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Eco-design implementation in Power Electronics: a literature review

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Objective – In our society, the production of electricity from renewable sources and its usage in the mobility, air conditioning, and manufacturing industries are increasing day by day. To be able to use this electricity efficiently and to control and shape such energy from the various sources to the numerous types of loads, the required interfaces are Power Electronic Converters (PEC)s. The production and usage of PECs are today increasing, proportionally to the share of electricity in the energy mix of our societies. Therefore, the environmental impact of these PECs has become critical considering their accelerated usage not only in renewable energy sources but also in electrical household products, electrical mobility, etc. Therefore, PECs should integrate eco-design requirements and be developed, used, and repaired in a circular perspective. This review paper explores the current PEC eco-design practices implementation and the corresponding environmental impact indicators considered in these approaches. From this review, the discussion highlights the opportunities to enhance PEC products' eco-design considering circularity scenarios in a Design for Sustainability (DfS) perspective.

Findings – Four main eco-design approaches applied to PECs have been identified: (i) energy efficiency optimization, (ii) eco-sizing, (iii) eco-reliability, and (iv) multi usage lifecycle innovation.

Originality – There is no available literature review gathering eco-design implementation in PE domain yet. Therefore, the main contributions of the research are: (i) identification of the existing eco-design practices in PE field based on an extensive systematic literature review to support researchers addressing (ii) the analysis of identified approaches in the generic Life Cycle Assessment (LCA) framework and the proposition of the relevant method or the development of the one that is lacking for their context.

Keywords – Eco-design, Design for Sustainability, Life Cycle Analysis, Multi-Criterion Analysis, Power Electronics Converter, Sustainable Circularity Strategy, Energy Efficiency, Eco-sizing, Eco-reliability, Multi-usage Lifecycle Innovation

1. Introduction: Eco design approaches in Power Electronic Converters

Power Electronic Converters (PEC)s are used to convert and control electrical energy from one form to another form. The integration of PECs in various systems has enabled the implementation of a wide range of applications, including but not limited to electric mobility, household appliances, residential heating, photovoltaic and wind power generation systems, and air conditioning systems [1]. Especially by enabling the use of renewable energy sources, PECs have become a key technology in our modern society toward the decarbonization of many applications energy source [2]. However, the policies aim to achieve carbon neutrality by 2050. This implies systemic changes in switching current energy sources from fossils to electric renewable while carefully checking all potential environmental impacts shifted from one process to another. For this purpose, Power Electronics (PE) engineers and designers need to consider the entire life cycle of the products during the design process. This requirement helps to identify the potential rebound effect or burden shifting, that result from the systemic changes designed to achieve carbon neutrality targets. The nine Planetary Boundaries defined by Steffen et al. (2015) [3] and Persson et al. (2022) [4] need to be considered to stay in a safe operating space in the future, which include the resources extraction required for electronics and associated land-use, the emissions to air, water and soil at each steps of the process considered, as well as the electronic waste production. In these sustainable goals and for answering the Paris Agreement to keep global warming within 1.5 degrees Celsius of pre-industrial levels eco-design principles aiming to achieve circularity in PEC is a topic of growing interest.

A PEC is generally composed of wiring, mechanical fasteners, heat sinks for power semiconductors, the outer casing of the equipment, semiconductors, capacitors, magnetic elements, integrated circuits, and Printed Circuit Boards (PCB). The environmental impact of a PEC is the result of various factors such as design choices, technology, manufacturing processes, End-of-Life (EoL) management practices, and societal cultural, and environmental awareness. For example, Tin-Lead (SnPb) solder has been widely utilized in the PEC industry due to its cost-effectiveness and high reliability in a wide range of operating conditions, as well as its technical characteristics, such as low melting point and resistance to fatigue. However, it has become legally mandated by RoHS (Directive 2002/95/EC) [5] (stands for Restriction of Hazardous Substances) to replace lead in solder with more environmentally friendly alternatives, due to the toxic nature of Pb and the associated environmental concerns. Another example is that the production of power semiconductors involves the use of a large number of chemicals, many of which are toxic and used in significant quantities. These chemicals can potentially cause negative impacts on air, water, and soil, and also expose workers to an occupational hazard in the production line. The process consumes a substantial amount of electricity and large amounts of high-purity water and also requires the use of elemental gases. Purification of chemicals also requires a large amount of energy input. For the magnetic components, low-frequency components have a relatively low environmental impact during manufacturing and are easily recyclable. On the other side, high frequency components are much more compact, lowering the pressure on material resources. Also, high-frequency elements use materials that are more polluting during the manufacturing process and are more difficult to recycle [6].

