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Life Cycle Assessment and Environmental Impacts of Power Electronic devices

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Resumen

La Tierra se enfrenta actualmente a una crisis medioambiental planetaria próxima a un punto de no retorno, donde el cambio climático, la pérdida de biodiversidad y la contaminación conllevan consecuencias catastróficas para la humanidad. El compromiso internacional se centra en la mitigación del cambio climático, con el objetivo de alcanzar un sistema de Cero Emisiones Netas mediante estrategias de descarbonización. Esto implica la transición de los combustibles fósiles hacia energías renovables, mediante un aumento de la electrificación y la mejora de la eficiencia energética. En este contexto, los convertidores de Electrónica de Potencia desempeñan un papel clave, al ser elementos presentes en todos los sistemas eléctricos—desde la movilidad eléctrica y las energías renovables hasta la automatización industrial.

No obstante, aunque los convertidores sean cruciales en la mitigación del cambio climático, su impacto también está asociado a la generación masiva de residuos electrónicos, la extracción intensiva de materias primas y la contaminación química. Por tanto, es imprescindible abordar sus efectos de forma íntegra, y no solo desde la perspectiva climática.

El objetivo de este proyecto es explorar cómo incorporar la sostenibilidad en la Electrónica de Potencia, a través de estrategias como la economía circular, el Análisis del Ciclo de Vida (ACV) y el ecodiseño. Estos tres enfoques se analizan tanto desde el estudio teórico como mediante casos de estudio prácticos, ofreciendo una visión integral de sus beneficios y limitaciones.

Para ello, el capítulo 2 plantea el marco teórico, justificando la necesidad de un cambio ante la crisis planetaria e introduciendo los conceptos clave que se desarrollarán. Las tres líneas de trabajo en relación con la Electrónica de Potencia que se exploran son: el Análisis del Ciclo de Vida (ACV), un modelo Paramétrico de ACV y el Pasaporte Digital del Producto.

El capítulo 3 analiza el Análisis del Ciclo de Vida aplicado a un inversor de 150 kW. Se presentan las características de este método sistemático para cuantificar los impactos ambientales del inversor, desde la extracción de materias primas, su fabricación y uso, hasta su fin de vida.

El capítulo 4 presenta el modelo Paramétrico de ACV aplicado a la Electrónica de Potencia. A través de un modelo desarrollado en Python, se estudia el caso de un convertidor Buck y se aplica parte de la metodología a un convertidor Boost.



Finalmente, el capítulo 5 propone el Pasaporte Digital del Producto, una iniciativa de la Unión Europea y el Plan de Acción en Economía Circular. Se plantea una estructura adaptada a componentes de Electrónica de Potencia, aplicada al caso de estudio del convertidor modular CSC GM20V5A.

El objetivo final es construir una visión integral del estado actual de la sostenibilidad en Electrónica de Potencia, poniendo en valor las sinergias entre las herramientas y metodologías analizadas. Se busca así contribuir a la reducción del impacto ambiental y avanzar hacia una transición energética más justa y alineada con los límites planetarios.



Index

1. Introduction	13
1.1.- The planetary crisis and the role of Power Electronics	13
1.1.1. The environmental planetary crisis.....	13
1.1.2. Climate change mitigation: electrification and Power Electronics.....	13
1.1.3. The broader picture: Planetary Boundaries	14
1.1.4. Sustainability and the state-of-the-art in PE, the G2ELab Group	15
1.2.- Scope and structure of the project	16
1.2.1. Objectives	16
1.2.2. Summary of the case studies	17
1.2.3. Methodology	18
2. Theoretical Framework	19
2.1.- The environmental crisis	19
2.1.1. The Planetary Boundaries	19
2.1.2. Net-zero-emissions and electrification: Power Electronics case.....	21
2.2.- Sustainability as a solution.....	26
2.2.1. Circular economy.....	26
2.2.2. Eco-design.....	27
2.2.3. Life Cycle Assessment – LCA	29
2.2.4. PE approaches.....	29
3. LCA of a 150 kW inverter.....	35
3.1.- LCA methodology.....	35
3.1.1. Goal and scope definition	36
3.1.2. Life Cycle Inventory analysis	37
3.1.3. Life Cycle Impact Assessment	38
3.1.4. Interpretation.....	38
3.2.- Critics and conclusion	41
4. PLCA meta-model for PE	43
4.1.- General characteristics of the PLCA meta-model	44



4.2.- PLCA meta-model, application in a Buck Case	45
4.2.1. Establishing the Functional Architecture coupled with environmental indicators	47
4.2.2. Identifying the main critical technical parameters.....	51
4.2.3. Elaborating a design strategy: key-design parameters	52
4.2.4. Evaluating the technico-environmental performance of the design choices	56
4.3.- Critics and conclusion of the PLCA meta-model and the Buck case.....	60
4.4.- PLCA meta-model application in a Boost Case	62
4.4.2. Establishing the functional architecture coupled with environmental indicators	66
4.4.3. Identifying the main critical technical parameters.....	68
4.4.4. Critics and conclusions of the PLCA meta-model for the Boost case	73
5. Digital Product Passport	77
5.1.- Accessibility to information for improving circularity.....	77
5.2.- Proposal of a DPP for PE	79
5.3.- DPP of the CSCGM20V5A.....	81
5.3.1. Modular approach and generic characteristics	81
5.3.2. Technical contributions to the DPP of the CSC GM20V5A.....	82
5.4.- Critique and conclusion of the study case.....	91
5.5.- Insights and perspectives from Expert Interviews.....	93
6. Conclusions	95
7. Bibliography	101

Annex I. Equations of the Parametric Life Cycle Assessment Meta-Model

Annex II. DPP Structure for PE- Applied at the CSC GM20V5A

Annex III. Altium and manufacturing files from the CSC GM20V5A

Annex IV. BOM of the CSC GM20V5A and the Control Board

Annex V. MCSC20V5A Insights- Characterisation Tool

Annex VI. LTSpice Model

Annex VII. CSC GM20V5A Experimental Results



List of tables

Table 4.1.-Technical Constraints of the Boost Converter	63
Table 4.2. BOM of the DC-DC Boost.....	65
Table 4.3.- Ecoinvent references associated to the Boost components.....	67
Table 4.4-Environmental impact output of each of the life cycle phases after executing the Boost code	68
Table 5.1- General information of the CSC GM20V5A belonging to its DPP, Annex II	83
Table 5.2.- Components present in the CSC GM20V5A, Annex II [44].....	84
Table 5.3.- BOM of the CSC GM20V5A	86



List of figures

Figure 2.1. Current status of the nine planetary boundaries [3].	20
Figure 2.2- Announced manufacturing project throughput and deployment of key technologies in the NZE Scenario, [5]	22
Figure 2.3-Proven solutions in NZE Scenario available today, [5]	22
Figure 2.4-E-Waste in 2022: 62 billion kg, [9]	24
Figure 2.5-E-waste in billion kg evolution and prediction, [9]	25
Figure 2.6-Diagram of global focus on climate change and its consequences	25
Figure 2.7-Circular economy processes, [11]	27
Figure 2.8-Circular economy concept, emphasizing design decisions on all life-cycle phases, [7]	28
Figure 2.9-Circular strategies (green) categorized in three levels, with traditional WEEE approaches (red), [26]	31
Figure 2.10-Summary of concrete PE strategies analysed	33
Figure 3.1-Main LCA steps applied on the Inverter study, [8]	36
Figure 3.2- Environmental impact categories used in LCA, based on the PEF framework, [29]	37
Figure 3.3- Standardized environmental impacts related to the product life cycle phases, use (brown) and manufacturing (blue) the most significant contributors, [20].	39
Figure 3.4- Hierarchy of environmental impacts using Planetary Boundaries normalization, [8], Mineral Resources Depletion (MRD), Freshwater Ecotoxicity (FET) and Human Toxicity (HT) emerge as the most critical.	40
Figure 4.1-Example of data visualization supported with the PLCA meta-model, [12]	45
Figure 4.2-FAST diagram with functional structure of the buck converter [34]	48
Figure 4.3- Parametric model equations that calculate the environmental impact of manufacturing, [12]	49
Figure 4.4-Manufacturing phase code following the FAST block for the output filter	50
Figure 4.5-Total Manufacturing impacts after aggregating the FAST blocks	50
Figure 4.6. Manufacturing impacts output after executing the code	50
Figure 4.7- Reminder of the Environmental impact categories used in LCA, [27]	51



Figure 4.8-Potential environmental impacts generated by the buck converter after normalization [34]..... 52

Figure 4.9-Main eco-design strategies and key parameters affected, [34]..... 53

Figure 4.10-Environmental impacts distribution of life phases for the target impact categories, [34] 54

Figure 4.11-Eco-design scenario by applying functional innovation strategies [12]..... 55

Figure 4.12-Eco-design scenario by applying resources sufficiency strategies, [12] 56

Figure 4.13-Comparison of scenario A and B..... 57

Figure 4.14-Environmental impact evolution between proposed scenarios A and B 58

Figure 4.15-Normalized impacts of proposed scenarios across impact categories..... 59

Figure 4.16-3D layout of implemented ecodesign scenario..... 59

Figure 4.17-Final LCIA result comparison, distinguishing between conceptual and detail design 60

Figure 4.18-DC-DC Boost topology schematics, [37]..... 63

Figure 4.19-DC-DC Boost functional requirements, [33]..... 64

Figure 4.20-Hardware selection, [37] 64

Figure 4.21-3D routing, [37] 64

Figure 4.22-FAST diagram with functional structure of the Boost converter 66

Figure 4.23-Manufacturing phase code for the Energy Stockage functional block..... 68

Figure 4.24-Normalised impacts repartition of the DC-DC Boost converter 69

Figure 4.25-Ecotoxicity of Freshwater repartition along the whole life cycle of the Boost converter; measured in Comparative Toxic Unit for ecosystems (CTUe)..... 70

Figure 4.26-Energy Resources: non-renewable, fossil fuels; repartition along the whole life cycle of the Boost converter, measured in MJ of Abiotic Resource Depletion (ADP)..... 70

Figure 4.27- Climate Change repartition along the whole life cycle of the Boost converter, measured in Global Warming Potential (GWP), kg of CO2 equivalent 71

Figure 4.28- Manufacturing impacts distribution in the Boost converter's functional blocks 72

Figure 4.29-Use phase impacts distribution in the Boost converter's functional blocks..... 72

Figure 4.30-Schematic comparison of environmental impact distribution of the study cases: 150kW inverter, Buck Converter and Boost Converter 74



Figure 4.31-Schematic comparison of the life cycle phases the most affected by the environmental impact of the study cases: 150kW inverter, Buck Converter and Boost Converter 75

Figure 5.1-DPP proposed structure for PE..... 80

Figure 5.2-Multi-Cell Converter built with 18 Power Conversion Blocks, [44] 82

Figure 5.3-Interconnections among elementary power conversion blocks through copper bars, [45] 82

Figure 5.4-Output current versus efficiency (left) and versus converter temperature (right) for three prototypes of the CSC GM20V5A, Annex II [44] 84

Figure 5.5- Altium Schematics of the CSC GM20V5A..... 85

Figure 5.6- Altium Schematics of the Control board of the Microprocessor..... 85

Figure 5.7-LTSpice DAB electric layout 87

Figure 5.8- MCSC20V-5A top view for Vds N7 measurement..... 88

Figure 5.9- Transistors commutation for a phase shift of 3,4°: hard switching 88

Figure 5.10-Example of one of the thermal camera pictures 89

Figure 5.11-Characterisation Tool in Excel 90

Figure 5.12-Reparation criteria applied on the components of the CSC GM20V5A, resulting on a disassembly score based on criteria such as reliability, accessibility or soldering characteristics [48]. 92

Figure 6.1-Complementary cycle of data collection, evaluation and refinement 98



Abbreviations

The following terms with their corresponding abbreviations are frequently used:

DAB	Dual Active Bridge
CSC (SCC)	<i>Cellules Standards de Conversion</i> (Standard Conversion Cells)
EEE	Electric and Electronic Equipment
FAST	Functional Analysis Technique
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
PE	Power Electronics
PEBB	Power Electronics Building Blocks
PEC	Power Electronics Converter
PLCA	Parametric Life Cycle Assessment
WEEE	Waste of Electric and Electronic Equipment



1. Introduction

1.1.- The planetary crisis and the role of Power Electronics

1.1.1. The environmental planetary crisis

The Earth is currently facing a planetary environmental crisis that has reached a critical point. The scientific community has long warned of widespread and rapid changes in the atmosphere, oceans, and biosphere, with increasingly adverse consequences for both nature and humanity [1]. Evidence of extreme weather events, rising global temperatures, changing precipitation patterns, prolonged droughts, and intensifying storm systems has continued to grow stronger in the last years. Moreover, the number of people living outside the optimal climate niche or displaced by climate-related disasters has risen sharply, while disruptions in vegetation cycles keep critically affecting the global food production [2], [3].

In short, this global crisis is driven by three interlinked phenomena: climate change, biodiversity loss, and pollution. Together, they are contributing to severe environmental degradation across terrestrial and marine ecosystems, posing some of the most significant threats to human well-being and the long-term stability of the Earth system [1], [3].

1.1.2. Climate change mitigation: electrification and Power Electronics

In response to this crisis, international efforts have largely focused on climate change mitigation. Central to this response is the goal of limiting global warming to well below 2°C—and ideally no more than 1.5°C—above pre-industrial levels, as outlined in the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) emphasizes that each fraction of a degree beyond this threshold increases the risk of severe consequences for human health, food security, and water access [2], [4].

