevant in the industry. More than 50 % of the process optimisation criteria are considered a priority by the interviewed stakeholders. This is because optimising resources efficiently while minimising waste is critical.

The criterion with the highest score (95 %) was '*Reduce use of hazardous process chemicals (e.g. volatile solvents)*' (Table 2). This is consistent with the top criterion in the '*Use of low impact materials*' strategy, driven by the need to comply with the REACH directive [30]. Also highly ranked, with 80 %, was '*Reduce production waste*'. The MC1 expert emphasised that '*We try to optimise designs as much as possible so that there is no waste, which in the end is money wasted. We have measurement programmes to control the efficient use of resources*'. MC3 (Table 1) reported that '*In the last 5 years we have automated almost all production, we have eliminated manual processes that did not add value, reducing operator errors and making our semiconductor production more efficient*'. The lowest rated criterion in this strategy, 'Increase use of repaired and/or remanufactured parts' scored only 3 % (Table 2) suitability by stakeholders. This is mainly because the PE sector places high priority on performance and reliability, and the use of CE strategies such as repair or remanufacture are still unexplored in the sector [86].

PE manufacturing, particularly semiconductor production, is highly resource-intensive, requiring large amounts of energy that result in significant economic costs and environmental impact [4,14]. Improving process efficiency is key to mitigating these impacts.

In recent years, optimising production has gained importance in the manufacturing sector, giving rise to new methods for optimising manufacturing processes: First, automation and robotics. The Dalsaniya and Patel study presented robotic process automation (RPA) as an efficient solution to improve the productivity of semiconductor fabs. RPA improved process speed by ensuring semiconductor quality and automated repetitive and complex tasks [19]. Nguyen et al [68] developed a real-time automated algorithm for the inspection of PCB defects. The results of the study showed an accuracy of 97 % under ideal illumination conditions. Second, through additive manufacturing, electronic components such as PE semiconductors of high precision and complexity were created. Additive manufacturing remains a promising approach due to its capacity to reduce material use and enable rapid prototyping [24]. Third, Roccaforte et al [82] examined the challenges of ion implantation. This technique is becoming increasingly important and is fundamental to preserving the electrical properties of semiconductors (especially in SiC and GaN semiconductors), but there is still a need for improved thermal control to minimise structural damage. Fourth, digital models are postulated as drivers for a more sustainable transition of PE fabrication. Through digital models, energy and material resource consumption can be predicted and the environmental impacts of equipment manufacturing can be monitored. They also optimise semiconductor manufacturing by improving device performance, yield and cost [66].

Meanwhile, Gang Leil et al [60] have introduced a robust design technique called design for six-sigma to improve the manufacturing quality of both electrical machines and drive systems. PE products, such as electrical machines, are subject to manufacturing variations and uncertainties that can affect performance and reliability. The robust design approach takes these variations into account and can help optimise PE design to ensure consistent performance in series production.

The production optimisation strategy is a key issue in both industry and the academic literature owing to the importance of improving resource efficiency, reducing costs, and minimising the environmental impact of production processes. This synergy between both communities highlights the importance of implementing advanced and sustainable technologies that can help boost productivity in a more responsible and sustainable way [69].

3.2.5. Optimisation of distribution systems

The product distribution strategy was one of the least implemented in the PE sector. Although aspects such as route optimisation and reducing over-packaging receive acceptable suitability scores of 64 % and 60 % (Table 2), respectively, criteria relating to reducing transport-related impacts are often overlooked in the design of EEE, scoring a mere 18 %.

The PE academic literature approaches the optimisation of distribution systems from the perspective of an efficient supply chain, mainly for components. Scholars highlight the importance of using circularity and environmental sustainability criteria to help minimise the impacts resulting from the distribution of PE. These criteria include route optimisation, downsizing of production plants, use of reverse logistics models, and optimisation of packaging. Such strategies not only reduce the environmental footprint, but also reduce transport costs [83].