Therefore, the implementation of eco-design principles such as materials, energy efficiency, EoL management, etc. plays a crucial role to reduce the environmental impact of PECs. This paper aims to provide a comprehensive overview of existing literature on the eco-design of PECs by summarizing and organizing them. It clarifies current knowledge, identifies gaps, and highlights emerging trends in PECs eco-design approaches.

2. Material and Method: a scoping review of PE eco-design approach

The research method applied in this article is a scoping review proposed by Arksey and O'Malley (2005) [7]. The stages of this study are: identifying the research question, identifying relevant studies, study selection, charting the data, and collating, summarizing, and reporting the results, cf. Figure 1.

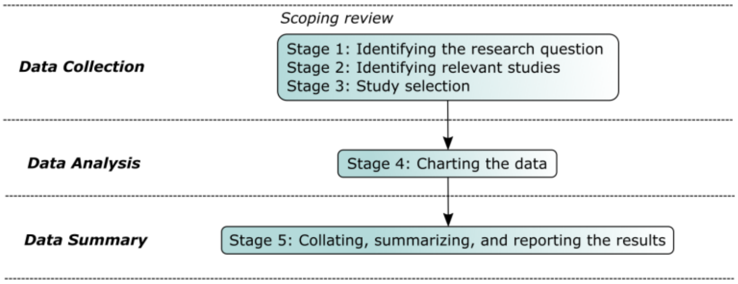

Figure 1: Stages of the framework for conducting a scoping study adopted in this research [7].

The state-of-the-art search questions formulated are twofold: (SQ1) What are the eco-design approaches developed for Power Electronics in up-to-date literature? (SQ2) Which environmental impact indicators are considered by the PE designer along the product life cycle stages? As these search questions deal with the intersection of two fields, the keywords encompass: (A) Eco-design keywords: eco-design, design for environment, lifecycle analysis, circularity, sustainability; and (B) Power electronics keywords: Power electronics, power converter, all the passive and active components.

These two sets of keywords are combined for the database search, including IEEE, Science Direct, Springer, Web of Science, and Google Scholar. Table 1 provides a summary of all the criteria and related research items used for the literature review.

To identify studies on PE-related eco-design applications, the collected articles were screened by examining the topics, abstracts, introductions, main content, and conclusions. The articles that did not address PE-related products or related environmental conscious design concepts in their main content or discussion were ultimately excluded. Among the significant amount of energy efficiency and reliability studies in the PE field were only included the one addressing environmental considerations. As a reminder, LCA is used to quantify the environmental impact of a product during its entire life cycle, from the extraction of raw materials to the end of its useful life, and identify improvements to reduce the environmental impact of the products. In the perimeter of this study, LCA studies not contributing to a PEC environmental impact reduction was not considered. The criteria used for this examination are: the approach must (C1) integrate environmental considerations and aims to reduce environmental impacts; (C2) address Power Electronics-based products design; and (C3) be tested and documented in a peer-reviewed publication.

Table 1. Literature research criteria and research items.

Criteria	Research Item
Keywords	(eco-design **OR** design for environment **OR** lifecycle analysis **OR** circularity **OR** sustainability) **AND** (power electronics **OR** power converter **OR** all the passive and active components)
Database	IEEE, Springer, Science Direct, Web of Science, Google Scholar
Language	English
Publication Year	1999 – Feb 2022

Relevant eco-design approaches are identified from current PE design research. The articles related to the findings are charted with the author(s), year of publication, location, PE related case study, and system level addressed (Table 2).

In the results collation stage, these approaches are firstly analyzed in a generic life-cycle-analysis framework (Figure 3). Then the environmental impact categories and life-cycle stages addressed in different approaches are highlighted.