To meet this challenge, decarbonization strategies focus primarily on transitioning from fossil fuels to renewable energy sources, increasing electrification, and improving energy efficiency.



Within this shift, electricity is expected to play a central role in a multi-carrier energy system—driven by a massive deployment of solar PV, wind power, and battery-based storage [5], [6]. In this context, Power Electronics (PE) plays a pivotal role in enabling this transition. As the technology responsible for converting, controlling, and conditioning electrical energy, PE acts as the interface between generation sources and end-use applications. It is fundamental not only in renewable energy systems but also in electric mobility, energy storage, and smart grids. More specifically, Power Electronic Converters (PECs) are key components of all electrification processes. Present in wind turbines, PV inverters, chargers, and electric vehicles, PECs adjust voltage, current, frequency, and power flow to meet system requirements—thus playing a vital role in reducing emissions and improving efficiency [7]. These concepts will be explored in Section 2.1.2 with more detail.

1.1.3. The broader picture: Planetary Boundaries

However, while mitigating climate change is essential, it is not sufficient [7]. Scientists claim that the Earth state must be considered as an interconnected system, and focusing solely on carbon emissions risks neglecting other critical environmental dimensions. This broader understanding is captured by the Planetary Boundaries framework [1], [3].

Developed by Rockström et al., the Planetary Boundaries theory identifies nine Earth system processes that regulate planetary stability and resilience. These include climate change, biosphere integrity, ocean acidification, stratospheric ozone depletion, atmospheric aerosol loading, biogeochemical flows, land-system change, freshwater use, and the introduction of novel entities (e.g., synthetic chemicals or plastics). Transgressing these boundaries could lead to irreversible environmental damage. Alarmingly, six of the nine planetary boundaries have already been breached, highlighting the critical need to address these issues in behalf of both planetary health and human survival [1], [3].

In the field of Power Electronics, the Planetary Boundaries framework is particularly relevant. Although Power Electronic Converters play a vital role in reducing greenhouse gas emissions and enabling the energy transition, their environmental impact extends beyond climate change. The systems are complex and composed of numerous materials, often with limited recyclability and short functional lifespans of around 20 years [7]. Without a more integrated and systematic approach, their deployment may intensify environmental pressures—such as mineral resources



depletion, eutrophication of freshwater, or electronic waste (e-waste) generation—further contributing to the transgression of other planetary boundaries [7], [8]. For instance, in 2022 alone, over 62 million tonnes of e-waste were generated globally—equivalent to 7.8 kg per person—containing both hazardous and valuable materials [9]. This rising challenge highlights the urgent need to rethink the design, production, and end-of-life management of PE devices. Section 2.1.1 elaborates further on the theoretical framework, illustrating the complexity of the current situation.

1.1.4. Sustainability and the state-of-the-art in PE, the G2ELab Group

To address these challenges, one promising path is to embed **sustainability** into the development of technologies—including Power Electronics. But this raises a fundamental question: *What makes a technology sustainable?*

At the national level in France, the CNRS working group CEPPS (*Convertisseurs Électroniques de Puissance Plus Soutenables* – More Sustainable Power Electronics Converters) has been formed within the SEEDS network (*Systèmes d'Énergie Électrique dans leurs Dimensions Sociétales* – Electrical Energy Systems in Their Societal Dimensions) [10]. This community seeks to unite researchers around the challenges and methodologies of sustainability in PE. Part of their members and co-animators belong to the **G2ELab** research group in Grenoble, who investigate tools, indicators, and methods for eco-design, circularity, and sustainability assessments in PE, as well as materials, design concepts, and manufacturing processes that support these goals [11].

From June to August 2024, I completed a research internship at G2ELab under the supervision of Jean-Christophe Crebier (Research Director CNRS-G2ELab) and Pierre Lefranc (Senior lecturer at Grenoble-INP, ENSE3, G2ELab). My work focused on sustainable Power Electronics, including experimental and theoretical analysis of the CSC GM20V5A—a modular converter characterised by its sustainable approach. This included technical characterisation (Altium files, BOM, datasheets), experimental measurements (LTSpice modelling and lab testing), and the development of a transversal documentation structure, adapted to the emerging Digital Product Passport (DPP) framework. The aim was to improve information accessibility and traceability in the PE field.



Building on this first experience, I aimed to explore more deeply how Power Electronics relates to broader environmental challenges. To this end, during the 2024–2025 academic year, I developed the present research project under the Collaboration Grant in University Departments from the Ministry of Education, co-supervised by Joaquín González Norniella (Professor at University of Oviedo) and Pierre Lefranc (Senior lecturer at Grenoble-INP, ENSE3, G2Elab). The primary objective of this work is to explore and assess the state of the art in sustainable Power Electronics, by examining existing strategies and evaluating how they contribute to reducing the environmental impacts. Three fundamental approaches have been identified, notably:

- **Circular economy principles**
- **Eco-design practices**
- **Life Cycle Assessment (LCA) methodologies**

These frameworks define the basis of sustainable technologies and are increasingly being explored in the PE research community. However, significant gaps remain regarding their implementation, integration, and evaluation.

1.2.- Scope and structure of the project

1.2.1. Objectives

The central aim of this work is to explore how circular economy, eco-design, and Life Cycle Assessment (LCA) approaches can contribute to more sustainable practices in Power Electronics. To address this, the project sets out three key objectives:

- To identify and analyse sustainable strategies applicable to Power Electronics.
- To assess their effectiveness, limitations, and synergies.
- To explore whether a more holistic and sustainable design and development model for PE systems is achievable.

Chapter 2 presents the theoretical framework, justifying the need for a shift in response to the current planetary environmental crisis. Afterwards, from the basis of Circular Economy, Eco-



Design, and Life Cycle Assessment, three core lines of work emerge—each rooted in and shaped by these approaches. These three pillars will structure the development of the work:

1. Life Cycle Assessment (LCA)

- A systematic method to quantify the environmental impacts of a product from raw material extraction through manufacturing, use, and end-of-life. It will be analysed through the 150 kW inverter study case of Briac Baudais [8], Chapter 3.

2. Parametric LCA (PLCA)

- A meta-model tailored for PE that links technical parameters to life cycle indicators, enabling early-stage eco-design decisions. The study case of a Buck converter by Li Fang will be presented [12], while the PLCA model was applied during this project to a Boost converter, Chapter 4.

3. Digital Product Passport (DPP)

- Proposed as a digital tool to support transparency and circularity, a DPP structure tailored for PE components is developed and applied, Chapter 5. The study case is a modular converter, the CSC GM20V5A; which was tested during the G2Elab internship. On the basis of the results, the DPP structure has been completed and analysed in more in detail with regard to the general framework.

1.2.2. Summary of the case studies

- **LCA of a 150 kW inverter** by Briac Baudais: used to understand the LCA methodology, identify key environmental hotspots, and assess modelling challenges, Chapter 3.
- **PLCA applied to a Buck converter** by Li Fang: analysed to understand the benefits of parametric modelling and eco-strategy formulation, Chapter 4.
- **PLCA applied to a Boost converter**: implemented with support from G2Elab; results were obtained despite access limitations to the Ecoinvent database, Chapter 4.
- **Digital Product Passport of the CSC GM20V5A converter**: standards and frameworks were analysed to propose a structure relevant to PE, tested on the CSC GM20V5A converter, Chapter 5. The study case also enhances the modular approach, a key strategy in eco-design.



1.2.3. Methodology

The work combines:

- Literature review and theoretical analysis of largely different topics: from climate and environmental data, to Power Electronics specifications, to industrial standards and European regulatory frameworks.
- Data collection for Python modelling: analysing technical specifications of power electronics converters, retrieving datasheets and creating inventories, understanding the Ecoinvent dataset characteristics for final application on Python scripts for the PLCA model.
- Experimental validation and analysis of the measurements: Altium and manufacturing files, Bill of Materials, LTSpice simulations, experimental measurements on the CSC GM20V5A prototype, data curation in Excel.
- Collaboration with researchers and experts at G2Elab and University of Oviedo: work supervised by Pierre Lefranc (Senior lecturer at Grenoble-INP, ENSE3, G2Elab) and Joaquín González Norriella (Professor at University of Oviedo), PLCA exchanges oriented by Li Fang (PhD Engineer, Ecodesign expert), Python code executed by Gaëtan Heller (PhD student at G2ELab).



2. Theoretical Framework

2.1.- The environmental crisis

The environmental planetary crisis has reached a non-return point, with numerous environmental issues facing extreme situations. Climate change, loss of biodiversity and pollution represent some of the biggest threats to humanity, with severe impacts on human rights such as adequate food, water, education, health or development. In 2023, 600 million people were already living outside the optimal climate niche [1].

Extreme weather events are resulting in prolonged droughts and heatwaves, increased instances of extreme precipitation and flooding. Wildfires are affecting by now more than one third of global vegetated areas. Global coral bleaching is leading to extensive ecological damage and biodiversity loss. Changes in land use are affecting vegetation productivity, with direct correlation on food production, soil degradation or water pollution. Waste is exponentially increasing, with millions of deaths linked to air pollution, and plastic debris widespread in the majority of world's freshwater ecosystems [1].

2.1.1. The Planetary Boundaries

The Planetary Boundaries framework offers the theory for maintaining Earth's environmental functions under stability, resilience, and life-support conditions [3]. Johan Rockström et al., consider the Holocene as the scientific reference for a desirable planetary state for life on Earth, heavily perturbed since human action and altered to the Anthropocene epoch. To avoid catastrophic impacts on Earth, nine planetary boundaries limit deleterious states not to be transgressed. These delimited states are biophysical and biochemical systems that quantify the critical processes under anthropogenic perturbation: biosphere integrity, climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows, freshwater change and land system change (Figure 2.1).

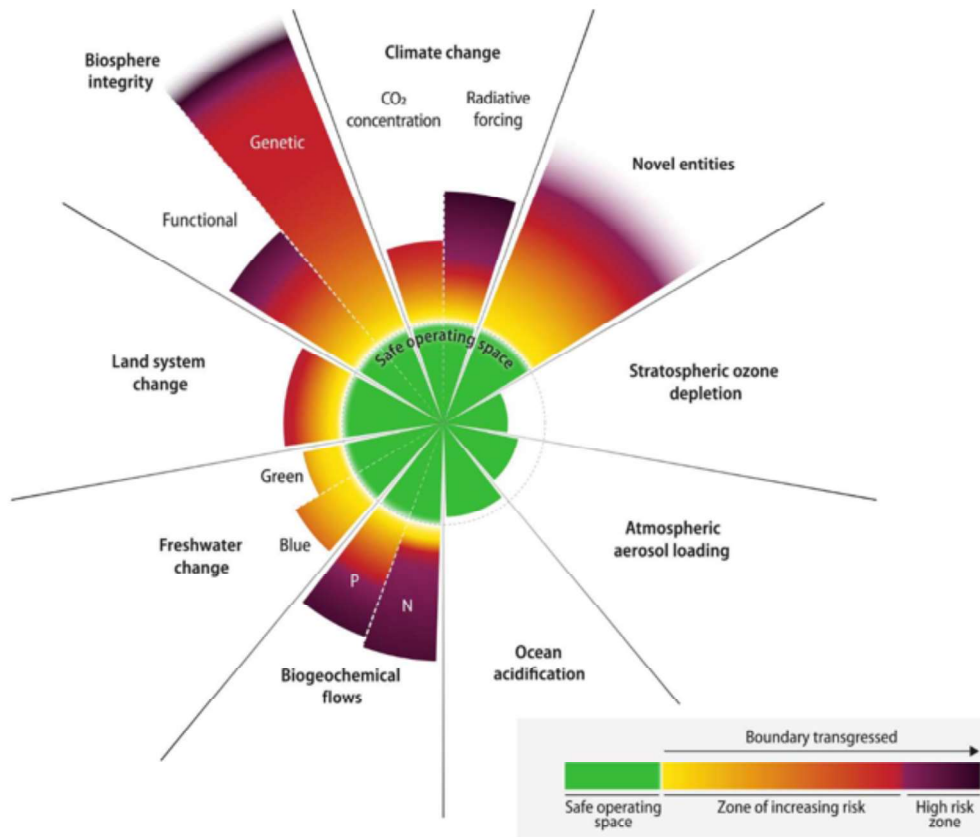


Figure 2.1. Current status of the nine planetary boundaries [3].

It is important to enhance that the state of the Earth system must be considered as a whole, which means that the planetary boundaries are interrelated and interdependent on each other. The effects of the perturbations are not separate issues, as they bring nonlinear interactions that aggregate effects on the overall state of the Earth system [3]. In the current situation, six of the nine planetary boundaries are transgressed, and human and environmental welfare (and societal development) are experiencing devastating consequences. As depicted in Figure 2.1: novel entities, climate change, biosphere integrity, land system change, freshwater change and biogeochemical flows have transgressed their safe operating boundaries, leading to significant environmental impacts.

Some of the several well-known symptoms of crossing planetary boundaries include extreme weather events (droughts and heatwaves, precipitation, flooding), extreme events (drought-wildfire affecting by now more than one third of global vegetated areas, global coral bleaching), water scarcity (irrigation, land use changes), changes in vegetation productivity (impact on food production), increase in waste or declining global carbon sinks (carbon sequestration) [1].