Once again, discrepancies emerge between industrial practices and the literature. While industry focuses mainly on circularity and environmental sustainability aspects such as over-packaging and route optimisation, key issues such as reducing the number of production locations, reducing energy consumption, and transport emissions are largely ignored. In the words of MC1 '*We don't pay much attention to these criteria as we outsource logistics operations*'. The ESPR, on the other hand, approaches this strategy from a more holistic viewpoint, advocating the use of ecodesign practices that favour the reduction of environmental impacts associated with this stage [39]. This difference underscores the need for the PE industry to adopt an integrated approach that incorporates social and environmental considerations into distribution practices.

3.2.6. Use of low-impact materials

The use of low impact materials was not a priority for the PE industry, less than 33 % of design and LCM decisions were related to the use of sustainable materials (Table 2). The interviews conducted with the PE industry stakeholders support this finding. Specifically, the criteria '*Select and/or increase the use of renewable, reused, recovered, and recycled materials*' received the lowest implementation score of 5 %. Stakeholder TC (Table 1) acknowledged that 'W*e have never considered using reused items, we buy them new. But we don't know anyone in the industry who is implementing them either, so rather than technical difficulties in incorporating these elements, we see difficulties of supply and demand*'.

In contrast, almost all stakeholders agreed on compliance with regulations on critical and hazardous substances. The criterion '*Substitute and/or reduce the use of hazardous substances*' achieved a high suitability score of 90 %, driven mainly by strict European regulations (e.g. REACH Regulation [30] and RoHS Directive [31].

Normally, the materials used in PE are inorganic semiconductors with hazardous alloys such as lead telluride (PbTe) or antimony(III) telluride (Sb_2Te_3) that present major challenges due to their scarcity, toxicity and high production cost [15]. In recent years, researchers have turned their attention to the development of new low-impact materials to create more sustainable alternatives for industry. For example, Kausar [54] has promoted environmentally friendly nanocomposites as alternatives to polluting energy sources. Brunetti et al [15] has proposed the use of organic thermoelectric materials to replace PbTe in semiconductors. Gao et al [46] have studied advances in green materials, such as carbon materials or biopolymers, for application in electronics or energy storage. Although much progress has been made, these green alternatives have several limitations, such as thermal stability or chemical resistance, which could compromise equipment performance and durability.

The reliance on critical conventional materials in industry, such as neodymium, or hazardous substances such as lead, highlights the absence or limited use of sustainable alternatives (Table 2). In contrast, the academic literature identifies several sustainable solutions. This highlights the gap between research and the reality of the industrial sector, which may arise from barriers such as costs, a lack of incentives, or specific regulations.

3.2.7. Optimisation of end-of-life management systems

The results were clear in terms of PE EoL management. The industry results showed that EoL is not taken into account in the design and LCM of PE equipment, and there are no strategies in place to improve the circularity and sustainability of products. On average, the criteria addressed in this strategy did not exceed 12 % suitability (Table 2). TC stated that '*These criteria do not apply to our activities',* suggesting that measures such as improved material efficiency and recovery or recycling processes are not valued.

Moreover, once the equipment is in the market, EoL is not managed by the manufacturer. MC1 commented that '*The management of this equipment is entirely the responsibility of the distributors*'. This would explain why industrial stakeholders negatively assessed all aspects related to the treatment and management of the equipment, as this is consistent with the reality in which they operate.

RC (Table 1) did, however, stress the importance of using sustainable materials that can be easily separated and recycled. They also highlighted the need for modular and easily disassembled designs to effectively separate components and recycle them correctly. Surprisingly, even recycling and EoL management experts found the choice of material challenging, stating that '*Recycling processes are not yet standardised, so the selected material may or may not be compatible, depending on the specialised recycler*'.