3. Results

3.1 Statistical Analysis and Summary of the Literature Review Results

A total of 11 relevant articles were found from 2007 to 2022 after the search and practical screening. Based on the selection criteria, four eco-design approaches are identified from current PE design research: (i) energy efficiency optimization, (ii) eco-sizing (iii) eco-reliability, (iv) multi usage life cycle design.

The distribution of articles on eco-design practices in PEC is strongly focused on the integration of new technologies to achieve optimal energy efficiency and power density during the usage stage. A search of the IEEE database using the keywords "efficiency", "power density", and "power electronics" revealed that 2465 papers were published worldwide in the past one year (2021-2022). New technologies to achieve optimal energy efficiency and power density in power electronics are usually proposed by authors.

However, the study of the other specific approaches such as eco-sizing, eco-reliability and multi usage life cycle design are limited to a few research laboratories and has not yet been widely promoted on a global scale. The review results show that the first publication on eco-sizing was in 2007 by B. Multon and his research team [8]. Since then, the research team has applied this method from 2007 to 2012. So far, a total of four papers have applied this method to eco-design of PEC. Eco-reliability, which is an eco-design approach proposed by Nissen et al. in 2012 [9], has been applied in PE in one article in the case of bond wires in discrete semiconductors.

Multiple usage life cycle is a relatively new approach, first proposed by Rio et al. in 2020 [10], which aims at incorporating circularity concept in product-service systems. Based on this concept, two publications have been published in 2021 in this field [8][9], and a project called “VIVAE” (funded by French National Research Agency) has been started in 2022 to deepen the understanding of this approach [12].

An overview of the articles reviewed in literature is provided in Table 2. The first column lists the eco-design approaches along with their definitions. The second column displays the location of the research work. Columns three outlines the environmental indicators. Column four shows different life cycle stages addressed in the design approaches. (To ensure comprehensibility for readers who may not be familiar with the concept of product life cycle stages, Figure 2 has been included to depict the different life cycle approaches.) Finally, the fifth column specifies the case studies in which the related eco-design approaches were applied. To better understand and compare the application of eco-design approaches, case studies were classified into four different levels: (i) Material level (e.g. Copper, Iron, and Aluminum); (ii) Component level (e.g. individual ECs); (iii) Converter level (e.g. PCB-based PEC); and (iv) System level (final PCB-based PEC product including the casing, cables, safety equipment, fan, etc.).

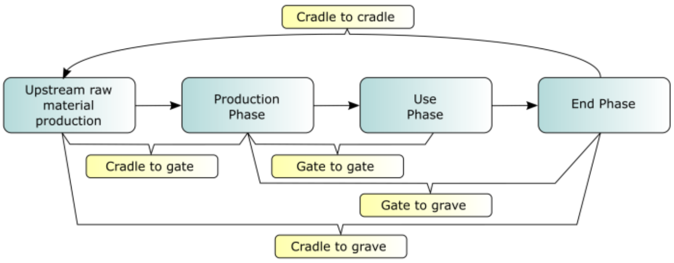

Figure 2: Life cycle stages (green) and life cycle approaches including those stages (yellow) [13].

Table 2. Eco-design approaches developed and applied in PE design research.

Approaches	Study location	Environmental impact consideration	Life cycle approaches	Case study
Energy efficiency (η = Pout / Pin)[1]	Global	Energy consumption	Gate to gate during use Cradle to grave from raw material extraction to end of life treatment	**Electronic component level:** Power transformers in the electric power system [14]. **Converter level:** Inverter for AC Drives [15]; Converter system using SiC MOSFET for EV [16]Inverter for AC Drives[15]; Converter system using SiC MOSFET for EV [16]. **System level:** drive system [17] (other references not listed among the 2,465 publications from 2021 to 2022 in the database IEEE).
Eco-sizing PEC and environmental performances sizing	France	Global primary energy and material mass	Cradle to grave from raw material extraction to end of life treatment	**Electronic Component level:** Single-phase transformer connected to a fixed-frequency tension network [8] Planar Transformer in a Dual Active Bridge [18]. **Converter level:** Self-oscillating DC-DC flyback converter [19]; Electro-mechanical energy converters connected to three-phase squirrel-cage induction machine [20].
Eco-reliability Achieve the balance between environmental and reliability requirements	Germany	Toxic potential indicator, Resource Availability and Risk Indicator (RARI), Cumulated Energy Demand (CED), CO_2eq.-Emissions during primary and secondary metal production stages, masse	Cradle to grave from raw material extraction to end of life treatment and recycling	**Material level:** Bonding wires in power electronics [21]
Design for Multi usage life cycle Integrate circularity constraints in PEC design	France	Multi-impact analysis, ISO 14040 LCA impact indicators	Cradle to cradle from raw material extraction to multi usage life cycle	**Converter level:** Multi-Cell PEC [8][9]

