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*Review*

# State of the Art of Research towards Sustainable Power Electronics

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**Abstract:** Sustainability in power electronics is a recent research topic. It takes place among current actions to grasp design choices that enable eco-design and circular economy in the domain. This paper shows the results and analysis of a literature review at the intersection of power electronics and sustainability without considering the reliability study of the power electronics systems. The first part explains the scope of the study. The second part shows a bibliometric analysis of the collected publications that underlines a pioneering position at the European level. The third part details the state-of-the-art and its analysis over four investigation topics which are: tools and methods, indicators, circularity and materials. This paper and the work behind are the results of collaboration at the French national level, as part of the workgroup CEPPS (*Convertisseurs Electronique de Puissance Plus Soutenables*—More Sustainable Power Electronics Converters) supported by the CNRS (*Centre National de la Recherche Scientifique*—French National Centre for Scientific Research) research group SEEDS (*Systèmes d'énergie électrique dans leurs dimensions sociétales*—Societal dimensions of electrical energy systems).

**Keywords:** power electronics; eco-design; circular economy; sustainability; state-of-the-art; literature review

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## 1. Introduction

Power electronics converters are key enablers of the energy transition. They ensure the adaptation of electric power between sources, including renewables and loads. A great deal of research has gone into developing increasingly efficient, high-power-density, reliable, and increasingly cost-effective electrical power conditioning systems. The advent of new technologies, materials and components, combined with the discovery of new conversion architectures, are behind this continuous progress. As a companion of electrical energy distribution, power electronic converters are penetrating all application sectors of our modern societies. This leads to new products and new needs that put pressure on critical materials and also on planetary limits under economic and societal constraints [1,2]. There is an urgent need for a better understanding of the environmental impacts of the technology and to introduce environmental constraints into the design and production processes that will make power electronics more sustainable. The workgroup CEPPS (*Convertisseurs Electronique de Puissance Plus Soutenables*—More Sustainable Power Electronics Converters) from the CNRS (*Centre National de la Recherche Scientifique*—French National Centre for Scientific Research) research group SEEDS (*Systèmes d'énergie électrique dans leurs dimensions sociétales*—Societal dimensions of electrical energy systems) has been created to organize a scientific community, at national level, to address this issue. Consequently, a state-of-the-art study was conducted to identify ways of making power electronics more sustainable [3]. Four topics have been defined inside the work group to tackle the wide scope of the topic. These topics are tools and methods, indicators, circular economy, and materials. Reliability and aging studies and models of power electronics-related technologies are not covered in this paper. Models are necessary to feed these databases, but the methods and tools used to assess the lifespan of a power converter and its parts are out of the scope of this paper. The interested reader is invited to read the existing review papers on the subject [4,5].

This paper is the result of a first step and presents the state of the art that the work group has built during the academic year 2022–2023. In each axis, the most relevant papers are referenced and for some topics, analyses are provided. In addition, the main points emerging from each axis are synthesized in order to reach initial general conclusions that can help the scientific community address the problem of sustainability in power electronics, which is one of the paper's objectives.

The outline of this paper is the following: the methodology of the paper collection and analysis is explained in Section 2; then the bibliometric analysis is performed in Section 3; the synthesis of the state of the art for each topic is detailed in Section 4; and the last section concludes this paper and shows some perspectives.

## 2. Method of Data Collection and Analysis by the Workgroup

The CEPPS workgroup has been supported by internal funding from the SEEDS research group in the budget of 2022. Thanks to this funding, a bibliographic extraction was entrusted to TKM, a French company located in Voiron, France [6]. The extraction methodology has been defined with two groups of keywords: one group related to power electronics and the other one to sustainability. All keywords are in English and available in the companion documents available in [7]. Approximately 17,000 documents have been extracted with around 10,000 patents and 7000 papers in a time period ranging from 2010 to the end of 2022. The patents have been discarded as most of them did not match the scope of the study. Therefore, the efforts have been focused on scientific papers. A manual sorting of the papers has been performed by the contributors of this paper to remove those out of scope. In the end, more than 200 papers have been selected [7]. This analysis has been completed by the contributors of each topic based on their knowledge. The analysis of the most relevant papers among the selected ones is performed in Section 4. This list includes around 60 papers selected for their value to the power electronics engineer/researcher wishing to deepen their knowledge about sustainability in the field of power electronics.

## 3. Bibliometric Analysis

The bibliometrics analysis has been performed on the 227 selected papers. This analysis focused on identifying the main players, the main concerned geographical institutions that are active in the field and the "intensity" of research activity. Regarding the last point, the number of published papers is low, which indicates a rather low research activity on this topic. More precisely, Figure 1 illustrates the fact that the research activity is low until 2017, and afterward it increases regularly. The plateau in 2020–2021 is probably due to the COVID-19 pandemic because the majority of the papers are conference proceedings. In addition, data for the year 2022 has yet to be consolidated due to the latency period required to register publications.

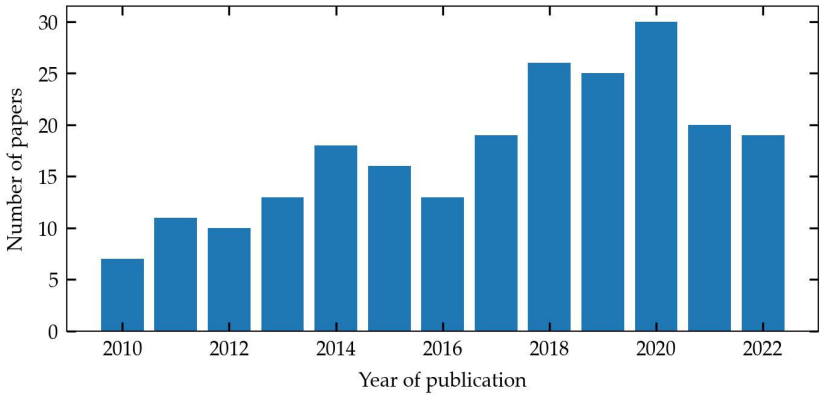



**Figure 1.** Number of published papers on the topic as a function of the year [7].

According to the selected papers, no main research center appeared as a leader in the considered sub-field. The ones that have been published on the subject have only a few papers.

Figure 2 depicts that the majority of the papers are concentrated in three great geographical areas: 36 papers in North America (mostly the United States of America with 28 papers), 105 papers in Europe (mostly Germany with 23 papers, United Kingdom with 18 papers and France with 16 papers) and 87 papers in Asia (mostly China with 33 papers). When the contributions of all European countries are gathered, Europe is the greatest publisher on the subject.




**Figure 2.** Geographical distribution of published papers on the topic.

The complementary papers brought by the CEPPS workgroup's members do not call into question the conclusions drawn here by the bibliometric analysis carried out with the IPMETRIX tool.

This bibliographical study enabled the workgroup to list the main conferences and journals dedicated to the theme of sustainability in power electronics and, by extension, electrical engineering. This list (not exhaustive) is available in [7]. In addition to the journals and conferences associated with sustainability in power electronics, those more specifically associated with the overall theme of sustainability (life cycle analysis, circularity, etc.) are also listed.

As sustainability is a field of research on its own, it is also important to list existing players specialized in this area, within or outside the electrical engineering spectrum, both nationally and internationally. This list is also available in [7].