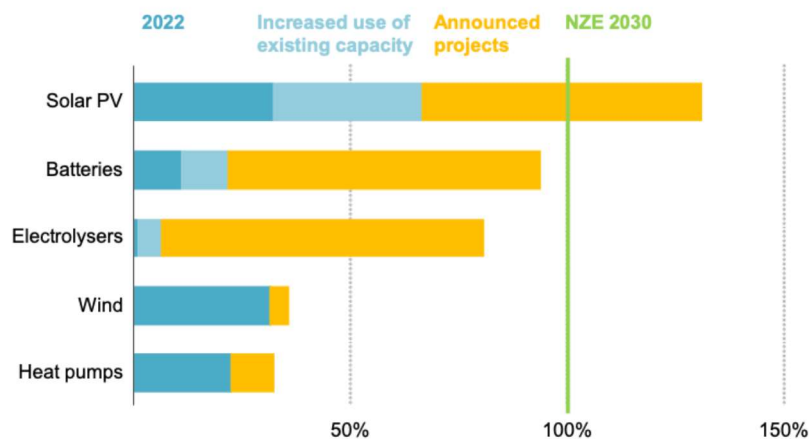
The climate change emergency in particular receives international commitment through legislation such as the Paris Agreement and a Net-zero-emissions energy system target [13]. The Intergovernmental Panel on Climate Change (IPCC) keeps enhancing how any further increase of global temperatures aggravates significant consequences for human health or negative impacts on food production and water availability [1]. Over the past two decades, climate change has been linked to 7,348 major disasters, resulting in 1.23 million deaths and \$2.97 trillion in economic losses. Further, 2.2 billion people lacked safely managed drinking water, and 3.5 billion lacked adequate sanitation, contributing to 1.4 million deaths annually [1]. Consequently, there is an urgent need for achieving carbon neutrality by 2050, in order to limit global warming to not more than +1.5°C above pre-industrial levels.

2.1.2. Net-zero-emissions and electrification: Power Electronics case

Net-zero carbon dioxide emissions are crucial for limiting the rise of temperatures and the fatality of its consequences. Net-zero commits to cutting carbon emissions, to a small amount that can be absorbed by nature and carbon dioxide removal measures, leaving zero in the atmosphere. The aim is to reduce emissions to 45% by 2030, reaching net zero by 2050 [13]. The emissions come from sectors such as land use, agriculture, industrial production and energy. Nevertheless, the energy sector is the source of around three-quarters of greenhouse gas emissions, and apart from electricity generation, it includes transportation, heating, cooling or lighting [6].

As a result, decarbonization is based not only on an increase of renewable energy sources (the largest driver though), but also on an increase of electrification and technical efficiency [5]. According to the International Energy Agency, the main strategies are switching from fuel to electricity, reaching a more efficient use of materials and energy, and adopting a behavioral change that reduces energy demand. Coal, gas and oil-fired power industry is expected to shift to alternative technology, cutting emissions with electric vehicles, heat pumps, hydrogen or carbon capture storage (Figure 2.2).

Additionally, the transition is predicted to come along with large new, smarter and repurposed infrastructure networks (distribution grids expanding by around 2 million kilometers each year to 2030); mechanisms to quickly balance time-varying differences between demand and electricity generation; or more nuclear power [5].



If all announced projects proceed, solar PV manufacturing will exceed the 2030 level needed in the NZE Scenario, and batteries manufacturing will get very close; other technologies see larger gaps.

Figure 2.2- Announced manufacturing project throughput and deployment of key technologies in the NZE Scenario, [5]

The predictions to 2030 aim to triple the global installed renewable capacity to 11000 GW, to double the energy intensity improvements, and to cut methane from fossil fuels by 75 % (Figure 2.3). These proven solutions would deliver more than 80 % of the emissions reductions needed by 2030.

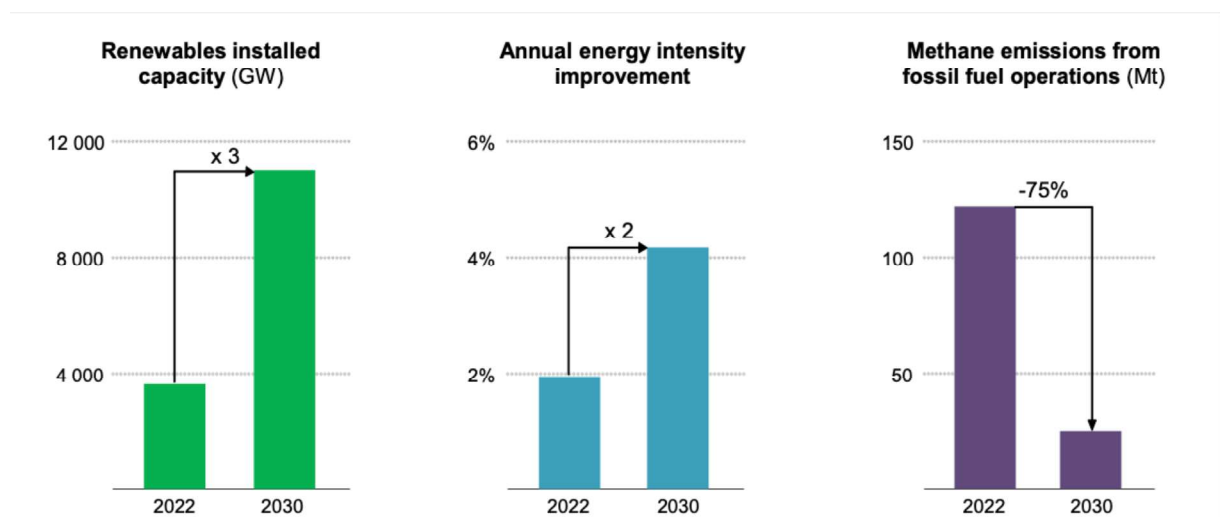


Figure 2.3-Proven solutions in NZE Scenario available today, [5]

In this context, Power Electronics (PE) is one of the principal technologies. It remains the interface between the electricity generation and the final effective applications, not only at the heart of energy production, but also in electric mobility [14].



Researchers such as Huber et al., estimate a total installed PE conversion capacity in the order of 100,000 GW in 2050, with power Electronic Converters (PECs) being the principal key-drivers [7]. While being present in any electrification process (from wind power generation to energy storage in batteries or electric mobility systems), PECs enable circuit control and conversion functions in Electric and Electronic Equipment (EEE¹). Regulating the expected adjustments of voltage, current, and frequency, they ensure the intermediate stages of power generation.

However, the controversy arises when analysing the environmental impacts of PECs themselves. The systems are complex, composed of a large number of materials, and characterized by functional obsolescence and a limited lifetime of around 20 years [7]. Its manufacturing leads to high energy and freshwater consumption, raw material use, chemical exposure and waste generation. Moreover, the immense heterogeneity of the devices adds a supplementary difficulty when it comes to end-of-life management. Few enterprises professionally work on converters' repairs, and second-life applications are not so common to implement. An example of research (Baudais, B. et al., 2023) [8] shows how, in the case of a 150 kW inverter, mineral resources, eutrophication of freshwater and human toxicity are among the main devastating impacts.

Further, electronic waste (e-waste) must be borne in mind. In 2022, a waste stream of EEE with hazardous and valuable materials of 62 billion kg was generated (equivalent to an average of 7.8 kg per capita per year), Figure 2.4. It contained 31 billion kg of metals, 17 billion kg of plastics and 14 billion kg of other materials (minerals, glass, composite materials, etc.) [9].

¹ EEE, Electric and Electronic Equipment, is defined as “all products with circuitry or electrical components with a power or battery supply”, PECs included. [9]

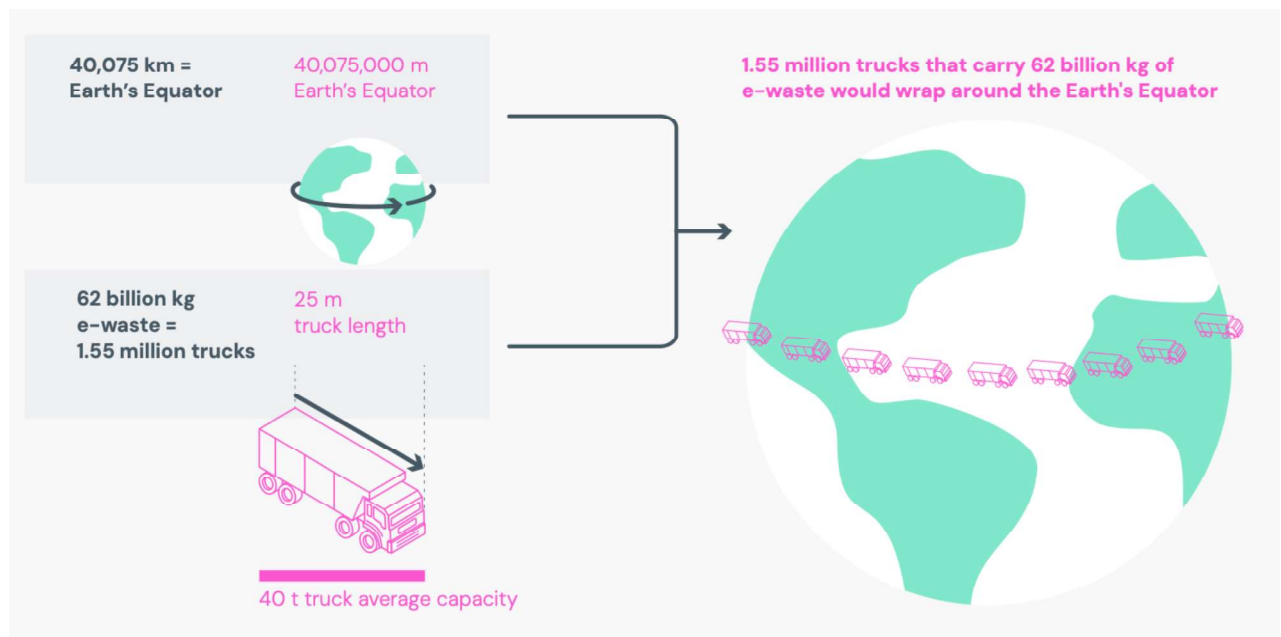


Figure 2.4-E-Waste in 2022: 62 billion kg, [9]

In particular, e-waste from photovoltaic panels was documented at 0.6 billion kg, but is expected to quadruple to 2.4 billion kg in 2030. Additionally, the small equipment category that comprises electronics itself resulted in 1 billion kg of copper from cables and printed circuit boards, as well as 1.6 million kg of precious metals such as gold, palladium and silver; 70 million kg of lead; and 34 million kg of cobalt [9].

Only a 22.3 % of this e-waste mass was documented as formally collected and recycled, and even if improved through the recent years, it keeps outpaced by a factor of almost 5 by the rise in e-waste generation (Figure 2.5). Technological progress, higher consumption, limited repair options and short product lifecycles are among the reasons identified by the Global E-waste Monitor [9] that slow down the adequate e-waste recycling.

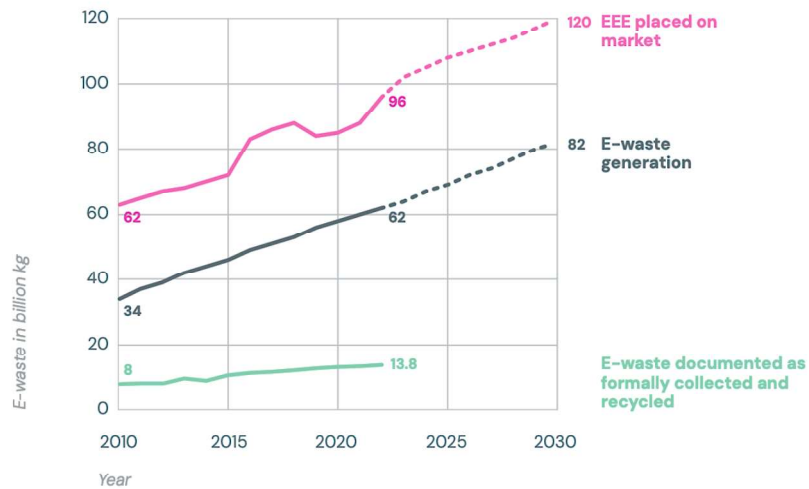


Figure 2.5-E-waste in billion kg evolution and prediction, [9]

The consequences go from air and water pollution to damage of land and biodiversity loss, as well as the ones derived from mining activities: human health and respiratory diseases from air pollution.

As a result, back to the Planetary Boundaries framework, it can be seen how the primary focus on climate change through an increased electrification, even if necessary, is affecting other environmental impacts and leading to massive e-waste (Figure 2.6) . The Earth state must be treated as a whole, and the rest of the planetary boundaries must be considered to avoid the aforementioned adverse consequences.

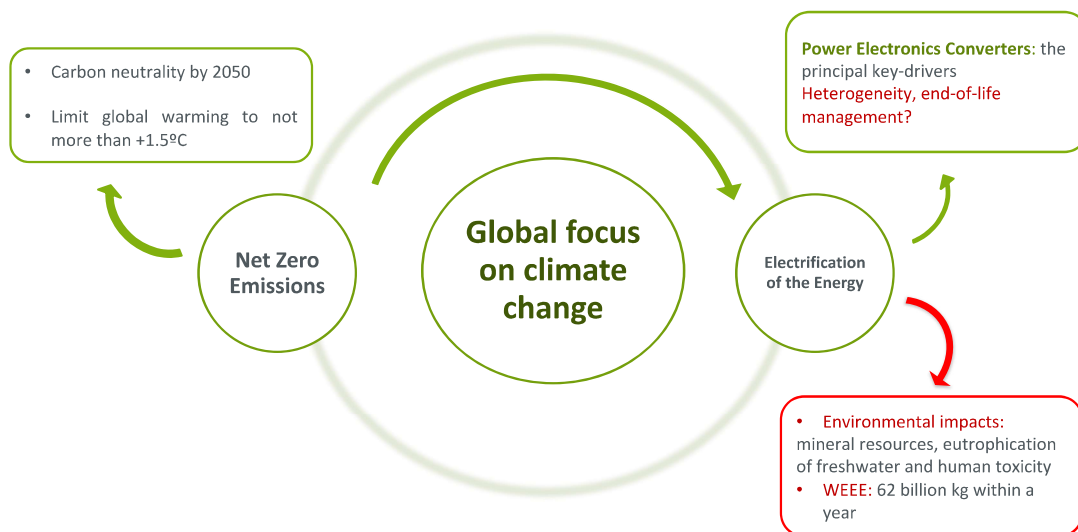


Figure 2.6-Diagram of global focus on climate change and its consequences



2.2.- Sustainability as a solution

One of the solutions to the environmental crisis problems may be integrating “*Sustainability*” in technology and PE. However, the following question arises: What are the conditions that must be met for a practice or technology to be sustainable?