[1] η: Efficiency, P_{out}: Output power, P_{in}: Input Power

3.2 Current Eco-design Approaches in PEC: Purpose, Usage and Results

Energy efficiency is the one of the key performance metrics in PE. The efficiency of a converter is determined by comparing the input power to the output power, and is calculated by dividing the output power by the input power (η = Pout / Pin). According to research by Popovic-Gerber et al. (2011) [15], the PE community has been actively working to improve the efficiency of PEC in order to reduce energy consumption, and related CO_2eq. emissions with respect to carbon intensity of the electricity dissipated in the converter. Several basic methods and procedures were proposed to improve PECs efficiency such as optimal topology selection, design optimization, efficiency optimization by digital control, and the use of faster switching devices [15].

Eco-sizing of PECs is first proposed by Multon et al. in 2007 [8], aims to optimize the product life cycle by improving dimensional parameters or material properties to minimize two conflicting criteria: global primary energy and material mass. This approach has been applied to various electronic systems, as demonstrated in the following examples: Debusschere et al. (2007) [20] applied a genetic algorithm to eco-size a power system (single-phase transformer) connected to a fixed voltage and frequency network. With the aim of minimizing the life cycle cumulative primary energy, also known as Gross Energy Requirement (GER) which is a measure of the total energy consumed during the entire life cycle of a product or system, they optimized the transformer size and the total mass of the active parts (magnetic circuit and winding). Jaouen et al. (2011) [19] proposed a study to eco-size a self-oscillating flyback converter, by using an optimization model linking loss characteristic parameters, component dimensions, and voltage and current ratings. Freitas Lima et al. (2021) [18] applied this approach to analyze and eco-size a planar transformer in a dual active bridge (DAB) application.

Eco-reliability approach appears as a first step toward a multi-criterion optimization approach. The novel concept of eco-reliability was first proposed in 2011 by Nissen et al. [9] from the Fraunhofer Institute for Reliability and Microintegration (IZM). This approach combines the principles of eco-optimization and reliability, with a core focus on a trade-off analysis across multiple design domains. In 2015, Andreas Middendorf et al. [21] introduced the concept of "eco-reliability" in PE. The main objectives are to support PE designers in making choices against the background of mission profiles, system requirements and available technologies, seeking a balance between the product's reliability and environmental soundness. A case study were conducted to demonstrate the applicability of a PE eco-reliability approach in the wires bonding, used to electrically connect the top surface power semiconductors [21]. The study has shown that a clear design decision on the choice of material (Cu, Fe) can be made by considering various criteria such as Toxic Potential Indicator, Resource Availability and Risk Indicator (RARI), Cumulated Energy Demand (CED), CO_2eq. Emissions during the production of primary and secondary metal[1] [21].

Design for multiple usage approach addresses circular economy issues into power electronics. Design for multiple usage is a holistic approach that promotes circular thinking by considering the entire lifecycle of a product, including repair, reuse, remanufacture, and recycling. In 2020, Rio et al. [10] introduced and adapted this approach to electronic designers to design modular power converters with a multiple-usage life cycle perspective. The proposed method involves requirement clarification, functional specification, LCA and risk analysis. In 2021, Rahmani et al. [11] proposed a multidisciplinary method using LCA and Design Failure Mode and Effects Analysis (DFMEA) to design modular power converters with the aim of optimizing energy cost and reuse cycles by evaluating the Mean Time Between Failure (MTBF). This approach involves implementing circularity strategies such as increasing the product's lifespan, facilitating maintenance and repairs, designing the subsystems of converters for reuse, repurpose and recycle. The method incorporates circular design constraints into product design, which aims to preserve the functional value of converters and minimize multiple environmental impacts.