Some major industrial players, such as Schneider Electric, are already offering refurbished products [8]. Most automotive equipment manufacturers tell the workgroup members that their customers ask them to design and produce repairable power electronics devices. Other operators, such as EATON for UPS and Alstom for powertrains, provide after-sales service for the repair and maintenance of some of their products via service providers. Suppliers of components for electrical engineering and power electronics include reconditioning solutions in their offer [9]. They are also developing monitoring solutions to better understand maintenance needs. All these players are in fact already engaged in a process of sustainability in power electronics through the original offers and services they provide, and these are just a few examples.

Industry groups are active around standards and regulations. Regulations in the form of an ecological passport are in place [10]. More information about standards at the intersection of sustainability and power electronics is available in [11,12].

With the COVID-19 crisis, disruptions in the supply of components and integrated circuits have created opportunities for the recovery of some components from existing boards, paving the way for the development of new business models.

Raw materials recycling players are positioning themselves in the market for the recovery of precious and/or critical metals. In France, recycling efforts are coordinated by eco-organizations, which work with producers to define strategies and conditions for managing end-of-life products. For electrical products, the eco-organizations involved are also listed in [7].

## 4. Analysis of the State-of-the-Art

This section is devoted to the presentation and analysis of the bibliography dealing with research activities in the field of more sustainable power electronics. It is organized according to the four above-mentioned topics.

### *4.1. Tools and Methods Topic*

The development of more sustainable power electronics converters relies on the consideration of environmental and technological indicators and requires the adoption of methods and tools to quantify and analyze environmental impacts throughout the entire life cycle. Life Cycle Assessment (LCA), illustrated in Figure 3, is a relevant method of environmental assessment, standardized by ISO 14040 [13] and ISO 14044 [14]. Other methods can be chosen to support more sustainable and reliable designs, such as FMECA analysis (Failure Modes, Effects and Criticality Analysis), which is not covered in this article.

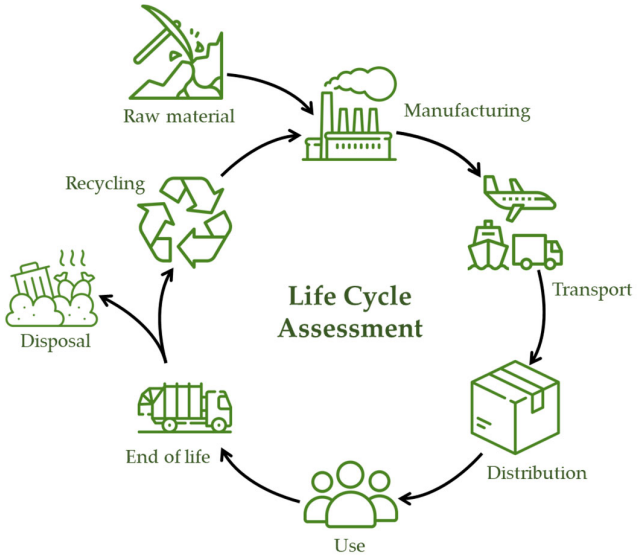



**Figure 3.** Schematic illustration of a Life Cycle Assessment.

#### 4.1.1. Life Cycle Analysis

LCA begins by defining the objective and scope of the study. Within the scope of the study, it is essential to define the functional unit. This enables the boundaries of the study to be defined and the usage to be specified quantitatively so that any comparative studies can be carried out.

For example, for a power converter, this may involve specifying the total number of hours of operation (duration of use) under a certain electrical load (power profile). This is followed by a Life Cycle Inventory (LCI), which consists first and foremost of listing the converter incoming flows (materials, energy) and outgoing flows (pollutants, wastes), such as materials, energy consumed, waste generated, etc., during the various stages of a product's life (extraction of raw materials, manufacture, transport, use, collect, sorting and end-of-life). It should be noted that the duration of use is not necessarily equal to the lifetime. A model for estimating the latter (aging and reliability) is therefore necessary for a complete LCA. Reliability studies are indispensable in parallel with eco-design investigations, constituting an integral part of the overall process. While eco-design focuses on developing environmentally sustainable products, reliability studies ensure that these products consistently meet performance standards and withstand the rigors of real-world usage. The synergy between eco-design and reliability studies is crucial for delivering products that not only minimize environmental impact but also provide long-lasting and dependable solutions. The work presented in [15] is an attempt to incorporate aging models of power semiconductors in LCA that allows taking into account part replacements in the power converters. Therefore, the evaluated environmental impacts are probabilistic and time-dependent. There are currently no methods or models to consider the probabilistic end-of-life scenario of the converter and its parts in the framework of circular economy. This topic is discussed in detail in Section 4.3 about circularity.

#### 4.1.2. Available Databases

The translation of each of these flows into environmental impacts is carried out during the LCA using a database that links each flow to the various environmental impact indicators selected in the study (e.g., climate change, energy consumption, water consumption, etc.). In this case, it is necessary to use a database that is as precise and exhaustive as possible and to know the product end-of-life mechanisms. Table 1 lists a few potentially relevant databases for power electronics.

**Table 1.** Some potentially relevant databases for power electronics.

| Name | Licence | Description |
|---|---|---|
| Empreinte | free | Supplied by ADEME [1], not suitable for electronics |
| EcoInvent | not free | Well documented, but insufficient data for electronics |
| Nexus | not free | Database collection accessible from OpenLCA |
| ILCD | free | International Life Cycle Data system, gathered from the European Platform on Life Cycle Assessment (EPLCA) |

[1] ADEME is the French Environment and Energy Management Agency.

All available databases present uncertainties/errors regarding a specific product.

To overcome these problems, the EcoInvent database began publishing data quality information in the form of pedigree matrices in version 1.01 of 2003. This information provides a quantitative characterization of data uncertainties. This reduces the time-consuming data collection stage for database users. In LCA tools such as SimaPro or Umberto, Monte-Carlo methods for propagating uncertainties have been in use since 2004.

It is essential to include a study of the sensitivity of these uncertainties to the environmental impacts of the product under consideration.

The quality of the inventory is particularly complex in power electronics, due to the heterogeneous nature of the components and technological processes used. The current state of the databases presented in Table 1 does not allow us to obtain reliable results in our field.

This situation motivates some research work, such as the one by Nordelöf et al. [16], which presents an LCI of an electric vehicle traction inverter, focusing on the materials used. This work complements another article by Norderlöf et al. [17], which supplements the LCI with data on manufacturing processes. The authors have developed a tool for estimating the masses of the main functions of an inverter as a function of its characteristics (voltage, power, type of cooling). Figure 4 shows two examples of the inventory of two inverters of different power ratings segmented by main components like Printed Circuit Boards (PCB), Direct Current (DC)-link capacitors, High Voltage (HV) connectors and others. The inventory shown is an input for a LCA; it is a macroscopic representation of a detailed inventory.

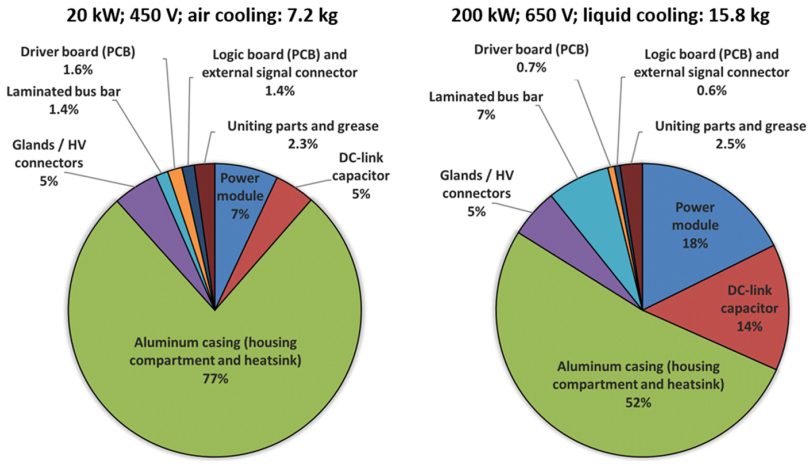



**Figure 4.** Inventory of components in two inverters [16] (replicated with the permission of the authors).

In addition, reference [18] presents a work on the recycling of electric vehicle converters. This work is based on the dismantling of 15 different converters. In [19], the authors discuss the manufacturing processes and end-of-life of converter components (transistors, capacitors, inductors) by means of a detailed state-of-the-art. These few references illustrate the level of knowledge and data available to carry out a life cycle inventory and analysis

in the power electronics field. However, precise knowledge of the quantities of materials and energy involved in manufacturing, and of the various processes used, is decisive in assessing the environmental impacts of a power converter.