The United Nations’ Brundtland Commission define *sustainable development* as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [15]. Nevertheless, discussion may be held when inquiring which are the human needs or the way in which they will be fulfilled in the future. Technological development will always be present and associated to environmental impacts. Therefore, it is argued that the finite boundaries of the planet must delimit economic growth so that the safe operating space for our civilization is respected [16], [17].

Hauschild et al., develop that an approach to “*Sustainability*” occurs when the *top-down* and *bottom-up* perspectives meet. The top-down perspective determines the limits not to excess, with man-made impacts translated from global to individual scale. It is framed by the Planetary Boundary concept developed by Rockström and colleagues [3]. The bottom-up perspective proposes the method and guidelines for designing sustainable products, at individual and at growing population levels.

These two perspectives help tracing a path towards “Sustainability”, that is considered to be nourished through three fundamental strategies: **circular economy**, **eco-design** and **Life Cycle Assessment (LCA)**, [7]. While integrating these approaches into the field of Power Electronics is the focus of ongoing research, identifying the existing gaps and exploring the most effective ways to implement them remains a promising and necessary objective.

2.2.1. Circular economy

Circular economy is the economic framework that decouples economic activity from the consumption of finite resources, aiming to tackle climate change and biodiversity loss while addressing important social needs. It is based on three principles: waste minimization, products and materials circulation, and nature regeneration. Its objective is to shift from a take-make-waste system to a close-loop one, keeping materials in use, either as a product, components or raw materials. For that, products are reused, repaired, remanufactured or recycled, while biodegradable materials can be returned to earth. Additional scenarios such as refusing,



rethinking, reducing, refurbishing, repurposing or recovering are also considered (Figure 2.7). While considering that the resources on the planet are finite, circular economy aims to maintain the highest value of these resources through multiple cycles [18].

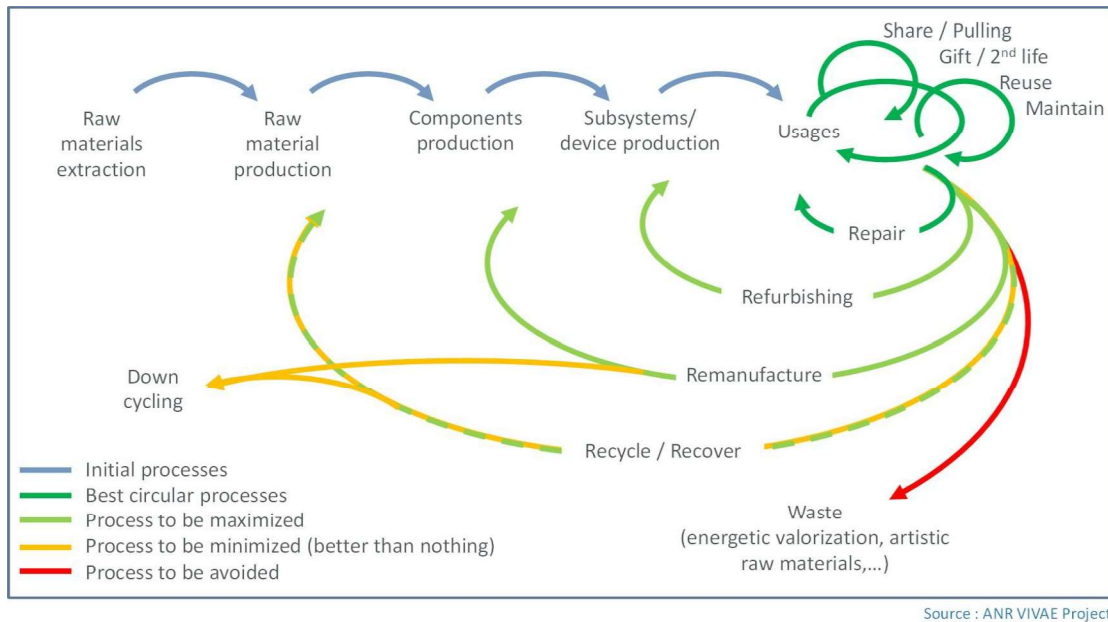


Figure 2.7-Circular economy processes, [11]

2.2.2. Eco-design

In circular economy, product design is essential, as exerts a strong influence on the rest of life-cycle phases. Figure 2.8 ([7]) depicts in grey shading the subset of the life cycle considered nowadays by design procedures, in contrast with the rest of circular processes.

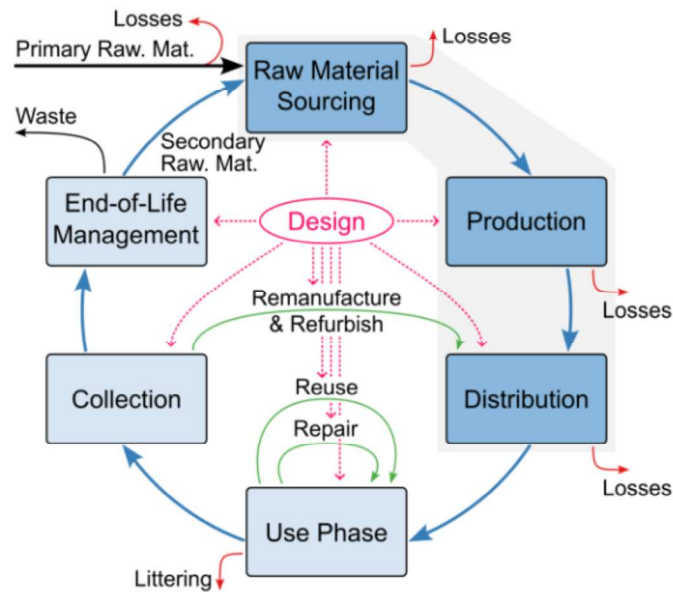


Figure 2.8-Circular economy concept, emphasizing design decisions on all life-cycle phases, [7]

It is estimated that 80 % of the environmental impacts can be determined at the product design stage, so it is of paramount importance to integrate circularity and sustainability strategies at the beginning of the life cycle of a product [7]. Following this principle, Eco-design is defined by ISO 14006 as “the integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product’s life cycle”. It allows to find the best compromise to globally reduce the environmental impacts, satisfying the same functionalities and delivering the best socio-technical values [19].

On the other hand, eco-design can be also approached through **eco-optimisation**. Traditional eco-design integrates environmental considerations from the earliest stages of the product life cycle, while eco-optimisation focuses on identifying optimal design parameters to fulfil specific objectives — with environmental impact reduction as a key goal [20].

It targets technical variables such as dimensions, materials, the mass of active parts, energy consumption or operating modes. By defining variables and constraints, the aim is to simultaneously achieve optimal performance —in terms of efficiency, power density and energy use— alongside the minimisation of environmental impacts [21].



2.2.3. Life Cycle Assessment – LCA

Life-Cycle-Assessment (LCA) is the technique to “address environmental aspects and potential environmental impacts throughout a product's life cycle; from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal”, as defined by the ISO 14044:2022 [22].

LCA study includes four main phases:

1. Goal and scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

The scope defines the functional unit of the system and its level of detail to consider (system boundary). The functional unit must describe the qualitative and quantitative aspects of the functions through the questions “what”, “how much”, “how well” and “for how long”. The life cycle inventory analysis (LCI) gathers the input and output data necessary to meet the goals of the defined study.

According to the ISO 14044, the LCIA is the “phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system”. Its objective is to relate the previous LCA results to impact categories, linked to entities to protect such as “Human Health”, “Natural Environment” and “Natural Resources”[22].

Finally, the interpretation phase summarizes the whole process leading to conclusions, recommendations and decision-making.

2.2.4. PE approaches

When examining how these three strategies can be implemented in Power Electronics, the following key insights emerge:

- Circular economy principles are difficult to implement due to the structural and functional complexity of the electronics system, but also to the restricted access to information. For PECs a new circular strategy aims to be applied, reconceptualizing, reusing or recycling; but for that environmental data and strategies have to be considered



as early as possible [7]. In this context, the EU Circular Economy Action Plan proposes a **Digital Product Passport** (DPP), with the objective to simplify digital access to product-specific information in the area of circularity.

- Eco-design in PE leads to a hardware design that favours disassembly, increases modularity improving repair, or selects the best material combination for recycling [23]. Furthermore, if electronic components were designed from a multiple-usage life cycle perspective, they might be kept in circulation as long as they remained functional.

When eco-design is approached through eco-optimisation metrics, some examples in PE – such as the analysis of an IGBT power module in [20] – show that the electrical parameters to target can be current and voltage ratings. However, the results revealed that minimizing environmental impact does not necessarily align with achieving maximum efficiency or optimal functional performance. Instead, focusing on scenarios such as replacement or reusing is more effective. Additionally, the analysis depends heavily on environmental data, which can be difficult to access and limits the application of this approach.

On the other hand, the modular design approach plays a crucial role as an eco-design technique. Designing a product through independent units -modules- can benefit all the stages of the product's life cycle: adding, removing and replacing modules facilitates disassembly, maintenance, repair and recycling.

- Regarding LCA and PE, the PEP (Product Environmental Profile) of Ecopassport follows the ISO 14025 standard providing common rules for LCA of electrical, electronic and HVAC-R products [24]. Nevertheless, the difficulty in PE arises when interpreting the LCA results. Support from lifecycle engineers and guidelines are often required, as the multicriteria aspects of LCA and the complexity of PE (multiple subsystems and components) make the field challenging. The information is not easy to access, and a circular life cycle model coupled with relevant environmental indicators in PE is missing [25].

More particularly at the national French level, 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) was created to



organize a scientific community focused on sustainability in Power Electronics [10]. Part of their members belong to the G2ELab PE research group, who also work on several approaches at the intersection of Power Electronics and sustainability [11].

One of their major contributions is the publication “*State of the Art of Research towards Sustainable Power Electronics*” [26], which provides a comprehensive literature review at the interchanges between PE and sustainability. Circularity principles are among the key areas explored, and Salomez et al. conducted a bibliographic study to identify ongoing research activities in this field.

Circular strategies were categorized in three rankings based on their scope and impact: global, product and material levels. While traditional approaches to circularity in electronics have focused primarily on compliance with WEEE (Waste Electrical and Electronic Equipment) directives—addressing the material level only—a more comprehensive and global approach extends circular principles throughout the entire value chain. Figure 2.9 highlights the traditional approaches in red, in contrast with the larger global level that should be where the focus should be hold [26].

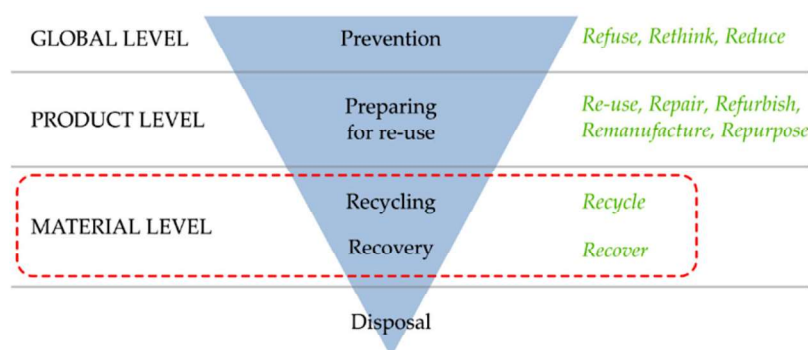


Figure 2.9-Circular strategies (green) categorized in three levels, with traditional WEEE approaches (red), [26]

The Global Level, also referred to as “Design and Business Model for Circularity”, emphasizes strategies that originate in the early stages of design. The literature review identified modularity and ease of disassembly as critical design enablers, along with the application of LCA to evaluate circular practices within eco-design processes.

With regards to eco-design, researcher Li Fang et al., in 2023 conducted a systematic literature review to identify current eco-design approaches in PE [19]. Four main axes were identified: (i) energy efficiency optimization, (ii) eco-optimisation, (iii) eco-reliability, and (iv) multi usage lifecycle innovation. Most of the practices focused on the integration of new technologies



to achieve optimal energy efficiency and power density, while the other approaches have not yet been widely promoted on a global scale. This narrow view on single design parameters doesn't consider the different environmental aspects across the PEC life cycle stages.

Additionally, regarding the limitations of eco-optimisation, it was found that the lack of environmental data, and the simplified impact modelling were critical. Most eco-optimisation models depend on LCA results, which are scarce in PE, while environmental databases offer partial alternatives but often lack detail. To address this, researchers such as Imperiali et al. [21] advocate for the inclusion of environmental impact data directly in component datasheets. Ideally, future “smart” datasheets would disclose not only electrical or magnetic properties under operating conditions but also the component's full environmental footprint.