The main barrier to the very low level of application of these criteria is mainly the lack of responsibility of designers and manufacturers for the EoL of products. However, there are also more reasons: firstly, compact and miniaturised designs that make material recovery and effective recycling strategies difficult [90]. Second, a lack of methods to re-qualify the condition of components to ensure the necessary reliability and safety requirements [87]. Third, limitations and high costs of the infrastructure needed for specialised recycling and recovery plants [86].

The lifespan of electronic products is one of the main challenges facing society, with high waste generation and low recyclability rates in recent years [97]. Academics and regulatory bodies are focusing on extending the lifetime of products to minimise e-waste, and equipment architecture is key to this. Turkbay Romano et al [94] argued the importance of modular and easy to disassemble design of power converters to implement EoL strategies. In their study, they presented the advantages of designing modular PE products and the close relationship between this strategy and circularity. For example, they propose grouping less reliable elements into disposable modules to improve the repairability and maintainability of converters. The authors also recommend grouping together high-value, long-life elements to facilitate their reuse in other applications. The work also underlines the advantages of creating modules containing materials that can be recycled without separation. In a more recent study, Sangwongwanich et al [87] stressed the need to assess the state of components during their lifetime and identify the most optimal CE solution (R-strategies) to close the loop. They highlighted the need for new testing and analysis methods to check the condition of components for use in other applications, as currently this is mostly conducted by visual inspections.

The gap between the industrial reality and the academic and regulatory literature regarding EoL optimisation is evident. In practice, manufacturers largely neglect EoL considerations, delegating this responsibility entirely to distributors or consumers. In contrast, researchers and regulatory bodies attach great importance to this strategy, largely due to the environmental impact of products at their EoL [32]. This disparity underlines the need to integrate EoL design in the early stages of product development, promoting greater co-responsibility in product stewardship and aligning it with EU regulatory requirements.

3.2.8. Optimisation of function (new product ideas)

At present, PE industry priorities are focused on energy efficiency and product reliability rather than creating new business models based on product revisions or new formulas to differentiate from the competition. As the MC4 (Table 1) technician explained '*I am not responsible for those decisions, but the company's priorities are different now. We are focused on continuing to develop efficient equipment and to start including new semiconductor materials in our applications, that's where our innovations are focused*'. The criterion '*Transform physical solutions (hardware, software, or services) into digital solutions*' scored 5 % for suitability. The criterion '*Maximise product use intensity. Ex: leasing, renting or sharing*' scored a low 2 % (Table 2). This demonstrates how little interest the industry currently has in developing new business opportunities.

In an attempt to move away from the traditional make-use-pull model, in recent years new projects are being developed that give rise to new sustainable business models in the PE sector. For example, the European SiC4GRID project aims to optimise integrated SiC-based technology for converter applications by developing triple innovations in hardware, software, and the IoT [29]. The overall objective is to place Europe at the forefront of suppliers of converter technology for the integration of renewable energy into the energy grid. This project will not only deliver converters that are more sustainable than conventional converters but will also include optimisation models and digital twins that maximise the value of the product throughout its lifecycle.

Nevertheless, this strategy has not received significant attention from either industry or the literature, in fact it is the least addressed by both sectors. Both prioritise other approaches related to efficiency improvement, circularity and sustainability of equipment, relegating functional innovation as a driver of transformation to the background. This lack of attention may reflect a broader need to optimise and innovate in energy efficiency or the use of new materials, rather than developing disruptive concepts, representing a missed opportunity for breakthroughs in the sector.

3.3. Challenges and opportunities for the application of circularity and environmental sustainability criteria in the PE sector

The first challenge identified in this study lies in the discrepancy between product life stages. PE designers focus their efforts on the energy efficiency of the equipment during use [87]. However, they do not design for the EoL of the product because, once sold, they do not consider it their responsibility [84]. The different importance given by PEE designers to product life phases makes it difficult to apply holistic approaches to closing material flows and optimising the sustainability of the product throughout its lifetime. This is reflected in the suitability results that while the criteria of the use stage are widely integrated into industry practice, those related to the EoL of equipment receive only 12 % suitability for application. This is mainly due to the fact that equipment designers and manufacturers do not address the EoL of the product. Therefore, they are not aware of the challenges that exist at the EoL of these products. The lack of a complete life cycle structure for PEE limits circularity efforts in the EoL phase.