#### 4.1.3. Methods and Software Used to Evaluate the LCA

The second step is to choose a resolution method suited to the objectives and scope of the study. There are two types of methods:

- Mid-point methods, which provide intermediate indicators (GWP climate change, ecotoxicity, ozone depletion, water consumption, fossil fuel depletion, eutrophication, human toxicity, etc.).
- End-point methods, which quantify the final damage (impact on human health, global warming, etc.) and generally represent a weighting of midpoint categories.

The criteria for choosing methods depend on the objectives of the analysis and the type of decisions required. It is important to note that there are no specific rules dictating the exclusive use of specific impact categories in Life Cycle Assessment (LCA). Instead, guidelines like ISO 14040 and ISO 14044 offer general recommendations for conducting LCAs consistently and transparently. However, in most Type 3 environmental declarations (self-declarations such as PEP eco-passport [20] of EDPs) governed by ISO 14025 [21], it is essential to include midpoint impact categories. Contrary to ISO 14040, which does not mandate the use of one category over another, specific regulations for buildings like the RE2020 [22] in France require certain products such as UPS, Distribution Transformers and EV Charging Stations to report both midpoint and endpoint impacts. Moreover, it is important to note that the European Commission recommends the use of the midpoint method of Product Environmental Footprint (PEF).

A LCA can finally be carried out using a software tool, in which elementary input and output flows are entered for each stage of the life cycle. The tool is also configured to provide output sets of indicators according to the impact calculation method. The choice of software tool depends on several criteria, in particular, the material and process databases and calculation method for the products under consideration. Table 2 lists some of the LCA software potentially relevant for power electronics. Reference [23] presents a good example of an LCA applied to a photovoltaic panel.

**Table 2.** Some potentially relevant LCA software for power electronics.

| Name | License | Description |
|---|---|---|
| OpenLCA 2.1 | free | Lots of methods. Many Nexus-compatible databases. |
| SimaPro https://simapro.com/about/ (accessed on 23 November 2023) | not free | Many calculation methods available. No associated database, but compatible with many external databases. |
| GabiLCA https://sphera.com/life-cycle-assessment-lca-software/ (accessed on 23 November 2023) | not free | Automotive-focused, but data missing for power electronics. Many methods. Black box approach reduces results confidence. |
| Brightway 2 2.4.5 | free | Lots of freedom in parametrization and modelling. Short calculation time. Difficult to take in the hand. To be linked with databases. |
| EIME 6 | not free | Focused on electronics, with an associated database. Easy to use, but few calculation methods and data to be completed/used. |
| Umberto 11 | not free | User-friendly interface with workflows. No associated database, but compatible with many external databases. |

Some research works are beginning to apply these LCA tools to power electronics. A LCA of a 150 kW inverter is presented in reference [24], using data from [16,17]. Figure 5 shows a comparison of the impacts of various inverter components on different standardized indicators. It has also been shown that, for the inverter studied and for the manufacturing phase, three "hot spots" have been identified, corresponding to the components with the greatest impacts: power module, aluminum housing/cooler and DC bus capacitance. Conversely, PCBs and drivers have minor impacts. These relative

approaches can be applied by power electronics researchers and designers to identify and evaluate which components they should put effort to reduce the overall environmental impacts of specific converters.

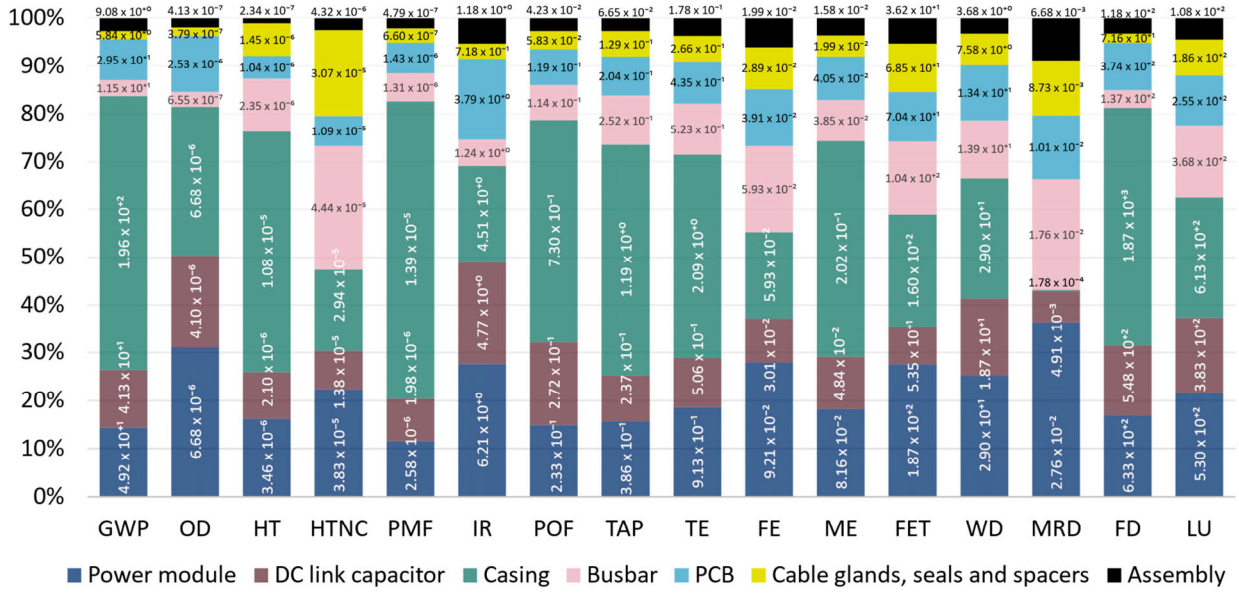



**Figure 5.** Results of a LCA of a 150 kW inverter: impact of different components on several indicators (acronyms specified in Figure 6) [24].

Reference [18] presents a LCA of a converter with a focus on the cost of recycling. [25] quantifies the carbon footprint of materials, manufacturing processes and recycling of a low-power DC/DC converter.

Some works in the literature focus on the LCA of one part of the converter. This is the case of reference [26], which compares soldering and sintering processes for power modules, using Open-LCA and Recipe. Reference [27] presents a very pragmatic view of the LCA of a cooking induction module, and in particular its electronic board. Reference [28] presents a comprehensive model for cooling technologies in power electronics. In [29], the authors study the impact of pollutants in the capacitor recycling industry.

Reference [30] introduces the notion of *energy payback time* for power electronics systems (like what is done for renewable energy sources) in order to highlight the energy gains obtained with power electronics systems. Two applications are presented on 2.2 kW and 11 kW converters.