4. Literature findings discussion: a framework to address lacks and requirements for future research

Since key principle of eco-design (IEC62430) is the concept of Life Cycle Thinking (LCT), in addressing the second research question, the identified approach and associated literature were analyzed under the framework of Life Cycle Assessment (Figure 3). On the X-axis, the stages of the product life cycle were listed. On the Y-axis, the indicators refer to the Product Environmental Profile (PEP Ecopassport®) standard, developed for environmental declarations specifically for Electrical and Electronic Equipment (EEE) products [22]. Two types of indicators are identified: (1) Seven environmental impact indicators (in blue)[2] and (2) Thirteen inventory flows indicators (in orange)[3]. Life cycle studies can be performed for various scopes: cradle to gate (e.g. raw materials until the factory gate), gate to gate (e.g. only focusing on the use stage) or cradle to grave (raw materials until disposal). Addressing the environmental issues during the whole life cycle of a converter system has to be conducted from a cradle to grave perspective, including potential reuse/repair/remanufacturing steps. Once the "hotspots" of the converter system (e.g. sub-module of converter system, manufacturing process) is identified, the type of design approach to reduce the environmental impact generated by any technical evolution may be chosen by PE designers. This system-view (X and Y axis) aims to highlight the life cycle stages and environmental impact indicators addressed in the current literature. The view provided by the analysis and organization through LCA framework has revealed some interesting trends that are worth to be emphasized, for instance, the limitation of current approaches, and the potential for coherence among them.

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[1] Primary metal: production of metal from primary resources; Secondary metal : production metal from recycling process;

[2] Global warming (kg CO2 eq), Ozone depletion (kg CFC-11 eq), Acidification of soils and water (kg SO2 eq), Water eutrophication (kg (PO4)3- eq), Photochemical ozone formation (kg C2H4 eq), Depletion of abiotic resources elements (kg Sb eq), Depletion of abiotic resources – fossil fuels (MJ);

[3] Total primary life cycle energy use/MJ, net freshwater use/m3, primary energy resources use/MJ, use of secondary materials/kg, energy use of secondary materials/kg, renewable secondary fuels use/MJ, use of non-renewable secondary fuels/MJ, hazardous waste disposal/kg, non-hazardous waste disposal/kg, radioactive waste disposal/kg, components for reuse/kg, materials for recycling/kg, materials for energy recovery/kg.