For example, the difference in the importance of each stage of the life cycle creates divisions in product responsibility in the EoL. Often, manufacturers do not take responsibility for the product when it reaches the life cycle phase and it is not clearly defined who is directly responsible for these products [36]. Furthermore, by not designing for the EoL phase of the product, there are difficulties in recovering materials, which limits the circularity of the sector. In addition, inefficient logistics also affects the other phases; not having a reverse logistics system in place increases the amount of waste that ends up in landfills, losing its residual value and the possibility to repair and remanufacture it [56]. This challenge faced by PEs is also reflected in the lack of communication between the different industrial actors in the sector, being the second challenge identified [76].

The third major challenge for the sector is the lack of sustainable material alternatives. Although new innovations in recycled or low-impact materials are reported in the literature, these are yet to be adopted in the PE industry, perpetuating the dependence on critical, non-renewable, raw materials [15]. Major advances have also been made in the development of new semiconductor materials, such as SiC and GaN, which improve the thermal performance and energy efficiency of PE devices, contributing to their overall sustainability [23,91]. However, the extraction and production of these materials are energy- and resource-intensive, presenting substantial environmental challenges [71]. Addressing these impacts is essential to ensuring the viability of these materials as sustainable alternatives in the sector. A further constraint is the lack of infrastructure for recycling and recovery processes [48]. This sixth gap in material recovery technologies limits the circularity of the sector and the potential to use high-quality secondary raw materials.

The PE sector also faces the fourth challenge of incorporating disruptive innovation to address organisational change. At present, manufacturers focus their efforts on improving efficiency, rejecting CE solutions such as rethinking that could offer substantial competitive advantages [86]. Adopting these CE solutions would allow companies to anticipate and adapt to emerging trends, positioning themselves as leaders in sustainability, innovation, and competitiveness.

Finally, the PE industry struggles to assess the true circularity its products. This fifth challenge is critical both for the internal management of a company and the ability to meet market standards and expectations. This challenge stems from several factors, including a lack of data (e.g. EoL data), absences of specific standards to measure circularity, and the inherent complexity of materials and products [86,96].

However, these challenges also present 5 significant opportunities for the PE sector. The current disconnect between the value chain stakeholders presents an opportunity to create new partnerships and collaborations to overcome technical and economic barriers. For example, consortia could be created to develop new standards or create shared technologies for EoL management. In this respect, the PE industry has the opportunity to develop new advanced technologies to optimise recycling systems.

The logistics stage, often overlooked by the industry, represents another opportunity for improvement. Optimising this phase can reduce emissions and costs associated with transport. The integration of electric vehicles would lower the carbon footprint of the sector and reverse logistics systems would close the life cycle of materials and components, improving circularity and sustainability [69].

In addition, the current lack of specific regulation driving the transition to the CE can be leveraged as an opportunity [43]. Companies that take the lead in complying with regulations such as ecodesign [39] or WEEE [32] will be better positioned in the global market and differentiate themselves from their competitors. This can present a good opportunity to enter new markets in which product sustainability is a priority.

Pioneering the use of innovative, low impact materials can also offer competitive advantage. As well as improving the environmental image of the sector in the eyes of consumers and governmental organisations, this could also open doors to emerging fields such as biotechnology applied to materials. Training workers in CE practices could further transform the innovation capacity of firms. CE strategies also strengthen resilience to global challenges such as resource scarcity and raw material price fluctuations. Staying ahead of these challenges is therefore key to ensuring the viability and continuity of companies.

Finally, prioritising product design and LCM as the main axis for the development of circular and sustainable products can deliver substantial benefits for the industry [77]. Incorporating circularity and sustainability criteria from the earliest stages of the product life cycle can deliver significant improvements for organisations. Focusing on aspects such as modularity, use of recyclable materials, and ease of disassembly not only improves the circularity of products, but also helps to reduce long-term costs and environmental impact.