It is not enough to assess a product's environmental impact. It is necessary to include an analysis of its impacts. This helps to guide the eco-design and/or eco-sizing process. At this stage, it is important to avoid "rebound effects" or "impact transfer". For example, if the use phase has a dominant impact (significant losses), the reflex is to reduce losses. However, this reduction will generally lead to component oversizing, with the manufacturing phase dominating. Therefore, a trade-off will have to be found, involving a global, multi-factorial approach.

#### 4.1.4. Summary

In conclusion, some tools and methods are available for analyzing the environmental impacts of converters. However, the input data required for these tools, concerning materials and processes, are insufficiently referenced, which makes reliable analysis impossible. Several research projects, mainly in Europe, have been identified above, paving the way for the development of LCAs in power electronics. To go further, efforts must now focus on establishing reliable and exhaustive databases adapted to the case of power converters. In

addition to materials, the database must consider as accurately as possible the incoming and outgoing flows of the manufacturing and dismantling processes.

Although there are several software (GaBi, EIME 6, Simapro, etc.) in use, the working group recommends giving priority to OpenLCA 2.1 and Brightway2 2.4.5 software. In fact, in order to strengthen the community, it would be interesting to work with common tools/databases that would motivate communications and interactions. OpenLCA and Brightway2 software are free of charge, which favors these aspects, as well as allowing non-negligible modeling freedom, especially for Brightway2, which seems to be particularly better suited to research work on Life Cycle Assessment than other software.

Concerning the databases, the most relevant seems to be EcoInvent and CODDE (EIME). However, the working group would like to point out that these are not sufficiently complete, and that initiatives such as those undertaken by [16,17] are welcome in order to increase and enrich data and tools for sustainability.

The modeling of the probabilistic end-of-life scenario of the power converter and its parts in a circular economy is also lacking. A decision tree should be available to the power electronics designer to model precisely the life cycle of the converter and its parts.

### *4.2. Indicators Topic*

An indicator is an assessment and decision-making parameter based on a set of measurable or assessable elements that can be used to describe the performance, state or impact of a system in figures. Efficiency ($\eta = P_e/P_s$) or mass and volume power densities are examples of such indicators. New indicators are necessary to qualify and quantify sustainability in the field of power electronics. Some of them are standardized and generic like the environmental impact indicators. Others are more specific to each field and support the evaluation and design process. They are defined hereafter as technological sustainability indicators.

#### 4.2.1. Environmental Indicators: State-of-the-Art Analysis

The environmental impact indicators are used in particular in LCA (Life Cycle Assessment). This method allows for the evaluation of the environmental impacts thanks to indicators computed on a defined scope for a system or product throughout its life cycle. Multiple indicators exist and they are classified by level as described in Figure 6.

The physical flows identified during the Life Cycle Inventory (LCI) are used to compute the midpoint impacts that are shown in Figure 6. Then, these impacts might be aggregated to compute the endpoint impacts that are related to the damages done to human health and the ecosystems. In a similar manner, these endpoint impacts might be aggregated to obtain a single score. The more aggregated the indicators, the easier and quicker it is for the stakeholders (manufacturers, users) to communicate and understand them. In exchange, the aggregation of indicators implies a loss of information on the physics of the environmental impacts of the product or system considered.

Considering the diversity of environmental indicators ensures that a global picture of the environmental impacts is obtained. Conversely, when only a subset of indicators is considered, for example, $CO_2$ emissions, rebound effects or impact transfer might occur. They result in a decrease in the effect of one given impact at the expense of an increase in the effect of another impact, which is neither desirable nor visible when using a single score or a limited number of indicators. In addition, interpretation difficulties arise due to the weighting used in the aggregation of several indicators into one single score. This is the reason why these weightings are subject to European recommendations which are adjusted each year and may also depend on the applications studied [31].

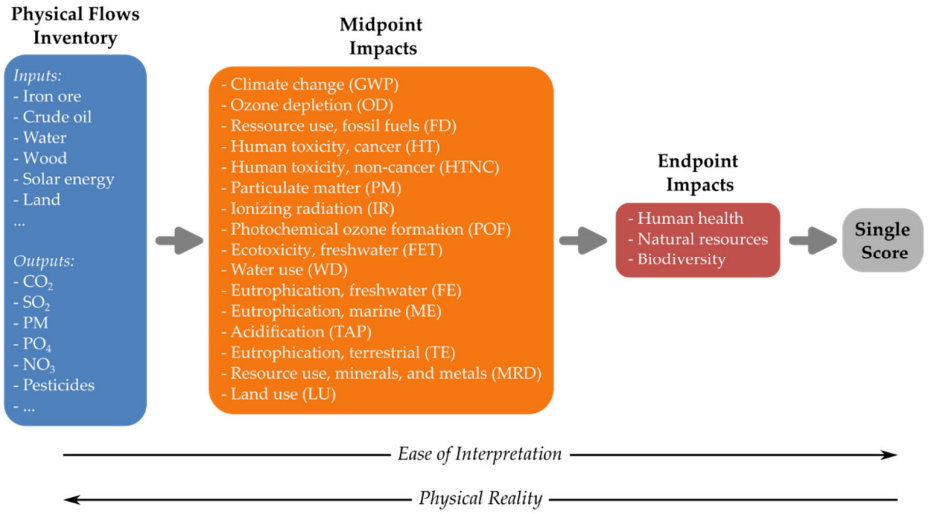



**Figure 6.** Environmental impact indicators—Compromise between physical reality and ease of interpretation.

Impact transfer and rebound effects are not only linked to a focus on too few indicators, they might also appear when only some parts of the entire life cycle are considered. Indeed, some environmental impacts might be low for the considered life cycle phases but great for the neglected phases. This can imply a serious discrepancy between the estimated environmental impacts and the real environmental impacts of the overall life cycle. This lack of a systemic approach has been pointed out several times in the literature in studies about the LCA of batteries [32,33] and solar panel systems [34]. This lack is also due to other factors, such as the diversity of approaches, methods, software and/or data used, the lack of transparency regarding the Life Cycle Assessments carried out in the literature, the diversity of *goal and scope* and/or applications considered. The consequences are significant difficulties in interpreting and/or comparing studies or difficulties in extracting general conclusions and/or recommendations.

In the field of power electronics, a number of studies have assessed the environmental impacts of power converters [16,17,24,35–37]. It should be noted; however, that with the exception of [24], which deals with a complete LCA of a 150 kW traction inverter, most of the research focuses mainly on single score energy or $CO_{2,eq}$ emission balances, which is not in line with the systemic approach previously mentioned.

These environmental impact indicators are necessary to design more sustainable power electronics converters, but they are not sufficient. These indicators are not suitable for decisions made early in the design process by the power electronics researcher or designer. This is why the development of new indicators is necessary.

#### 4.2.2. Development of Technological Sustainability Indicators for Power Electronics

In addition to the previously mentioned environmental impact indicators, it is important to complete state-of-the-art analysis with the Technological Sustainability Indicators. First, the indicators specifically developed in the literature towards sustainability in the field of power electronics are presented, and then those developed for electrical engineering in general are detailed. Next, a proposed approach for developing new technological sustainability indicators is put forward.

*Power efficiency* is one of the most used indicators for the design of power electronics. This indicator considers only the use phase of the life cycle of the converters. Therefore, it is not sufficient to assess the environmental impact of a converter. Another very popular indicator is the *mass power density*, which is indirectly part of the mass of raw material used in the manufacture phase of the life cycle of the converter. These two indicators are only a very partial response to the need to assess sustainability in power electronics, as they cover only part of the life cycle and consider only a few environmental indicators.