Having identified existing gaps and emerging trends, this analysis seeks to propose concrete strategies for advancing sustainability in Power Electronics. While circular economy principles, eco-design, and Life Cycle Assessment (LCA) each offer valuable contributions, no single methodology currently provides a comprehensive solution. The aim is therefore to combine three complementary strategies that, together, enable a more holistic approach, with each strategy addressing a different limitation of the current state of the art (Figure 2.10). Yet, their integration is not straightforward, raising the question of whether sustainability in PE still lacks other essential aspects.

The first element explored is the **Life Cycle Assessment of a 150 kW inverter**, as an illustrative example of a well-conducted LCA and circularity in the PE sector, Chapter 3.

The second case study delves into a **Parametric Life Cycle Assessment (PLCA) meta-model** tailored to PE applications [12], Chapter 4. This model enables the evaluation of environmental impacts by linking technical design parameters directly with life cycle indicators, thus supporting early-stage eco-design decisions. Its key advantage lies in its adaptability to various converter topologies. In this study, the methodology is illustrated through its application to a Boost converter, complementing previous work that used a Buck topology.

Lastly, the **Digital Product Passport (DPP)** is introduced as a digital framework to support circular economy decisions by improving data transparency and traceability across the value



chain; Chapter 5. Although DPPs have not yet been applied to PE devices, they hold significant potential in this field. A DPP structure specifically adapted to PE components is proposed, drawing from existing standards such as GS1 [27] and PEP Ecopassport [28]. This proposal is illustrated using data retrieved about the modular converter **CSC GM20V5A**, aiming to clarify the operation and sustainable potential. For that, an analysis including theoretical documentation and experimental work was carried out by the author, aiming to connect the sustainability principles of modularity to the DPP structure, a connection between product design for circularity and traceability tools.

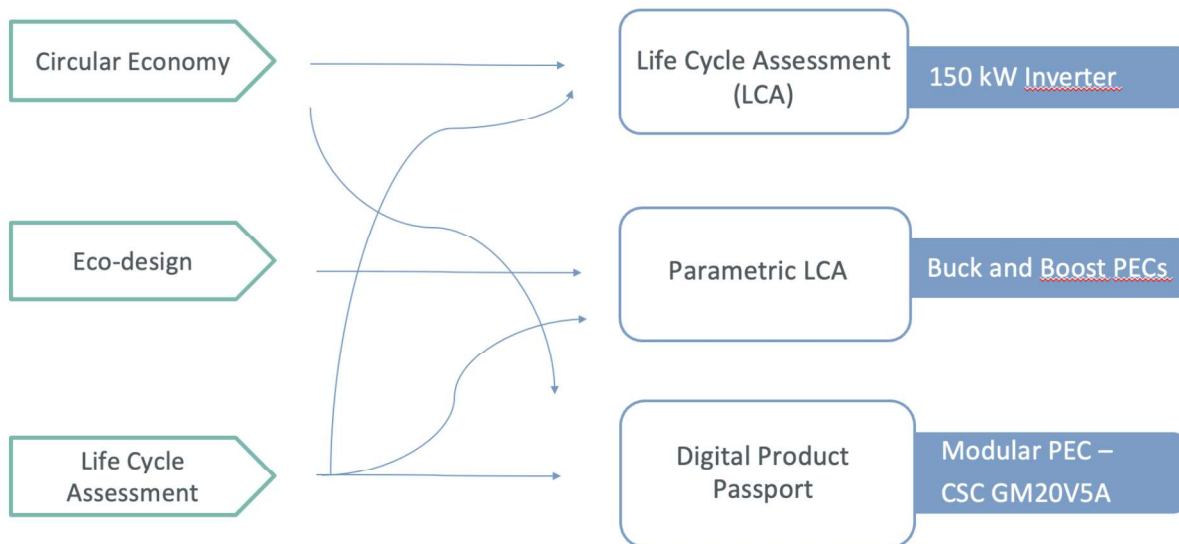


Figure 2.10-Summary of concrete PE strategies analysed

Taken together, these three approaches—LCA, PLCA, and a Digital Product Passport for PE—are analysed not in isolation but as interlinked strategies. The aim is to form a comprehensive picture of the current state of sustainable Power Electronics and to highlight the synergies between tools and methodologies that can be leveraged to reduce environmental impacts across the entire product life cycle.



3.LCA of a 150 kW inverter

Although Life Cycle Assessment (LCA) is widely regarded as one of the most effective tools for evaluating environmental impacts, its application in the field of Power Electronics (PE) remains particularly challenging. PE systems are complex, data availability is limited, and many LCA models fail to capture the full circular life cycle of products [25]. Common limitations in existing studies include non-transparent input data and inventories, a narrow focus on the Global Warming Potential (GWP) impact category, and insufficient analysis of individual components and the complete PE system [8].

One noteworthy exception is the study conducted by Briac Baudais, who applied an LCA to a 150 kW inverter, [8]. His research offers a comprehensive environmental evaluation by accounting for materials, manufacturing processes, usage characteristics, and end-of-life treatment—providing detailed insights into the most impactful components. This section analyses Baudais' approach, which serves as an illustrative example of a well-conducted LCA in the PE sector. The objective here is not to assess the methodology in depth but to outline the general procedure and highlight key results.

3.1.- LCA methodology

To start with, the four phases of LCA (described in Section 2.2.3) are followed, all summarized in Figure 3.1:

1. Goal and scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact Assessment (LCIA), evaluation
4. Interpretation

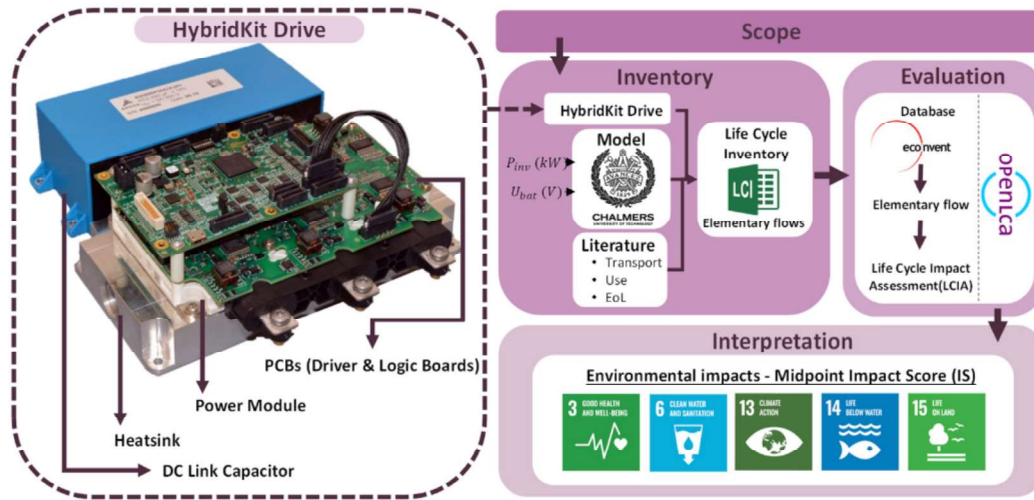


Figure 3.1-Main LCA steps applied on the Inverter study, [8]

3.1.1. Goal and scope definition

The functional unit of the study case– description of the qualitative and quantitative aspects through the questions “what”, “how much”, “how well” and “for how long”- is defined as: “Generate a three-phase AC electrical operating point for a 150 kW load (electric machine) from a 450 V DC power source, based on a lifespan of 15 years, i.e., equivalent to 10,000 h of operation.”, [8].

Then, the environmental impact categories were selected based on the Product Environmental Footprint (PEF) framework [29]:



Impact Category	Abbreviation	Indicator	Unit
Climate change	GWP	Radiative forcing as Global Warming Potential (GWP100)	kg CO ₂ eq
Ozone depletion	ODP	Ozone Depletion Potential	kg CFC-11 eq
Human toxicity, cancer	HTc	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer	HTnc	Comparative Toxic Unit for humans	CTUh
Particulate matter	PM	Human health effects associated with exposure to PM _{2.5}	Disease incidences
Ionising radiation, human health	IR	Human exposure efficiency relative to U ²³⁵	kBq U ²³⁵
Photochemical ozone formation, human health	POF	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification*	TAC	Accumulated Exceedance (AE)	mol H ⁺ eq
Eutrophication, terrestrial	TE	Accumulated Exceedance (AE)	mol N eq
Eutrophication, freshwater	FE	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Eutrophication, marine	ME	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Ecotoxicity, freshwater	FET	Comparative Toxic Unit for ecosystems	CTUe
Land use	LU	Soil quality index	Dimensionless (pt)
Water use	WD	User deprivation potential (deprivation-weighted water consumption)	m ³ world eq. deprived water
Resource use, minerals and metals	MRD	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, fossil fuels	FD	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

Figure 3.2- Environmental impact categories used in LCA, based on the PEF framework, [29]

3.1.2. Life Cycle Inventory analysis

The inverter analysed is particularly well documented, with an extensive and detailed inventory of data and components. The LCA encompasses manufacturing, use, transport, and end-of-life phases.

To build the inventory, Baudais draws from several data sources: Open-access data from Infineon, an in-depth analysis by System Plus Consulting of the power module, and the scalable Life Cycle Inventory (LCI) model developed by Chalmers University. Due to persistent data gaps in the PE field, a correlation model is also applied. This model, based on inverter volume and power, supplements missing data by referencing another 150 kW inverter study by Nordelöf [8], [20].

The final inventory includes highly detailed component-level information, such as manufacturing processes, material types, and references—further enhancing transparency, as all the details can be found in the Annexes of [10] and [18].



The transport phase is modeled using the default Product Environmental Footprint scenario, which estimates environmental impacts from the factory to the distribution center and ultimately to the customer.

The end-of-life treatment is modeled using Ecoinvent data for *waste electric and electronic equipment*, which is considered a representative proxy for current inverter disposal practices.

3.1.3. Life Cycle Impact Assessment

The environmental impacts of the system are quantified using the Ecoinvent database. Known for its comprehensive datasets, Ecoinvent enables the modeling of resource extraction, emissions to air, water and soil, energy inputs, and waste outputs across the product life cycle. To ensure the robustness of the results, Baudais applies both uncertainty and sensitivity analyses. These help to determine how input variations affect output reliability and to identify which factors contribute the most to output variability.

3.1.4. Interpretation

The results highlight two major phases with significant environmental impacts: manufacturing and use. Figure 3.3 depicts the standardized environmental impacts (abbreviations following Figure 3.2), with the use phase (brown) and manufacturing phase (blue) clearly dominating, [20].

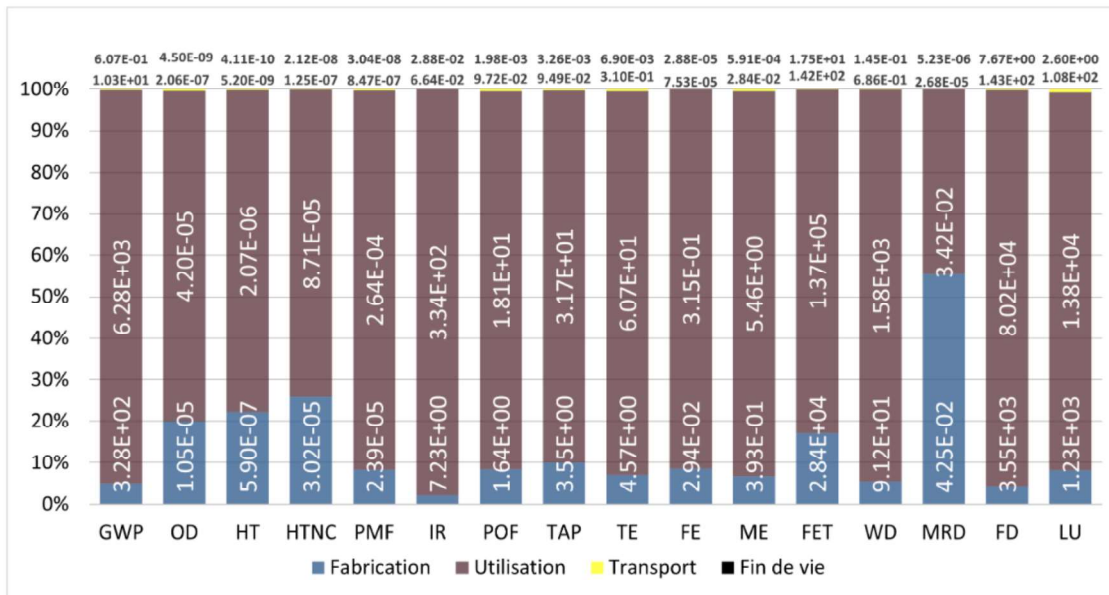


Figure 3.3- Standardized environmental impacts related to the product life cycle phases, use (brown) and manufacturing (blue) the most significant contributors, [20].

The use phase has the greatest influence mainly on **Global Warming Potential (GWP ≈ 95%)**, **Ionizing Radiation (IR ≈ 95%)**, and **Resource use- Fossil Depletion (FD ≈ 96%)**. However, since the use phase reflects electricity consumption, the results are highly dependent on the energy mix. The results account for the French energy mix (dominated by nuclear power): the extraction of radioactive materials is highly affecting the ionizing radiation. Consequently, the LCA is strongly affected by the energy sources, implying that a less polluting production of electrical energy can lead to certain impacts reduction.

The manufacturing phase is the second most impactful phase, particularly for **Mineral Resources Depletion (MRD ≈ 55%)**, **Non-cancer Human Toxicity (HTNC ≈ 26%)**, **Human Toxicity (HT ≈ 22%)**, and **Freshwater Ecotoxicity (FET ≈ 20%)**.