On balance, the PE sector has great potential to transform industry challenges into opportunities—from design to logistics to product EoL. The integration of circularity and environmental sustainability criteria will not only improve the environmental impacts of the sector, but also position the PE industry as a leader in innovation and competitiveness in a highly volatile global market.

3.4. Limitations of the research

One limitation of the study is the sample size of the interviewed industrial stakeholders. Although the interviewed population was small, it should be noted that with only five participants it is possible to identify 80 % of the usability problems of a product, tool, or process [16]. The sample of nine stakeholders includes key actors from the PE value chain, such as universities, technology centres, multinationals, and a waste manager (See Table 1 for further details). This provided a comprehensive overview of the perceptions of the PE sector, as each was selected for their expertise in the life cycle phases of PE equipment. Moreover, some of the participants are part of the European SiC4GRID project [29], and as such are directly linked to the latest developments in sustainable solutions for this sector. The sample ensures representation of all phases of the product life cycle, from design to EoL, while also enriching the analysis with perspectives aligned with reference projects.

However, another related limitation lies in the fact that each stakeholder evaluated the criteria from the perspective of their specific role within the value chain. Since no stakeholder has a complete view of the entire life cycle, the scores assigned reflect context-specific priorities and expertise. This variability is both expected and valuable for understanding real-world constraints, but it also implies that the aggregated results may be influenced by the relative representation of different stakeholder groups. For instance, if certain phases (e.g., design or manufacturing) are more represented than others (e.g., EoL), this could shape the overall perception of some criteria's relevance or feasibility. Future studies should involve a larger and more balanced stakeholder sample to provide a more complete and representative picture of the PE sector. Expanding the sample would also enable more robust statistical analysis and support conclusions with greater validity and reliability.

Secondly, the criteria analysed are relevant to the circular and sustainable design and LCM of EEE but are not unique to the PE sector and may even be too general in some cases. At present there are no specific guidelines and/or standards published for the sector, and this could limit the identification of needs and challenges for the PE industry. Furthermore, these criteria provide little guidance on practical implementation, further complicating efforts by industry stakeholders to adopt them effectively. To make it more practical, circularity and environmental sustainability criteria should be linked with specific metrics [75].

Third, this study is qualitative in nature. Qualitative assessments are essential to preliminarily identify the most relevant aspects of circularity and sustainability, providing practical information to guide more specific quantitative studies. These assessments are particularly useful in the early stages of projects, when limited information is available [72]. This approach not only optimises the use of resources and time, critical aspects in the development of LCAs, but also ensures that subsequent quantitative metrics focus on the areas with the greatest potential impact, maximising their relevance and effectiveness [55]. Therefore, complementing qualitative results with the integration of CE indicators and LCA and quantitative tools is one of the future directions of this work, which will help to measure the circularity performance and environmental impacts associated with applied circular design and sustainable LCM strategies.

Finally, the economic costs of applying these ecodesign criteria in the PE industry have not been directly analysed, which may present a limitation for the study. As highlighted by the studies of Ghisellini et al [47] and Kirchherr et al [57] the economic challenges faced by companies in terms of sustainability is one of the biggest challenges to transit towards a more circular and sustainable economy. Therefore, analysing economic factors would provide a more realistic view of the challenges and opportunities presented by the application of circularity and environmental sustainability criteria in the PE sector. Nonetheless, the perception of the stakeholders regarding economical barriers was still included in the feasibility score of criteria. This was a minor way to consider the economic factor of implementation of CE strategies, although for scaling-up processes a further economic assessment is needed.

4. Conclusions

This article presents a comprehensive list of circularity and environmental sustainability criteria applicable to the PE sector. In contrast to previous studies, we analysed the perceptions of industry and research stakeholders regarding the practical application of circularity and environmental sustainability criteria in the design, manufacture and LCM of PE. By classifying the criteria into life cycle stages and CE strategies, the study adopts a holistic approach not previously explored in the literature.