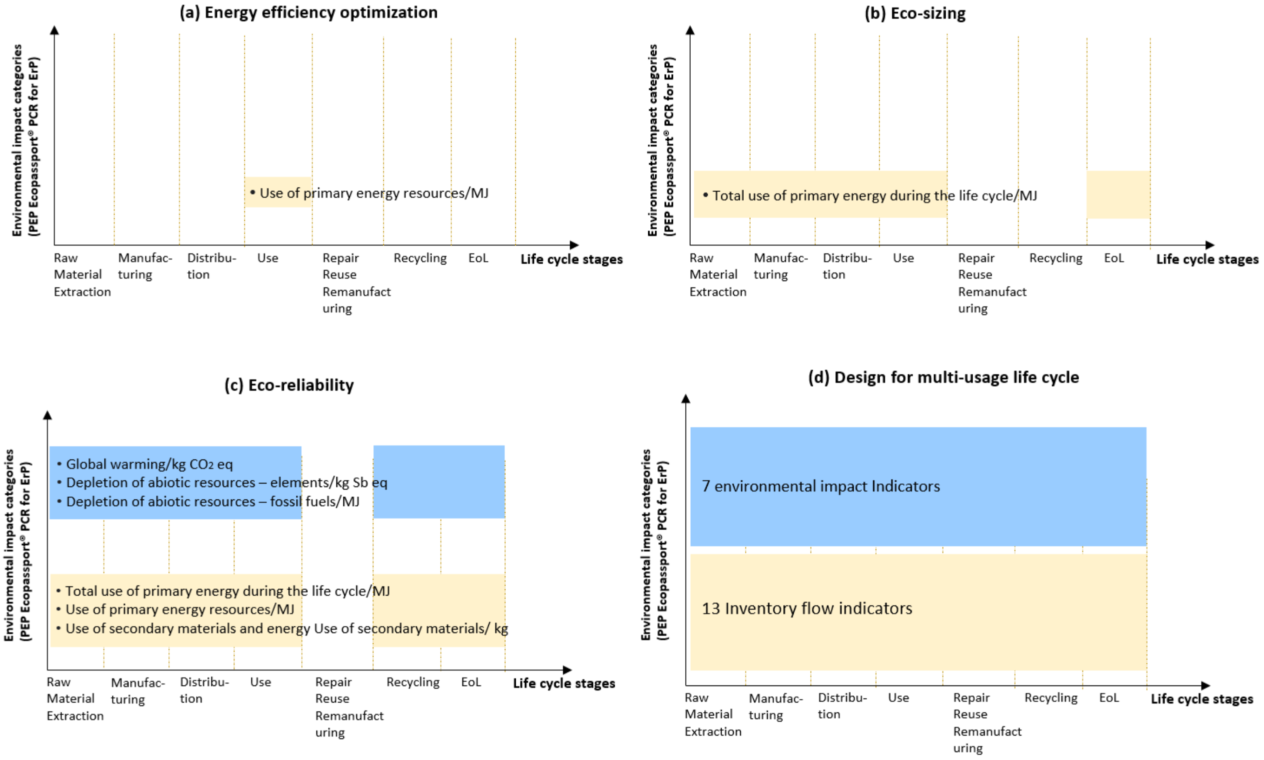

Figure 3: Analysis of current PE eco-design approaches in the generic framework of LCA.

4.1 Environmental Impact Categories Addressed

The energy efficiency optimization approach only considers the energy consumption indicator, related to the use of primary energy resources (inventory flow indicator). This has a limited connection to CO2eq. (global warming indicator), as the amount of CO2eq. produced is largely determined by the composition of electricity mix. As a result, any progress made through energy efficiency optimization can be negated or reversed due to an unfavorable electricity mix. Eco-sizing considered the two indicators CO2eq. and material consumption. Eco-reliability extended to various criteria, such as toxic potential indicator, raw material depletion, CO2eq. and mass. Design for multiple-usage approach has the ambition to include the ISO 14040 recommended environmental impact categories. The majority of literature founded in this research focuses on optimizing energy efficiency. This streamlined approach generates some side effects well known by eco-design experts. For instance, optimizing energy consumption during usage of a product may result in an increased consumption of the same device by users, which is a phenomenon known as the rebound effect. This was first demonstrated in the energy economics field during the 1970s oil crises, with the works of Khazzoom (1980) and Brookes (1990)[23]. Additionally, the side effect of optimizing only one indicator is to increase another impact category. In eco-design burden shifting from one design strategy to another are common and must be taken into consideration, meaning that efforts to solve one environmental issue (e.g. carbon footprint) create new ones and exacerbate others [24]. Eco-designing is finding the best compromise to globally reduce the environmental impacts generated by the product during its life cycle, while satisfying (at least) the same functionalities, and delivering the best socio-technical values.

4.2 Life Cycle Stages Considered

The majority of articles optimizing energy efficiency focus on the "use phase" or on a "gate to gate" period corresponding to the PEC operation time. In the proposition of Popovic-Gerber et al. (2011) the energy payback time also includes the energy used during the manufacturing process [15]. Whereas for the eco-sizing approach the study scope is extended to the entire life cycle, from raw material extraction to disposal, referred as "cradle to grave" scope. The eco-reliability considers recycling as a plausible end-of-life scenario. Finally, designing for multiple uses opens the perspective of circularity, with scenarios of re-use, repair, recycle, remanufacturing, and recycling. The circular ideal suggests “cradle to cradle” scenarios, which aims for regenerative systems without waste (or waste equal resources to another system). However, even if the reuse of PEC and its components may enter in the production of other products in the future, there is no 100% circular future for current PEC. A radical eco-innovation for sustainability would be required, addressing circularity issues at a socio-technical level.