Recently more systemic indicators have been designed for electrical engineering. The *Life Cycle efficiency*, developed in [37], considers the energy flows of all life cycle phases of the converter. It is defined as:

$$\eta_{LC} = \frac{W_{u,life}}{W_{u,life} + W_{losses,life} + W_{manufacture} + W_{EoL}} \quad (1)$$

With $W_{u,life}$ the delivered energy during the use phase of the converter, $W_{losses,life}$ the energy due to its losses during the use phase, $W_{manufacture}$ the energy used during its manufacturing phase and $W_{EoL}$ the energy used during its End-of-Life (EoL) treatment. Other indicators like the *residual value* [38], and the *embodied energy* [39] includes also several phases of the life cycle. All these indicators are intended to support the decision-making process considering the various product phases (design, manufacture, use, circularity scenario, and end-of-life management).

Some indicators have been specifically developed for production systems like the *Carbon* and *Energy Payback Periods* [30,40]. The *Health Index for Power Transformers* [41] might also be used as inspiration for new indicators.

A complete and more sorted inventory of indicators, together with their descriptions, is available in [7] (this document is provided as is for research purposes and does not constitute a recommendation by the workgroup CEPPS).

Various indicators could be developed over the next few years to respond specifically to sustainability needs in the field of power electronics. While these technological indicators represent a major challenge for the power electronics community, it is important to link them to a systemic approach (covering the entire life cycle). They should complement the environmental impact indicators (used to quantify the impacts of the studied device), and they should help with the design and development of more sustainable power converters as depicted in Figure 7.

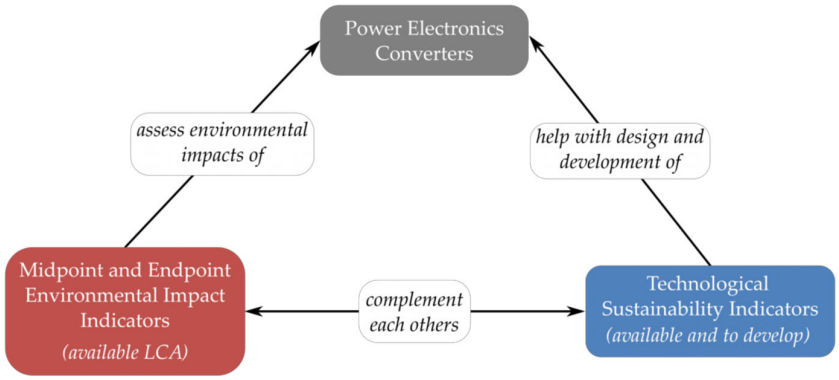



**Figure 7.** Indicators towards the sustainability: suggested approach.

There are many different types of indicators, some of which already exist, to develop or to improve for several design criteria like reliability [42], ease of disassembly [43], repairability [42,44], reuse, complexity and indicators. For example, the French repairability index is a decision-making tool for consumers, rather than for product designers. In addition, the use of a weighted sum may, in some cases, create bias, and therefore calls for an improvement in this indicator for designers [44].

The failure rate from the field of reliability is another example of an already existing indicator that can be incorporated into converter sustainability studies, in particular, to estimate the lifetime or the residual value at the end of usage.

Finally, the last European recommendations on eco-design include more and more electrical systems (motors and transformers). This augurs well for the arrival of new regulations and a market for the circularity of electrical equipment including power electronics,

which underlines the importance of using indicators that are both understandable and relevant for the power electronics designer.

#### 4.2.3. Summary

To conclude, even if there is a growing number of studies on sustainability in the field of power electronics, there is a lack of technological sustainability indicators tailored for power electronics converter design. This can be performed by developing links between existing indicators (i.e., energy efficiency, aging, reliability, etc.) and environmental impact assessment methods, or by developing new indicators explicitly linked to the notion of sustainability (i.e., reparability indicator, dismantling, circularity, etc.). The development and communication of such indicators is a major challenge for the community. A systemic approach in the development of the indicators is mandatory to tackle this challenge while limiting the rebound effects and impact transfer. In the long term, it might be relevant to develop application-specific indicators, as well as integrate economic and social aspects [2].

### *4.3. Circularity Topic*

The objective of this section is to provide an overview of the scientific research conducted on the application of circularity in power electronics.

#### 4.3.1. Circularity Concepts in General Overview

Circularity is a concept that aims to minimize waste generation and resource consumption by preserving the value of products and materials within the economy for as long as possible [45]. The levels of circularity can be distinguished based on the '10R' approach, which ranks these levels based on the extent of their impact, as depicted in Figure 8. At the material level, circularity consists of harnessing waste as a recoverable energy source or as recyclable materials. At the product level, circularity involves designing products that can be easily disassembled, reused, repaired, refurbished, remanufactured and/or repurposed. At the global level, circularity involves refusing, rethinking or reducing to minimize waste and maximize the value of materials. The traditional approach to circularity in electronics is mainly based on regulations such as the Waste Electrical and Electronic Equipment (WEEE) Directive, which focuses on the material level. However, a global approach to circularity involves implementing circular principles throughout the entire value chain [46].

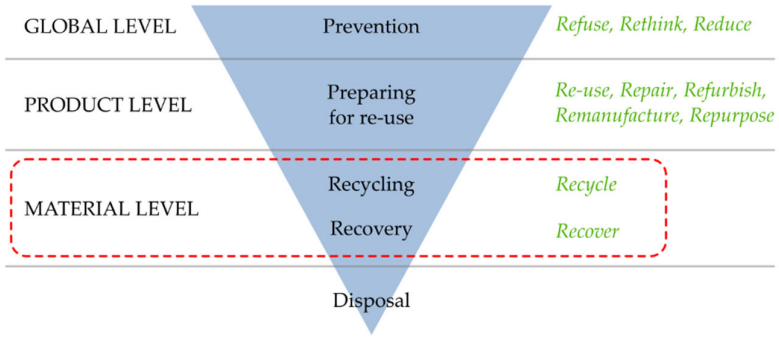



**Figure 8.** EU waste hierarchy (blue), circular strategies (green), and the EU WEEE directive (red), [46,47] (replicated with the permission of the authors).

#### 4.3.2. Circularity Applied in Power Electronics

The literature study was conducted in three steps. Initially, based on the 7000 papers collected thanks to the TKM expertise, the first batch was selected based on the content of the abstracts and keywords. This resulted in a set of 88 papers and four subtopics as listed below:

- Materials level circularity: Energy recovering and material recycling.
- Product level circularity: Extending life perspective: Repair, refurbish, or remanufacture damaged or obsolete products to extend their lifespan and improve their performance.

- Product level circularity: Second life perspective: Reuse or repurpose functional products or components for products in the same or other applications.
- Design and business model for circularity: Design products for modularity and ease of disassembly. Integrating circularity practices into eco-design methodologies. Rethink business models to integer circularity.

In the second step, a qualitative ranking based on the relevance of the publications (ranging from 1 to 5) was conducted, and only 11 publications were categorized as greater or equal to rank 4. In the third step, these were supplemented with 17 articles from additional research (outside the database obtained from TKM). A detailed analysis of the 28 publications ultimately identified is presented in the work below.

#### 4.3.3. Materials Level Circularity

In this subtopic, a small number of papers were identified with one paper addressing the recycling of power electronics converters for electric vehicles [18], and one paper dealing with recycling polymers containing Ni-Zn ceramic powders [48].