The results offer key insights into the current state of circularity maturity in the sector, identifying priorities and discrepancies between academic and industry perspectives. Thus, the analysis provides a broad and strategic perspective on the challenges and opportunities facing the industry as it transitions towards more sustainable models. The key contributions of the study are as follows:

- This study identifies five key challenges and five key opportunities regarding the application of circularity and environmental sustainability criteria in the power electronics industry. These results show both the challenges and opportunities for improvement in the transition to CE in the PE sector.
- The 61-criteria evaluation matrix for PE that provides stakeholders with a practical support tool to identify and select relevant circularity and environmental sustainability criteria, while considering how design and LCM decisions affect each stage of the life cycle.
- The analysis highlights the importance of addressing EoL challenges to implement ecodesign strategies and achieve greater circularity. Despite the attention in the academic literature, the EoL stage, does not receive sufficient attention from industry, underscoring a significant implementation gap. Similarly, strategies in the logistics management stage were also found to be lacking, such as implementing reverse logistics. This could help the implementation of CE strategies such as reuse, remanufacturing and/or even recycle, leading in turn to extended product responsibility (EPR).
- Interviews with stakeholders reveal disconnections in the value chain, such as a limited availability of alternative sustainable materials and an absence of reuse, recycling, and recovery technologies. These challenges point to a need to form alliances different stakeholders, develop new sustainable materials, and create adequate infrastructures to ensure circularity. Once turned into opportunities, these points could position the industry in emerging markets through the development of sustainable materials and advanced recycling technologies.
- The analysis identifies the need for more accurate metrics and standards to help calculate the circularity and environmental sustainability of products, which is key to assessing the impact (both positive and negative) of the strategies implemented.
- Governmental institutions must also become more involved in the development of sector-specific public policies. For instance, providing incentives to organisations for the development of new sustainable materials and infrastructures is crucial to close the product life cycle. On the other hand, companies adopting EPR would facilitate the implementation of EoL strategies by ensuring the proper management of PE at EoL. In addition to the adoption of EPR, the implementation of the digital product passport (DPP), an initiative to enhance transparency across product value chains, will facilitate waste management through detailed information on product composition, use and recyclability among other aspects. The DPP will be a key tool in the PE sector as it will provide transparency on products and facilitate the implementation of CE strategies such as repair or recycling.

This research establishes a foundation for building knowledge, improving communication, and fostering collaborative efforts throughout the value chain to improve the sustainability of PE products. To build on these findings, future lines include the following:

- Involve more value chain stakeholders in the evaluation of circularity and environmental sustainability criteria to obtain a more complete and representative picture. Expanding the sample will allow for more robust statistical analyses and the drawing of conclusions with greater validity and reliability.
- Incorporate circularity indicators and LCA to quantitatively measure the impact of the criteria applied, identifying critical points for improvement throughout the product life cycle.
- Benchmark CE efforts in the PE sector against those of other industries, such as the electric battery industry.
- Broaden the scope of the study to include non-EU contexts—such as Asia, North America, and emerging economies—to highlight both commonalities and regional adaptations.

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.

CRediT authorship contribution statement

Irati Ruiz de Azua Lahidalga: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eider Mendiburu-Valor:** Formal analysis, Data curation. **Daniel Justel:** Methodology, Formal analysis, Conceptualization. **Joan Manuel F. Mendoza:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

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Supplementary materials

Supplementary File for this study is available. It provides detailed information about the literature searches done to identify relevant journal papers (S1). The evaluation matrix of the circularity and environmental sustainability criteria used with stakeholders (S2). Prompts used in AI tools (S3). And finally, definition of life cycle stages and circular economy solutions and strategies (S4).

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2025.105199.

Data availability

No data was used for the research described in the article.

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