4.3 Lack of Literature in the Field of LCA Applied to PEC

Although a few LCA studies on PECs has been published recently, there is still a lack of data Life Cycle Inventory (LCI), including component design or material transformation processes. Nordelöf et al. (2019) [25], [26] proposed a preliminary solution by publishing a scalable Life Cycle Inventory (LCI) method based on the inverter's voltage and power requirements. This method represents a valuable contribution to the development of databases for power converters. It should be emphasized for its importance in LCI, which a useful step for the (d) Design for multiple usage approach. Another cradle-to-grave LCA study conducted for D-STATCOM by Quintana-Pedraza et al. (2019) [27] provides a more realistic carbon footprint estimation of electro-intensive PE products. The most recent study conducted by Kockel et al. (2022) [28] investigated the environmental impacts of microgrids at the building level using LCA. Kim et al. (2019) [29] evaluated the environmental impacts of the PV system containing second life components compared to a more conventional system using LCA as well. They repurposed the used power supply units to replace charge controller, used UPS units to replace inverter and used lighting, and ignition batteries to replace the typical deep cycle batteries. Smith et al. (2018) [30] LCA measured and compared the environmental impact of two different types of capacitors: Tantalum Electrolytic Capacitors (TECs) and Multilayer Ceramic Capacitors (MLCCs). Replacing TECs with MLCCs result in significant environmental savings referring to this assessment. In the literature, there is not enough data to summarize and provide easy access to significant literature data on PECs. If PEC manufacturing relies on traditional raw materials and processes, it remains difficult today to identify material and energy consumptions since no data is made available by manufacturers. This gap can be filled by PECs manufacturers providing the scientific community with significant LCI data related to materials and processes with the ultimate goal of facilitating eco-design methods.

4.4 Eco-design Methods and Tools Ready to Be Implemented in PE Industries

To strengthen eco-design implementation in PE industries, the PE eco-designer needs to further investigate and adapt the existing eco-design method in the field of Electrical and Electronic Equipment (EEE) to PE. The Eco-design Pilot EEE is a practical easy-handling tool facilitating the PE designer to fulfil the RoHS and WEEE directives. To address the PE’s circular design issues and meet the requirements set by the Circular Economy Action Plan (CEAP) [31] adopted by the European Commission, the CIRCit research project (2017-2021) proposed an impressive circularity toolbox supporting eco-design tools’ development and implantation, so as to guide companies toward circular economy[32]. Complementarily, ten circular design tools adapted to the EEE industry (e.g. Circular Design Guideline Group, R-strategies, Circular Product Design Vision, etc.) are classified in a recent scoping review by Suppipat et al.(2022) [33]. In addition, the Circularity-Indicator Advisor (CIA) tool [34] is proposed to facilitate the selection of suitable circularity indicators. Finally, Dangal et al.(2022) analyzed six scoring system to assess repairability of EEE products, which can be a basis for the development of an adapted scoring system for PEC[35]. Additional research in integrated eco-design should address the implementation of these available methods and tools into PE industries, to better support PE designers in a DfS process.

5. Conclusion

This research mapped two decades of research on eco-design in power electronics approaches to identify and rank available eco-design approaches for PE designers. This review provides a comprehensive and up-to-date overview of the progress in PE sustainable development, as well as comments on the limits of existing researches (e.g. focus on energy efficiency optimization) and remaining challenges to guide future research (e.g. expand the eco-design scope to various environmental impact indicators and life cycle stages). PE Eco-design is a very wide field of research and still many gaps need more efforts to be explored. However, a few studies attempted to provide a holistic approach taking into account both multiple life cycle stages of PEC and multi-environmental impact categories, such as abiotic material depletion, toxicity, waste generation, and water consumption. Most of the eco-design approaches are not applied in a systematic way of considering the influence of different system level of PECs. Additionally, the limited number of case studies indicates a lack of practical application in this field. Additionally, more attention should be given to designing for multiple life-cycles. The focus on system thinking for understanding of relations and interactions between elements among different system levels should be intensified. The relevant design for X guidelines [36] proposed in literature needs to be adapted to power electronics fields. Factors pertaining to the product's end-of-life (EOL) should be carefully considered, including the disassemblability of electronic components, the diagnosis of reliability or remaining lifetime for converter or its subsystems, and material recyclability for potential reuse or remanufacturing.

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