In [18], the authors analyze various material recovery strategies, with or without converter disassembly stages, evaluating their profitability and environmental impact through LCA. Environmental benefits are highlighted. However, economic benefits would be relevant only if the entire module is crushed. Indeed, disassembly channels are currently very underdeveloped, and the additional cost incurred remains too high. The lack of data on the power electronics disassembly channels can be attributed to the relatively new and rapidly emerging nature of this topic on a large scale. Only a few companies, such as Sibuet Environment®, have been identified as collecting components according to the WEEE directive.

#### 4.3.4. Product Level Circularity: Extending Life Perspective

For product level circularity, aiming to extend product lifespans, the number of identified publications is also relatively low, with [42] addressing the analysis of reliability and repairing data of power converters to estimate the maintenance costs of a photovoltaic plant, and [49] focusing on the refurbishing aspect, improving the control system of DC/DC converters to address issues related to aging and obsolescence.

In [42], the authors refer to two indicators describing the reliability of components, Mean Time to Failure (MTTF), and the repairing of the system, Mean Time to Repair (MTTR). The MTTR indicator depends on which component fails and the associated difficulty in replacing it. The power converters addressed are high-power devices 350 kW with the following main components: cooling fan, DC breaker, AC capacitor, gate driver and IGBTs.

#### 4.3.5. Product Level Circularity: Second Life Perspective

The circularity at the product level for a reusability perspective is further addressed. The two topics identified in the literature research are the reuse of passive components [50,51], and the repurposing of PC Power Supply Units (PC PSUs). In the latter topic, 14 publications were found from five academic institutions, namely the Universities of Sheffield, Toulouse, Vietnam, Bach Khoa and the Institute of Technology of Cambodia. Here are some of the articles [52,53].

Regarding the reuse of passive components, the key point is to estimate their remaining lifespan. As presented by [50], fault prediction methodologies exist based on MIL-HDBK-217/RIAC 217 Plus or the IEC62380 standard [54]. These authors analyze operating conditions to estimate the lifespans of an electrolytic capacitor. In comparison to the manufacturer's declared lifespan, the actual component lifespan was estimated to be three times longer in several representative operating situations. Thus, this type of component could be reused at least once if it were possible to accurately estimate its thermal history. In [51], thermal cycling and defect occurrence prediction analysis were carried out on a transformer and a capacitor to assess their reuse potential. Similar to [50], the result obtained shows that the electrolytic capacitor could be reused a maximum of

two times. On the other hand, the reuse rate of the transformer was estimated to be much higher, i.e., 5 to 10 times.

Regarding the repurposing of PC PSUs, the main objective of these studies is to propose a low-cost power converter in a frugal context, especially in developing countries. In [55], the authors conducted a Life Cycle Assessment (LCA) analysis of the environmental impacts of repurposing in a photovoltaic system. By comparing scenarios with and without complete system reuse, the environmental impacts of repurposing PC PSUs are marginal compared to reusing batteries or solar cells. Conversely, during use, the power converter's efficiency has the main influence on the environmental impacts. This analysis highlights the importance of reliability and efficiency constraints in repurposing solutions to avoid transferring the environmental impact from one stage of the product lifecycle to another, a common challenge in product circularity.

#### 4.3.6. Design and Business Model for Circularity

Studies on circularity in power electronics emphasize the importance of considering modularity and ease of disassembly from the design phase. Our literature review has allowed us to identify five articles [38,39,51,56,57] published by the University of Grenoble, addressing this issue. These studies primarily aim to develop methodologies and indicators for reliability, repairability, reusability and ease of disassembly to integrate circularity into the design process for component reuse and recycling. Reference [57] is a literature review on eco-design in the field of power electronics that contains additional information to what is presented here.

In the same context, LCA is essential for evaluating circularity in the overall eco-design process. However, as circularity sub-themes related to materials and products are underrepresented in the literature, there is a lack of studies on LCA that include circularity aspects. In addition to references [18,53] mentioned earlier, an LCA from cradle to grave, including end-of-life scenarios, has been conducted on a planar transformer [39], aluminum electrolytic capacitors [58], multi-layer ceramic capacitors and tantalum electrolytic capacitors [59], and electro-intensive power electronic products [60]. Furthermore, [26] presents a LCA in which the use of secondary raw materials, here silver in the sintering process, is taken into account.

Beyond the design perspective, authors also address in [56] the implementation of circularity in product-service systems, considering business-to-business and business-to-consumer models. Additionally, the broader study on the electrical and electronic industry sectors [61] identifies seven innovative business models for circularity.

#### 4.3.7. Summary

Overall, the number of papers collected is relatively low, highlighting the need for further studies on this field of power electronics. Bibliometric analysis shows that the main subtopics covered are product circularity in the second life perspective and design for circularity, see Figure 9.

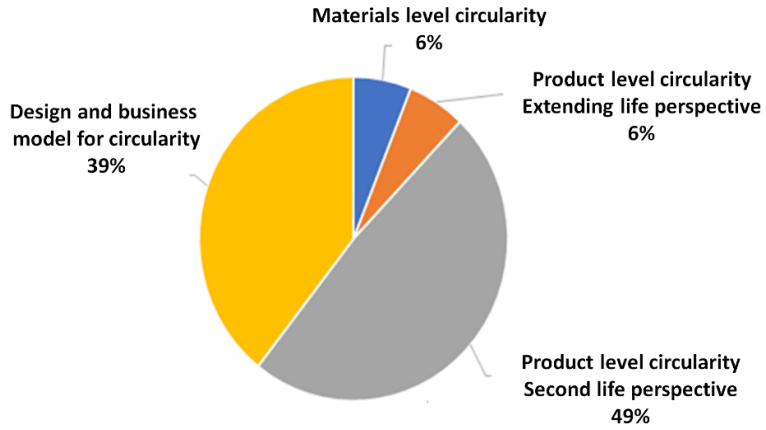



**Figure 9.** Repartition of collected papers by subtopics.

The literature analysis highlights several key points: the lack of identified actors in disassembly channels, the lack of studies addressing reparability, remanufacturing and refurbishing; the difficulty of addressing reusing in terms of component reliability and demounting process; the demonstrated interest in many articles for re-adaptation; the importance of integrating circularity into eco-design requirements, along with the need for cradle-to-cradle product LCA; andthe overall necessity to rethink the economic model.

Moreover, the notion of circularity does not specifically encourage recycling as the preferred end-of-life solution. For example, as shown in Figure 8, it is preferable to focus on solutions at the global and product level. In all cases, a systemic approach is essential when tackling the issue of circularity in power electronics, whether to optimize and improve recycling processes or to move towards end-of-life scenarios at the product level. Indeed, several factors explain why a new recycling chain is more complex to establish: the diversity of players along the entire value chain, the diversity of applications, the fact that converters represent only a fraction of the systems used in these applications and the growing quantity of WEEE. As a matter of fact, these factors make it easier for the use of a recycling chain that proceeds by recycling large tonnages. In the same way, it seems important to improve understanding of how the various players work and to have a global vision to set in motion effective actions to move towards circularity in power electronics, without which the efforts undertaken may be in vain.

### *4.4. Materials Topic*

Sustainability in power electronics and electronics puts materials and their processes at the forefront. Going towards more sustainable materials in the system is challenging because going from raw materials to devices there are a lot of processes and materials that are strongly entangled. The Uninterruptible Power Supply (UPS) of several kilowatts shown in Figure 10, illustrates the number of different components and materials involved in its design.