A second level of analysis focuses on identifying which environmental impacts are most significant overall, [20]. Baudais normalizes the results using Planetary Boundaries as reference values (explained in 2.1.1). The outcomes, shown in Figure 3.4, rank the most critical environmental impacts.

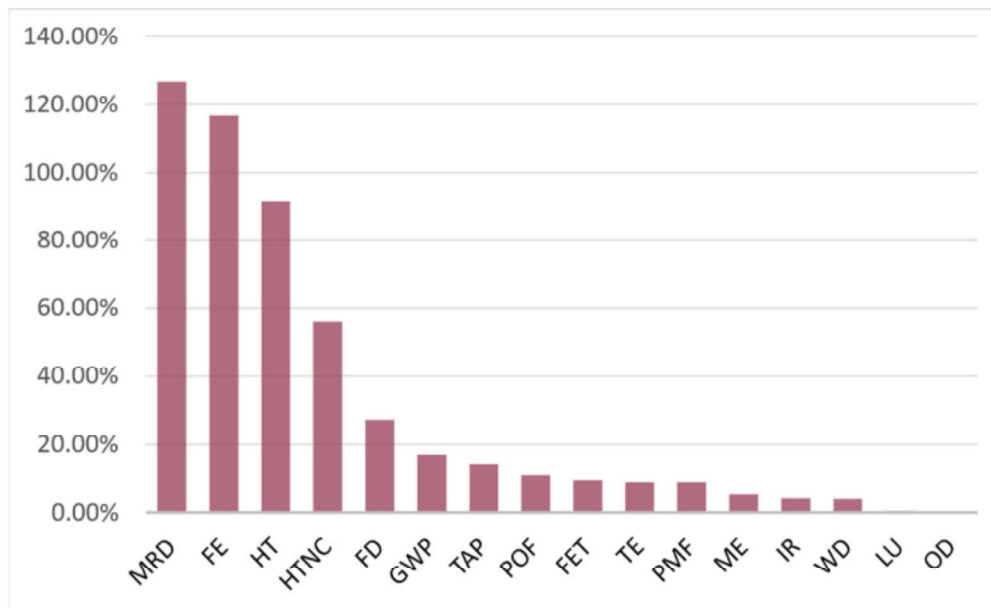


Figure 3.4- Hierarchy of environmental impacts using Planetary Boundaries normalization, [8], Mineral Resources Depletion (MRD), Freshwater Ecotoxicity (FET) and Human Toxicity (HT) emerge as the most critical.

Concluding, the most impactful categories of environmental impacts are **Mineral Resources Depletion² (MRD)**, **Freshwater Ecotoxicity³ (FET)** and **Human Toxicity⁴ (HT)**. A final analysis breaks down these impacts by component, identifying the power module and the aluminium casing as the most environmentally burdensome subparts. Notably, the power module alone is responsible for $\approx 43\%$ of the MRD impact.

² Mineral Resources Depletion (MRD) refers to the consumption of natural non-fossil resources beyond their rate of replacement [30].

³ Freshwater ecotoxicity (FET) refers to the potential of chemical substances released into freshwater environments to cause adverse effects on aquatic organisms and ecosystems. The environmental impact aims to evaluate the harmful effects of pollutants on freshwater species and their habitats. [31]

⁴ Human Toxicity (HT) refers to emissions to air, soil or water with direct or indirect harmful effects on human health, including cancer effects [32].



3.2.- Critics and conclusion

The case of the 150 kW inverter represents a detailed and well-executed example of a Life Cycle Assessment (LCA) applied within the Power Electronics (PE) field. It stands out for its highly comprehensive inventory, developed through the integration of multiple databases. Moreover, it encompasses all life cycle phases—manufacturing, use, transport, and end-of-life—providing additionally a component-level analysis.

If considered as a representative example of environmental impacts in PE, the main finding is that the use phase contributes the most to the overall impact, though it is highly dependent on the energy mix. The manufacturing phase follows in importance, offering greater potential for design interventions to mitigate impacts. The three most critical impact categories identified are **Mineral Resources Depletion (MRD)**, **Freshwater Ecotoxicity (FET)**, and **Human Toxicity (HT)**. The author suggests some strategies to reduce the manufacturing impact, including alternative materials, modified processes, or new component designs. Modularity is also proposed as a means to improve maintenance and facilitate the replacement of faulty subcomponents.

However, despite the rigor and detail of the analysis, a key limitation is that the LCA is used primarily as a **post-evaluation tool**. Once completed, the methodology typically concludes at the interpretation phase, without offering concrete, actionable guidance for impact reduction. In other words, while the results are pertinent and accurate, they do not necessarily translate into eco-design strategies. There is a step missing for how to tackle the environmental impacts and measure an improvement. Additionally, the life cycle perspective applied remains linear: it ends at the end-of-life phase and does not account for circular strategies such as repair, remanufacturing, or recycling.

In conclusion, as other authors have noted, a major challenge in current LCA approaches is the lack of integration of a **circular life cycle model**—one that includes several of the "R" strategies introduced in Section 2.2.1 and illustrated in Figure 2.7. Such integration would allow LCA to better support eco-design by providing targeted strategies for certain impact reduction [33]. In this context, **Parametric Life Cycle Assessment (PLCA)** emerges as a promising alternative, capable of addressing these limitations. Chapter 4 explores this approach through the development of a PLCA meta-model applied to a Power Electronics device, specifically a Buck converter.



4. PLCA meta-model for PE

In the case of Power Electronics, LCA is typically used as a post-evaluation methodology. While valuable for assessing environmental impacts, it analyses devices which have already been designed, but it is insufficient for guiding a previous eco-design or modelling from the beginning of the circular life cycle scenarios. Most existing LCA models rely heavily on detailed component inventories and adopt a linear life cycle perspective, omitting strategies such as reuse, repair, or remanufacturing. As discussed in the previous chapter, the main challenge is to integrate a circular life cycle model with relevant environmental indicators while also supporting eco-design decision-making [33].

The objective of this chapter is to build on the limitations identified in traditional LCA and to present the **Parametric Life Cycle Assessment** (PLCA) as an alternative methodology. Specifically, the general Parametric Life Cycle Assessment (PLCA) meta-model for PE products with circular life cycles, developed in Li Fang's PhD Thesis "*Toward functional value preservation for sustainability in Power Electronics*" [12].

The general structure and potential of a PLCA meta-model for Power Electronic (PE) products are explored through the case study of a Buck converter. While the results have been previously analysed in the PhD Thesis [12], this project also devoted time to understanding the overall structure of the associated Python scripts.

Building on this foundation, the methodology was applied to a Boost converter as part of a collaboration between the author and G2Elab. This second case study contributed to a deeper understanding of the PLCA method and provided additional insight into a different environmental profile. To conduct the analysis, the author compiled technical specifications and datasheets to construct the Bill of Materials and inventory of the Boost converter. The Python code for the PLCA and the Boost was written by the author, while the scripts were executed by Gaëtan Heller (PhD student at G2Elab), who had access to the Ecoinvent database license.



4.1.- General characteristics of the PLCA meta-model

As defined in the thesis: “PLCA establishes a parametric life cycle model based on design parameters that **control the environmental impacts generated**, assisting in more informed decision-making throughout the product design process.”, [12]. Originally proposed by Ostad-Ahmad-Ghorabi et al. in 2008 [34], the PLCA methodology was designed to support design decisions throughout the entire life cycle, as opposed to LCA, which remains largely a post-design evaluation tool. In this regard, PLCA may be a better modelling approach for PE case, as would make LCA a more proactive integrated method for eco-design, making it easier to evaluate the potential environmental impacts.

Nevertheless, despite its promise, PLCA had not been yet applied in the PE field. Complete life cycle datasets for PE products remain scarce, and support for eco-design decision-making in PE product development processes is still limited.

In the meta-model developed by Li Fang, each life cycle phase—manufacturing, transport, usage, product repair, components reuse, recycling, formal disposal, and informal disposal—is mathematically parameterized. The parameterization allows to relate design parameters (e.g., material and components composition) to environmental impacts (e.g., climate change, freshwater ecotoxicity) through mathematical equations or algorithmic rules. The clarity between the relationships of control parameters and environmental impacts, leads to an early identification of hotspots and supports preliminary strategies.

Another important feature of the PLCA meta-model is that the data structure is organized through product’s technical blocks: Functional Analysis Technique (FAST). The numerous electronic components can be associated to one or multiple technical functions within the converter, which would be subsequently decomposed into subfunctions and finally into functional blocks. For example, Li Fang et al, 2024; discretized a boost converter into three main functions: power conversion, control, and circuit connection. Consecutively, second-order functions would cover basic functionalities such as switching, energy stockage or PWM generation. Electrical requirements were met, as well as environmental impacts allocated depending on the block function [33].

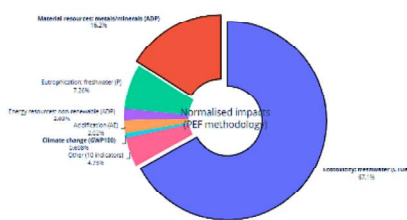
The meta-model itself is implemented through the python module of Brightway2 in the platform of Jupyter Notebook, with the package LCA Algebraic. The [open-source python code](#) also includes data visualization features that provide results interpretation, an example in Figure



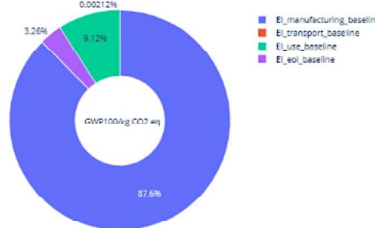
4.1. Additionally, several eco-design scenarios can be developed and analysed, quantitatively converging to the best strategy depending on the environmental impact results.

In summary, PLCA supports proactive eco-design by making the relationship between technical choices and environmental outcomes explicit. This facilitates the efficient development of sustainable design strategies and enhances decision-making throughout the PE product life cycle.

Indicators Normalisation



Impacts distribution across life cycle stage



Impacts distribution across technical blocks

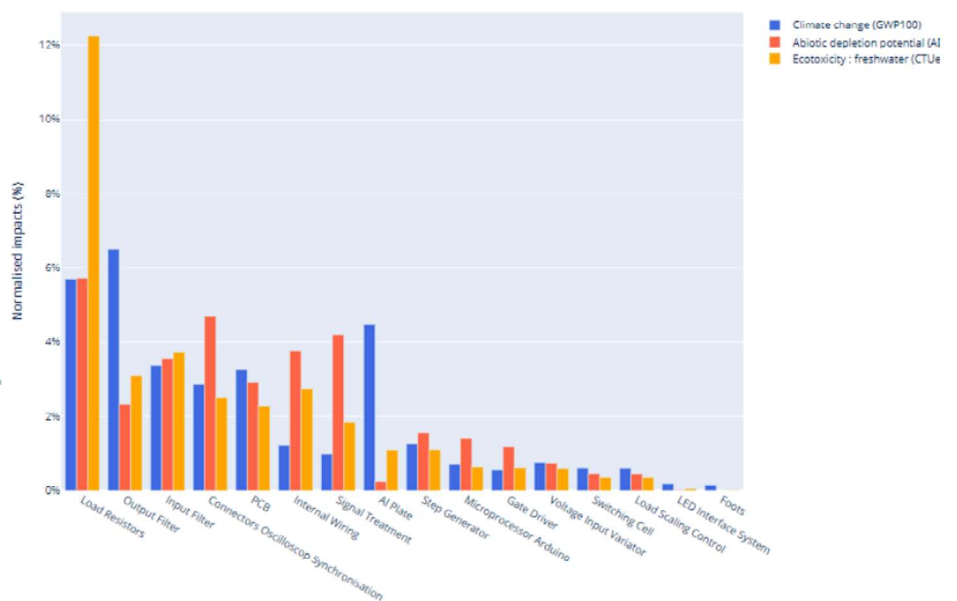


Figure 4.1-Example of data visualization supported with the PLCA meta-model, [12]

4.2.- PLCA meta-model, application in a Buck Case

Analysing in more detail the Functional Architecture and the PLCA meta-model procedure, four steps are mainly identified in the methodology [25].

1. Establishing the Functional Architecture coupled with environmental indicators:

The functional unit, the functional blocks and the code for the parametric meta-model in Python are defined.



2. Identifying the main critical technical parameters:

The meta-model code is executed, generating results about the environmental impacts of the life cycle. The most critical impact categories can be related to the technical parameters to modify.

3. Elaborating a design strategy on key-design parameters:

The technical parameters with a larger impact are modified, proposing different strategies and scenarios to reduce the environmental impact. The Python code is modified and executed, iterating until achieving the finest solution.

4. Evaluating the technico-environmental performance of the design choices:

The best scenario is selected, and a “Detail Design” phase implements the previous hypothesis in a modified device, supported by a sensitivity analysis. Hardware components are selected, and the optimal eco-design solution is delivered.

The procedure is comparable to the LCA methodology, but it is characterised by its direct application on Power Electronic devices thanks to the meta-model Python code. Moreover, the last two steps propose a methodology for reducing the environmental impact, through strategies that tackle the most critical aspects of the device.

To clarify, some definitions of important concepts that can be confounded are provided below:

- **Functional Unit:** description of the qualitative and quantitative aspects of the device through the questions “what”, “how much”, “how well” and “for how long”, [35].
- **Functional Analysis Technique (FAST):** decomposition of the electronic technical functions within the device into blocks (defined as **Functional Blocks**), subsequently decomposed into subfunctions and final components, [33].
- **Life Cycle Impact Assessment (LCIA):** phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system, [35].
- **Parameters:** elements that compose the meta-model equations to implement in Python; being foreground parameters when they are under the control of the eco-design team (number of electronic components or mass of the product), and background parameters when they are supporting infrastructures beyond direct control (impact of soldering the components), [36].
- **Impact categories:** 16 environmental classifications (climate change, ozone depletion, human toxicity...) defined by the Environmental Footprint technology, that result from



the aggregation of inputs and outputs from the life cycle inventory, [29]. Each of the impact categories has an **indicator**, that quantifies their impact with a **unit**; all found in Figure 3.2.

- **Strategy:** method that aims to reduce the environmental impact, targeting functional innovation, energy efficiency or resources sufficiency, [12].
- **Scenario:** framework that combines multiple possible strategies, aiming to attain the finest solution on the environmental impact reduction, [12].

The case study developed by the Li Fang et al., is a DC-DC Buck converter. The aim of this section is to analyse the four steps of the PLCA meta-model, providing better understanding of the whole process and the way it covers the limitations of the LCA.

4.2.1. Establishing the Functional Architecture coupled with environmental indicators

Similarly to the *Scope phase* of the LCA, a functional unit is defined, answering to general characteristics of the PE product (levels of voltage, service provision time, field of application...).

In this case, the reference PEC is a 30 V 90 W DC-DC Buck designed in a research laboratory for educational purpose in an engineering school. Its functional unit is: *'to explain the buck converter's functions to engineering students by generating a DC voltage ranging from 9 to 15 V for a variable load, using a 15 to 30 V DC source, 120 h per year over a service provision time of 30 years, i.e. equivalent to 3600 h of operation'* [34].

The life cycle stages cover: raw material extraction, electronic components manufacturing, product manufacturing, use, waste, recycling and disposal; and are applied to three buck converters, each with a technical lifetime of 10 years.

The inventory relies on the database Ecoinvent V3.10; characterized by its transparency and exhaustive content for environmental analysis of production and consumption processes.

Each of the components of the converter is identified in the database, and therefore the environmental data can be linked to the mathematical equations in the meta-model.

Then, the converter system, following the FAST (Functional Analysis Technique) is subdivided into functional blocks across multiple system levels, where the total of the electronic components are allocated, [34].



This step is similar to the Life Cycle Inventory of the LCA, but in this case, technical data is organised into blocks that account for the hardware inventory.



Figure 4.2-FAST diagram with functional structure of the buck converter [34]



Regarding the Python code, the meta-model is constructed with mathematical equations and the Ecoinvent references. All the life phases are considered: manufacturing, transport, use, repair, reuse, recycling, disposal; being related to the FAST blocks through the equations. The complete Parametric Model and its equations can be found in Annex I, Figure 4.3 as an example for the manufacturing phase.

Dependent variables	Background parameter	Foreground parameter	Parametric model
Environmental Impacts of Manufacturing (EI _{manufacturing})	<ul style="list-style-type: none"> Unit impact of components manufacturing ($I_{EC,i}$) Unit impact of product assembly (I_{PA}) Unit impact of components soldering ($I_{SD,i}$) 	<ul style="list-style-type: none"> Environmental impacts of technical blocks manufacturing (EI_{manTBj}) Number of technical blocks (TB) Number of electronic components (EC) Technology of electronic components ($T_{EC,i}$) Manufacturing site of electronic components ($MS_{EC,i}$) Size of electronic components ($M_{EC,i}$) Soldering technics (ST), Number of soldering points (SP) Mass of product (M_p) Number of products (N_p) Service provision years ($Y_{service}$) Technical lifetime of product (Y_p) 	$EI_{manufacturing} = N_p \times \sum_i^{TB} (I_{manTBi}) + I_{PA} \times M_p$ $EI_{manTBj} = \sum_i^{EC} (M_{EC,i} \times I_{EC,i} + SP_i \times I_{SD,i})$ $I_{ECi} = f(T_{EC,i}, MS_{EC,i})$ $I_{SDi} = f(ST)$ $M_p = \sum_i^{EC} (M_{EC,i})$ $N_p = \lceil Y_{service} / Y_p \rceil$

Figure 4.3- Parametric model equations that calculate the environmental impact of manufacturing, [12]

The foreground parameters comprise the elements under control of the eco-design team, while the background parameters consist of the supporting infrastructures beyond direct control. They are related through equations that will be later implemented in Python.

Taking the example of the code that calculates the impact of the manufacturing phase, in Figure 4.4, the output filter block is subdivided into its components: capacitors, inductors, electric connectors and brass. Each of them is individually assigned the Ecoinvent reference (the text in red that accounts for the hardware description) and its individual mass (number in green). Directly through the Ecoinvent database and the mass of the components, the manufacturing environmental impact of the output filter is calculated when executing the code.



```
output_filter= agb.newActivity(DB_Buck_baseline,
    "output_filter",
    "unit",
    exchanges = {
        agb.findActivity("capacitor production, film type, for through-hole mounting", db_name="ecoinvent-3.10-cutoff"):0.0262,
        agb.findActivity("inductor production, ring core choke type", db_name="ecoinvent-3.10-cutoff"):0.2321,
        agb.findActivity("electric connector production, peripheral type buss", loc="GL0", db_name="ecoinvent-3.10-cutoff"):0.002,
        agb.findActivity("market for brass", loc="RoW", db_name="ecoinvent-3.10-cutoff"): 0.024151,
        agb.findActivity("electric connector production, wire clamp", loc="GL0", db_name="ecoinvent-3.10-cutoff"): 0.05066,
    })

df_output_filter= agb.printAct(output_filter).sum().to_frame().T
Amount_kg_output_filter = df_output_filter.iloc[:, 1].tolist()
```

Figure 4.4-Manufacturing phase code following the FAST block for the output filter

At the end, the manufacturing impact of the total of blocks is calculated. Figure 4.5 depicts how the rest of the blocks (switching cell, input filter, output filter, voltage input variator...) are considered, aggregating them all for the manufacturing impact.

```
EI_manufacturing_baseline=agb.newActivity(DB_Buck_baseline, "EI_manufacturing_baseline", "unit", {
    switching_cell:N_p_baseline,
    input_filter:N_p_baseline,
    output_filter:N_p_baseline,
    voltage_input_variator:N_p_baseline,
    gate_driver:3*N_p_baseline,
    step_generator:1*N_p_baseline,
    microprocessor_arduino:1*N_p_baseline,
    load_resistors:1*N_p_baseline,
    load_scaling_control:1*N_p_baseline,
    signal_treatment:1*N_p_baseline,
    microprocessor_arduino:1*N_p_baseline,
    foots:1*N_p_baseline,
    al_plate:1*N_p_baseline,
    PCB:1*N_p_baseline,
    LED_interface_system:1*N_p_baseline,
    internal_wiring:1*N_p_baseline,
    connectors_oscilloscop_synchronisation:1*N_p_baseline,
})
agb.printAct(EI_manufacturing_baseline)
```

Figure 4.5-Total Manufacturing impacts after aggregating the FAST blocks

The output results in the manufacturing impacts for each of the impact categories defined, Figure 4.6.

	Climate Change	Material Resources: non-metals/minerals	Energy Resources: non-renewable	Acidification	Ecotoxicity: Freshwater	Human Toxicity: carcinogenic	Human Toxicity: Non-carcinogenic	Eutrophication: Freshwater	Eutrophication: Marine	Eutrophication: Terrestrial	Ionising Radiation	Land use and land use change	Ozone Depletion	Particulate Matter Formation	Photochemical Oxidant Formation: human health	Water Use
	[kg CO2-Eq]	[kg Sb-Eq]	[MJ, net calorific value]	[mol H+-Eq]	[CTUe]	[CTUh]	[CTUh]	[kg P-Eq]	[kg N-Eq]	[mol N-Eq]	[kBq U235-Eq]	[kg CO2-Eq]	[kg CFC-11-Eq]	[disease incidences]	[kg NMVOC-Eq]	[m3 world Eq densified]
EI_manufacturing_baseline	205.936	0.0402524	2576.5	4.35184	30163.4	7.60073E-07	1.33593E-05	0.203367	0.313035	3.68502	19.2992	0.318353	2.3814E-06	1.52105E-05	1.39421	67.3762

Figure 4.6. Manufacturing impacts output after executing the code



The transport data is defined after *PEP Ecopassport*, whose hypothesis totalize for international transport 19,000 km by boat, plus 1000 km by lorry; for intercontinental transport: 3500 km by lorry; and for local or domestic transport: 1000 km by lorry. Further, it is noted that in the use stage, the energy consumption assigned is relatively low because of the educational purposes of the PEC (defined through another equation by the average load power and the total operation time, found in Annex I). Finally, the modelling of recycling and end-of-life treatment is based on French national data from 2020 [34].

4.2.2. Identifying the main critical technical parameters

The meta-model in Python allows to calculate the environmental impact of the converter, providing results, a normalization and an uncertainty distribution through Monte Carlo simulation. The complete code can be found in [Zenodo](#) as an open-source Jupyter Notebook, [36]. Once the whole file is executed, different results are obtained.

In the same way as in the LCA third step, a Life Cycle Impact Assessment is also carried out from the results obtained. The environmental impact categories considered are the same previously defined based on the Environmental Footprint technology (Figure 4.7 as a reminder), [29]:

Impact Category	Abbreviation	Indicator	Unit
Climate change	GWP	Radiative forcing as Global Warming Potential (GWP100)	kg CO ₂ eq
Ozone depletion	ODP	Ozone Depletion Potential	kg CFC-11 eq
Human toxicity, cancer	HTc	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer	HTnc	Comparative Toxic Unit for humans	CTUh
Particulate matter	PM	Human health effects associated with exposure to PM2.5	Disease incidences
Ionising radiation, human health	IR	Human exposure efficiency relative to U ²³⁵	kBq U ²³⁵
Photochemical ozone formation, human health	POF	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification*	TAC	Accumulated Exceedance (AE)	mol H ⁺ eq
Eutrophication, terrestrial	TE	Accumulated Exceedance (AE)	mol N eq
Eutrophication, freshwater	FE	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Eutrophication, marine	ME	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Ecotoxicity, freshwater	FET	Comparative Toxic Unit for ecosystems	CTUe
Land use	LU	Soil quality index	Dimensionless (pt)
Water use	WD	User deprivation potential (deprivation-weighted water consumption)	m ³ world eq. deprived water
Resource use, minerals and metals	MRD	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, fossil fuels	FD	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

Figure 4.7- Reminder of the Environmental impact categories used in LCA, [27]



In this case, Figure 4.8 depicts the final result (after normalization) of the most critical environmental impacts. It can be seen how **Freshwater Ecotoxicity (FET) and Material Resources Use (MRD)** are again among the most critical impacts, covering more than 80% of the impact categories affected by the converters' life cycle. The research of Li Fang et al., decided to also target Climate Change (GWP) because of the carbon neutrality European policies.

Impacts normalisation of a Buck converter based on Environmental Footprint normalization factors recommended by the European Commission

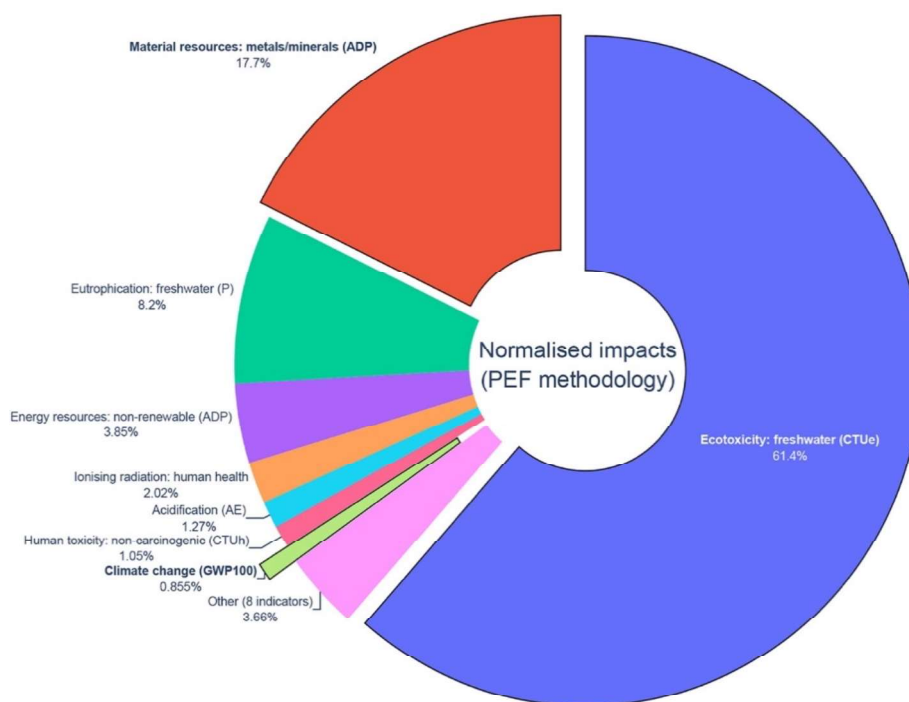


Figure 4.8-Potential environmental impacts generated by the buck converter after normalization [34]

4.2.3. Elaborating a design strategy: key-design parameters

Once the main impact categories have been identified, the meta-model allows to propose strategies to reduce the environmental impact. The strategies include certain variations of the structure, components or other parameters that affect the model, and through multiple iterations with the code, the evolution of the environmental impact can be tackled. This is the main difference with respect to the classic LCA, as in this case the PLCA allows to go a step further and propose a reduction of the environmental impact.



Three main categories of eco-design strategies (Figure 4.9) allow to tackle the impact through functional innovation, energy efficiency or resources sufficiency.