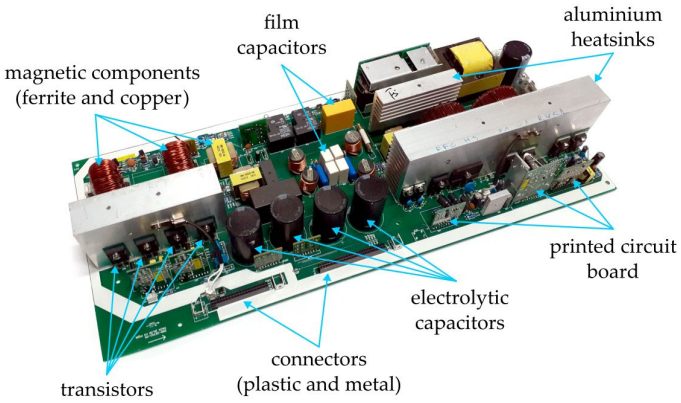



**Figure 10.** Photograph of an uninterruptible power supply of few kilowatts to illustrate the disparity of components.

Common design methodology decouples materials and processes used to manufacture components from their function. To handle this complexity, only the most relevant characteristics based on components specifications (on-state resistance, electrical, thermal resistivity, permittivity, permeability, etc.) are used. Some requirements are also interdependent: the use of lead-free solder has led to an improvement of the thermal stability of the substrate (increase the temperature of the glass transition), or wide band gap semiconductors switching faster than silicon counterparts, they produce large dV/dt and therefore need better integration with advance control of the parasitic capacitance to avoid Electromagnetic Interferences (EMI). Moreover, the design of passive components needs to be with low parasitic capacitance. This highlights the need to study the converter at different scales (system, components, materials). To deal with this complexity, researchers study

the problems with top-down and bottom-up approaches. On the one hand, top-down approaches go from the system to the materials [16,17,24,36] and it is mostly performed after or during the design of the system. On the other hand, bottom-up approaches aim to explore methods to make components, starting from the materials (composition, substitution, etc.) to the process. Bridging the gap between these two approaches is still far away. In this section, where many research fields are gathered, we choose to classify materials by their functional use in power electronics, like in the bottom-up approaches:

- Magnetic materials for inductors and transformers are mainly based on ferrite but nanocrystalline, amorphous, iron powder and permalloy materials can also be used;
- Dielectric materials are for capacitors with electrolytic, ceramics and polymers;
- Electrical interconnections are based on metal (Cu, Al, etc.), solder paste (SnBi, SnAgCu, Ag, etc); insulator substrates are based on composite made of fiberglass and epoxy or ceramic and packages are made of thermosetting polymers;
- Semiconductors for static switches are based on silicon or on Wide-Bandgap (WBG) semi-conductors.

Although they are important for the LCA evaluation as shown in [16], the chassis, housings, other enclosures and passive or active heat sinks are not discussed in this work.

As each material category is vast. The aim of the following sub-section is to give a short introduction to the subject, focusing on the main components and their associated materials, without going into details on the process parts. The figures announced in the following sub-sub-sections cannot be dissociated from their context as presented in the corresponding references. Nevertheless, to provide a quantitative overview some values have been picked up.

#### 4.4.1. Magnetic Materials: Ferrites

Soft ferrites, for their good performance at high frequencies, are widely used for inductors and transformers in power electronics. Manganese-zinc (Mn-Zn) ferrite and nickel-zinc (Ni-Zn) ferrite are economical for high-volume production. The article [62] proposes a life cycle analysis and their environmental impacts for different compositions. It shows the manganese and nickel content need to be known, otherwise, the environmental impacts vary quite significantly, ranging from 20% to 500% depending on the composition. As an order of magnitude, the impact indicators are around 1000 mPt and 1 kg $CO_{2eq}$ per kg of ferrite. Under the ReCiPe methodology, most Ni-Zn ferrites have a lower impact than Mn-Zn ferrites, but this remark is no longer valid if we consider the carbon footprint.

#### 4.4.2. Dielectric Materials

There are three types of capacitors: polymer, ceramic and electrolytic capacitors, with the latter two being the most used in power electronics. Electrolytic capacitors are widely used for their high capacitance, low cost and compactness, and ceramic capacitors for their higher operating frequency and better robustness with temperature.

In [63] the authors propose a LCA of different types of aluminum electrolytic capacitors with polymer, liquid or hybrid electrolytes. They show that their environmental impacts are mainly due to aluminum production. For hybrids, if they are used long enough, their environmental impact is reduced by a factor of two. Typically, they produce 42.6 $tCO_{2eq}$, 10.4 t oil equivalent and 86.1 kg NOx equivalent per million units.

Smith et al. [59] propose an LCA of tantalum-based electrolytic capacitors and MLCC (multi-layer ceramic capacitor). They show that the transition from tantalum to MLCC technologies is interesting from an environmental point of view. Indeed, the LCA of tantalum technology is degraded by the need for highly pure material. MLCC is better but not perfect because the nickel used in MLCC for the internal electrodes and the copper paste for the external ones are the elements that degrade the LCA. They provide a high capacitance in a small volume. This paper shows clearly the complexity and the interdependence of the process, the material, the required physical properties and the environmental impacts. For

example, the addition of rare earths (dysprosium or holmium) allows maintenance of good electrical insulation over a long period which results in thinner layers with a longer service life.

Although no studies have been found, film capacitors could have a low impact thanks to the use of thermoplastic materials. Furthermore, bio-based packaging research has paved the way for capacitors made of bio-sourced/bio-degradable materials [64].

Depending on the capacitor technology, its temperature and its use, lifetimes are highly variable. Hence, the LCA calculated for the same cumulative energy [63] is an interesting way of making reliable and normalized comparisons. However, the application constraints (filtering of a DC bus or resonant circuit) also need to be considered.

#### 4.4.3. Interconnections, Substrate and Packaging

Packaging and substrate provide interconnections, insulation, mechanical support and protection for components. The substrate historically used, a composite made of epoxy resin reinforced by glass fiber (commonly referred to as "FR4" for Flame Retardant), has been optimized to increase glass transition temperature (Tg > 150 °C), mechanical strength and electrical performance in relation to application and requirement of manufacturing processes. To obtain L94V-0 certification, which ensures flame extinction, they contain a brominated flame retardant (TBBPA). For more demanding applications in terms of electrical and thermal conditions, ceramic-based substrates ($Al_2O_3$, AlN, $Si_3N_4$, etc.) bonded to thick-film metallization, generally in copper, are preferred.

The work of Herrmann et al. [65], dating from 2001, proposes a comparative LCA from cradle to gate using an epoxy and a ceramic hybrid substrate ($Al_2O_3$) in the case of an automotive circuit. Hybrid substrate achieves a gain, thanks to a reduction in surface area, over six categories of impact (energy consumed, GWP100, toxicity, etc.).

More recently, there has been strong interest in alternatives, with bio-sourced and bio-degradable substrates. Kovacs et al. [66] introduce the subject with the study of various substrate alternatives, including a bio-sourced epoxy for temperature-demanding applications and a biodegradable cellulose acetate substrate for other applications.

Among biodegradable materials, poly-lactic acid (PLA), a material widely used in additive manufacturing by Fused Deposition Modelling (FDM, commonly referred to as "3D printing"), occupies an important place in the literature [67]. There are also intermediate substrates where either the matrix or the binder is biodegradable.

Improvement of the flexible electronics industry offers alternatives to poly(ethylene naphthalate) (PEN), poly(ethylene terephthalate) (PET) and nanosilicate-filled cellulose [68]. However, characteristics differ from the standards. For example, their low glass transition temperature hinders the use of SnAgCu brazing alloys because they need more than 200 °C or high-temperature operating conditions.

#### 4.4.4. Semiconductors Materials

Although the research on new semiconductor materials shows great promise in terms of efficiency and the reduction in the Global Warming Potential (GWP) environmental impact of solar panels [69] or converters [44,70], the decrease in the overall environmental impacts of power converters is not guaranteed. Semiconductor materials, used here to manufacture power transistors and diodes, are the result of a combination of complex processes leading to wafers of outstanding manufacturing quality and purity (99.9999%). These wafers are then transformed using a variety of processes in controlled environments (clean rooms) that require significant resources (energy, chemicals, pure water, etc.). Semiconductors for power electronics represent around 7% of the market but with an etch size a decade larger than that for microelectronics [71]. The use step of the life cycle of a semiconductor device can be well estimated; however, the manufacturing step remains difficult to apprehend, as explained by Andersen et al. in the case of photovoltaic cells [72]. This assessment is made even more complex by considering the semiconductor's end-of-life. The most detailed reference to an analysis of the production step concerns the silicon industry in electronics [73]. It supports the idea that one of the ways to improve the situation in

the short term is to make the production of semiconductor materials more sustainable by optimizing production processes.

The study of the sustainability of semiconductor components for power electronics has received little or no attention in the literature. The fact that the cumulative mass of semiconductors is negligible in proportion to that of the converter [17,24], raises questions about the contribution of semiconductor materials to sustainability. The question is delicate, considering the amount of resources needed to produce such high-value materials. In perspective, WBG materials such as silicon carbide (SiC) and gallium nitride (GaN) further reduce the mass of semiconductors without necessarily considering the overall balance of costs in resources and gains over the converter's life cycle [74,75].

Perhaps like in microelectronics, the thinking is based on function per cm², with the idea of optimizing manufacturing and material costs. The underlying philosophy is to reduce size to improve the sustainability, but this implication has not been formally demonstrated. One recent work [70] has tried to answer it by comparing two power modules made with different semiconductor materials (one Si and another SiC) with the same current rating. The results show that even if the SiC components have the biggest $CO_{2,eq}$ impact by square meter, the SiC module has a better $CO_{2,eq}$ impact because the die size is much smaller than for the Si counterpart. The paper also warns that due to the lack of primary data and the complexity of the manufacturing processes, these figures can only be considered as approximate values.

A more recent one [76] has studied the cradle-to-gate LCA (manufacturing phase in this paper) of a GaN power semiconductor device. The originality of this study lies in the primary data acquisition conducted to perform the LCA of a 650 V 30 A GaN on a Si device. The data concerning the energy, water and gas consumptions of each step of the process are obtained with a hybrid bottom-up top-down approach measured wherever possible and allocated from clean-room global consumptions otherwise. A sensitivity analysis shows also the environmental hotspots in terms of process and chosen material. The comparison with other power devices (Si, SiC) is also difficult because of the lack of standardized LCI and LCA methodologies, as has been pointed out previously in Section 4.2.1 about the rebound effect and the lack of systemic approach.

The impact on the use of the other materials in the converter is also very important since increasing operating frequencies can reduce the size of passives and thus the amount of material consumed, nevertheless the impact of the additional constraints need also to be studied (passives, thermal, partial discharge, etc.).

#### 4.4.5. Summary

The issue of the sustainability of materials for power converters is difficult to address in a few paragraphs because of the diversity of materials and their processes, but also because of their entanglement with the system. By going from the material to the system and from the cradle to the grave, the following points of interest are proposed:

- The materials' purity which can be essential to obtain the required properties may lead to a significant environmental impact;
- Because an LCA is intrinsically dependent upon the considered application, there is only one comparative study available in the literature (for example MLCC vs. tantalum, Mn-Zn vs. Ni-Zn ferrites, ceramic vs glass fibre and epoxy, etc.);
- An interdisciplinary approach in the design and the assembly of a power converter is necessary to ensure the inter-operation of the manufacturing chain, the respect of the standards, the increase in the lifetime and reliability;
- The knowledge of the reliability of a power converter is of great importance to estimate its lifetime. Component failure is highly likely to degrade the LCA. For example, interconnection currently accounts for 10% to 30% of the causes of failure [77], but the use of alternative substrates/solders/processes will have to take this issue into account to avoid a lifetime reduction;

- The energy gain from using the system versus the extra consumption involved in producing more efficient converters can be assessed through LCA, as can the choice of converter architecture, switching frequency, etc.

It is important to understand that the material topic, in addition to being crucial and complex, is also one that needs to be approached from a systems perspective. A more sustainable material does not necessarily imply a more sustainable system, and the diversity of applications and functionalities means that it is essential to work on materials by considering systems and applications in their entirety.

## 5. Conclusions and Perspectives of Research Activities towards Sustainability in Power Electronics

This paper highlights an emerging activity in more sustainable power electronics. The literature review, analyzed in four complementary topics, has shown the broad diversity of topics that remain to be addressed and the significant amount of research that remains to be carried out to address the issues.

Overall, the members of the working group pointed out a number of issues for sustainable power electronics: the lack of data (industrial processes, mining industries and raw materials), the lack of data quality regarding LCA databases and software, the lack of indicators dedicated to the problem of sustainability in the field of power electronics, the lack of identified actors in disassembly channels, the lack of studies addressing repairability and the importance of integrating circularity into eco-design requirements. Moreover, an interdisciplinary approach in the design and the assembly of a power converter is necessary to ensure the inter-operation of the manufacturing chain regarding materials and circularity, the absence of transparency obligations (compliance with standards, publication of data), the lack of positions taken by public authorities and the absence of arbitration. One of the challenges is to develop communication channels between the communities and players at stake to tackle the aforementioned issues.

To face the urgent need to protect our environment (as we approach many points of the planetary limits), it is very welcomed to see that sustainability started to be visible in power electronics. Nonetheless, it is an emerging topic where today, studies are quite erratic. This review will help power electronics experts who want to start taking sustainability into account in their work. The main and preliminary scientific conclusions of this paper are:

- A systemic approach is essential to assess the sustainability of the power converters (consider the entire life cycle, the entire system, a sufficient number of indicators, all the players in the value chain, etc.).
- Standardized methodologies to conduct LCA on power converters are necessary to compare different technological solutions and applications. These standards remain to be developed.
- The databases used for LCA needs to be evaluated regarding data quality and uncertainties. Any work that could enrich them with first-source precise and reliable data is also welcome.
- The indicators from LCA are not sufficient to guide the design of more sustainable power converters. The lack of complementary indicators related to end-of-life scenarios (modularity, reusability, reparability, etc.) should be identified and new indicators should be developed if necessary.
- Circular economy studies on the existing and future value chain for power electronics converters and their parts are necessary. The study on power electronics design's impact on the deployment of the strategies of the circular economy at the product level (reuse, repair, refurbished, refabricate and repurpose) should be prioritized due to the lack of relevant papers on the subject.
- Materials are enablers of more sustainable power converters but to assess their true potential a systemic approach is necessary. For example, the semiconductor material should be studied within the power electronic converter due to indirect effects, positive or negative, on the other components and their environmental impact.

These preliminary conclusions need to be strengthened. This paper points out a curated list of references available in [7] as a starting point for further research in the field. Because sustainability has emerged as a discipline on its own and also as a part of others, work-group CEPPS has gathered researchers from different fields to address sustainability. Yet, it still needs to be consolidated and gain credibility. The work of the CEPPS workgroup will now focus on a detailed state-of-the-art analysis with regard to all the issues and barriers in the field, in an attempt to draw up a roadmap.

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**Data Availability Statement:** The data presented in this study are available at [7] and on request from the corresponding author.

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