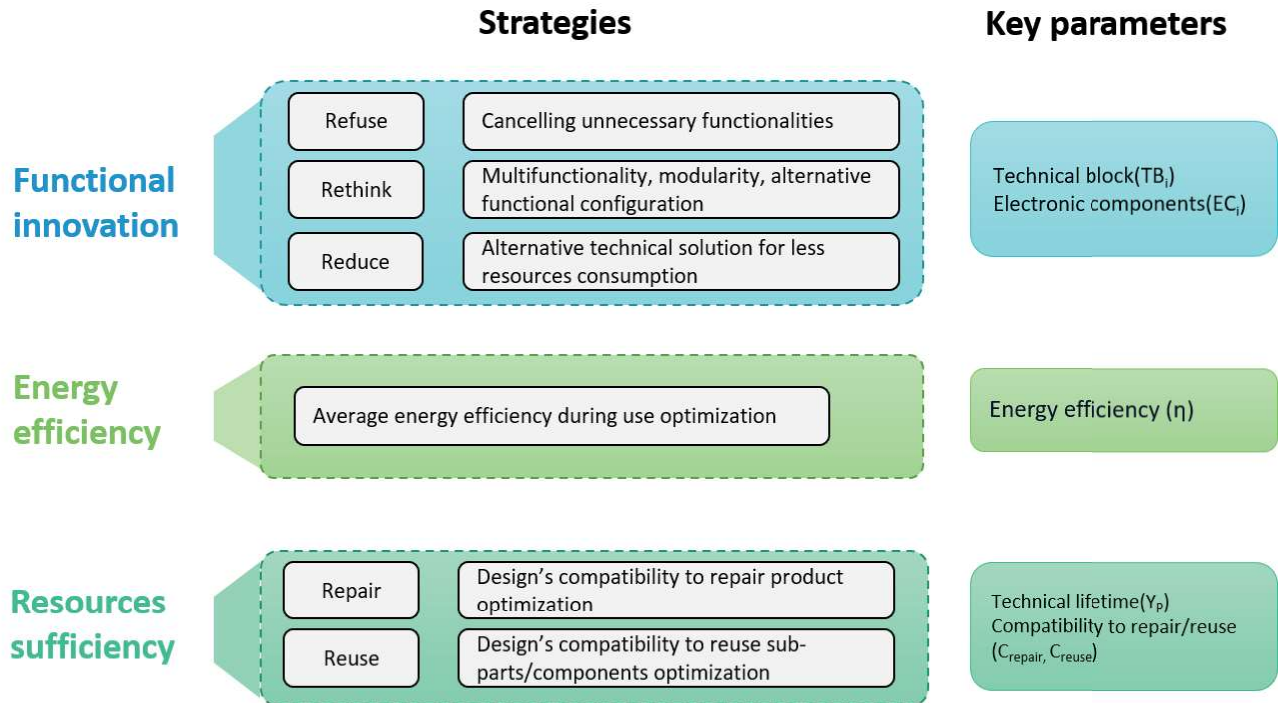


Figure 4.9-Main eco-design strategies and key parameters affected, [34]

The relevant parameters are modified on the Python code and the proposed scenarios lead to different results that enable comparison. After discussing the benefits and drawbacks of the propositions, the software can be executed several times, iterating until achieving the finest solution.

Nevertheless, to identify which are the hotspots affected or the design parameters, another analyse is previously made. In this case, each target environmental impact category (climate change, resources use and ecotoxicity), is analysed through the life cycle stages (manufacturing, transportation, electrical consumption, replacement and treatments at End of Life), Figure 4.10.



Figure 4.10-Environmental impacts distribution of life phases for the target impact categories, [34]

After the analysis, it is seen how the manufacturing phase (in blue in Figure 4.10) is the most significant contributor to the targeted environmental impacts. This means that the focus will be held in the main variables of the meta-model that affect the manufacturing phase.

The results depend on the Ecoinvent database and the equations, but targeting some specific parameters (from the list of Annex I), the environmental impact can be reduced. In this case, the key design parameter groups to target (all listed in Table 1 of Annex I) are [34]:

- Environmental impacts of the technical block manufacturing (EI_{manTBi}), affected by the technology of electronic components (T_{ECi}) and its size (M_{ECi}).
- Number of products required throughout the service provision time (N_p), affected by the number of repair interventions (RP) and design's compatibility for repair (C_{repair}).
- Reuse of the product and its sub-parts, affected by the functional wear of components after their service provision cycle ($a_{EC,i}$).

These key parameters can be associated to two of the eco-design strategies mentioned in Figure 4.9: **functional innovation** and **resource efficiency**.

Functional innovation strategy: refuse, rethink and reduce strategies (Figure 4.11)

- **Refuse strategy:** the functional blocks are reanalysed and unnecessary functions for the product are identified. The function “provide different load” is identified as redundant (as could be fulfilled by an existing rheostat).
- **Rethink strategy:** the “Al plate” technical plate could be replaced by less impactful materials such as PMMA (plexiglass) for mechanical support. Additionally, the “control



dynamics” could be integrated into the “microprocessor”, removing the “CPLD step generator”.

- **Reduce strategy:** in the “input/output filter” the size of capacitors and inductors could be reduced by a factor of 15, after increasing the system’s switching frequency 15-fold (what would lead to three times lower manufacturing environmental impacts). However, the MOSFET-Silicon (Metal Oxide Semiconductor Field Effect Transistor) should be replaced by HEMT-GaN (High Electron Mobility Transistor – Gallium Nitride) that operate at 300 kHz. This modification would require a DSP (Digital Signal Processor) instead of the current Arduino microprocessor, a resizing of the gate drivers and therefore changes in the circuit design and PCB size.

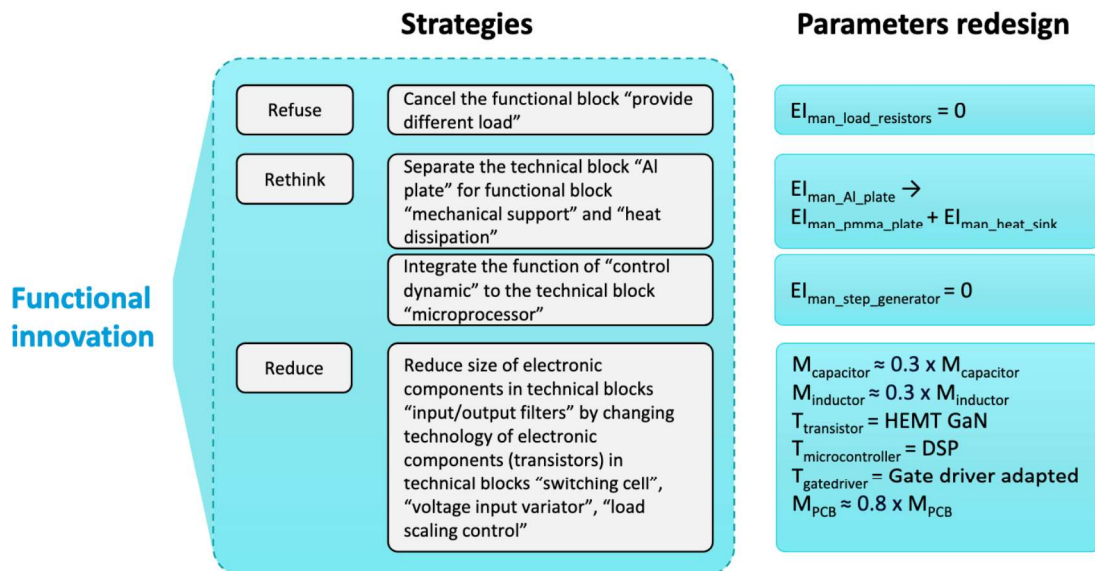


Figure 4.11-Eco-design scenario by applying functional innovation strategies [12]

Resources sufficiency strategy: repair and reuse strategies (Figure 4.12)

- **Repair strategy:** compatibility for repair is evaluated, assuming a returning rate of 100% of the PEC (reparation on site in the research laboratory). The researchers used an [Excel template](#) following the EN45554:2020 standard (“General methods for the assessment of the ability to repair, reuse, and upgrade energy-related products”). The evaluation with the Excel template leads to a compatibility with the design for repair of 67%, equivalent to replacing 33% of the converters in every 10 years. However, a



new technical block “ease-repair block” with connectors and test points should be integrated (with additional environmental impacts during manufacturing).

- **Reuse strategy:** the input and output filter, microprocessor, LED system, internal connectors and external connectors can be reused after the first life cycle. Researchers estimate a wear of 20% of the functional values, that can be considered negligible during operational time (non-intensive mission profile).

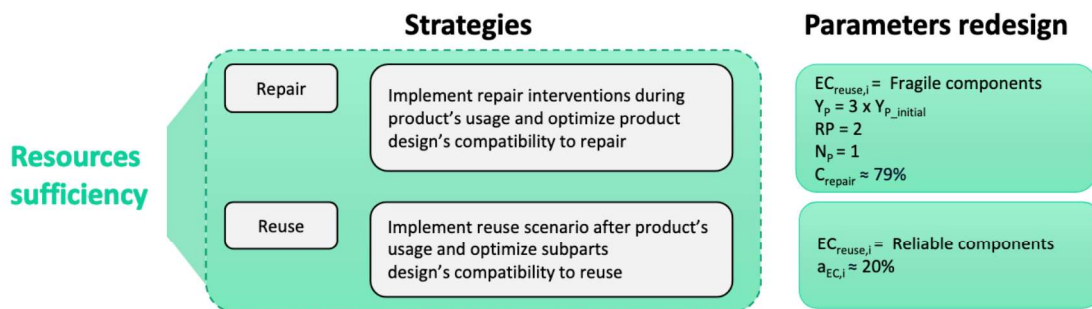


Figure 4.12-Eco-design scenario by applying resources sufficiency strategies, [12]

Once these two main strategies are proposed, they must be evaluated for analysing if they lead to an impact reduction.

4.2.4. Evaluating the technico-environmental performance of the design choices

Scenarios comparison

The proposed strategies cannot be implemented simultaneously. The HEMT-GaN transistor (of the “reduce” scenario) uses a package (DFN, Dual Flat No-Lead) difficult to disassemble. In consequence, the “repair” scenario is not compatible with the “reduce” one.

As a result, the researchers proposed two combined scenarios with the different strategies. Figure 4.13 compares *Scenario A* with the “reduce” option (and HEMT-GaN) and less repairability possibilities (compatibility of 73%), and *Scenario B* without “reduce” (and MOSFET-Silicon) but better compatibility for repair (compatibility of 79%). In both cases, design compatibility for repair was studied with the Excel following the EN45554:2020 standard.

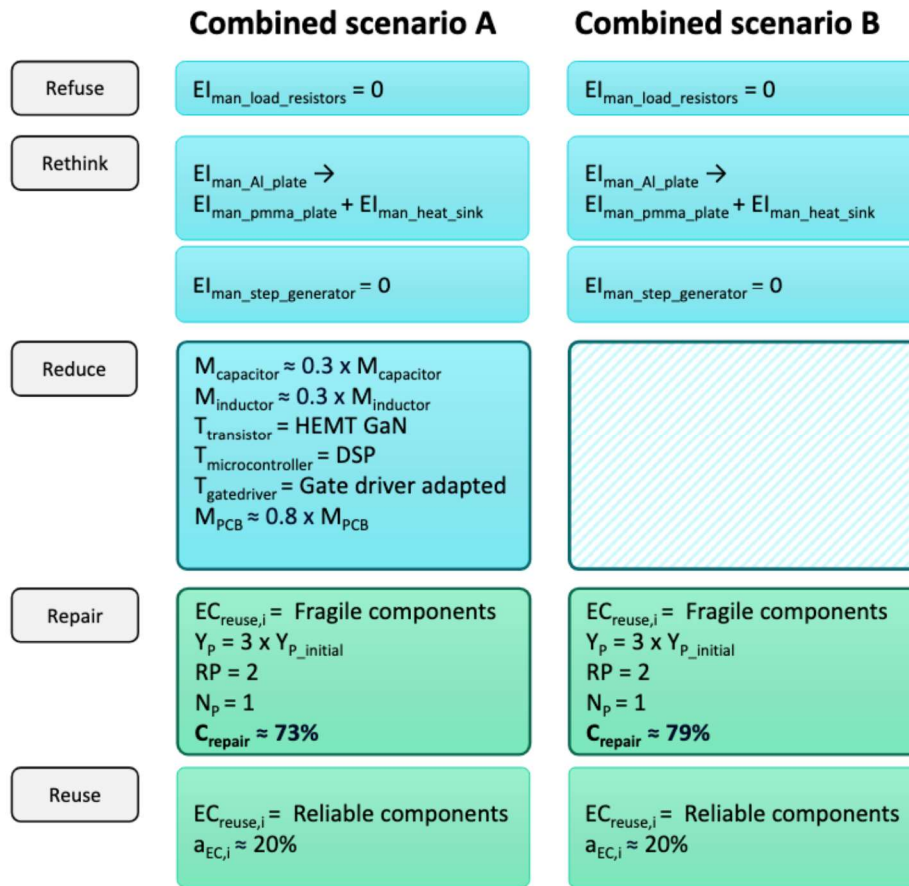


Figure 4.13-Comparison of scenario A and B

The proposed scenarios are now evaluated with the meta-model in Python, computing the environmental impacts along time (Figure 4.14) and normalized to the baseline scenario (Figure 4.15). Both scenarios significantly reduce the targeted impact categories, being *A* slightly more performant. However, it is highlighted that for a longer service provision time, *scenario B* would be more advantageous for its better repairability.

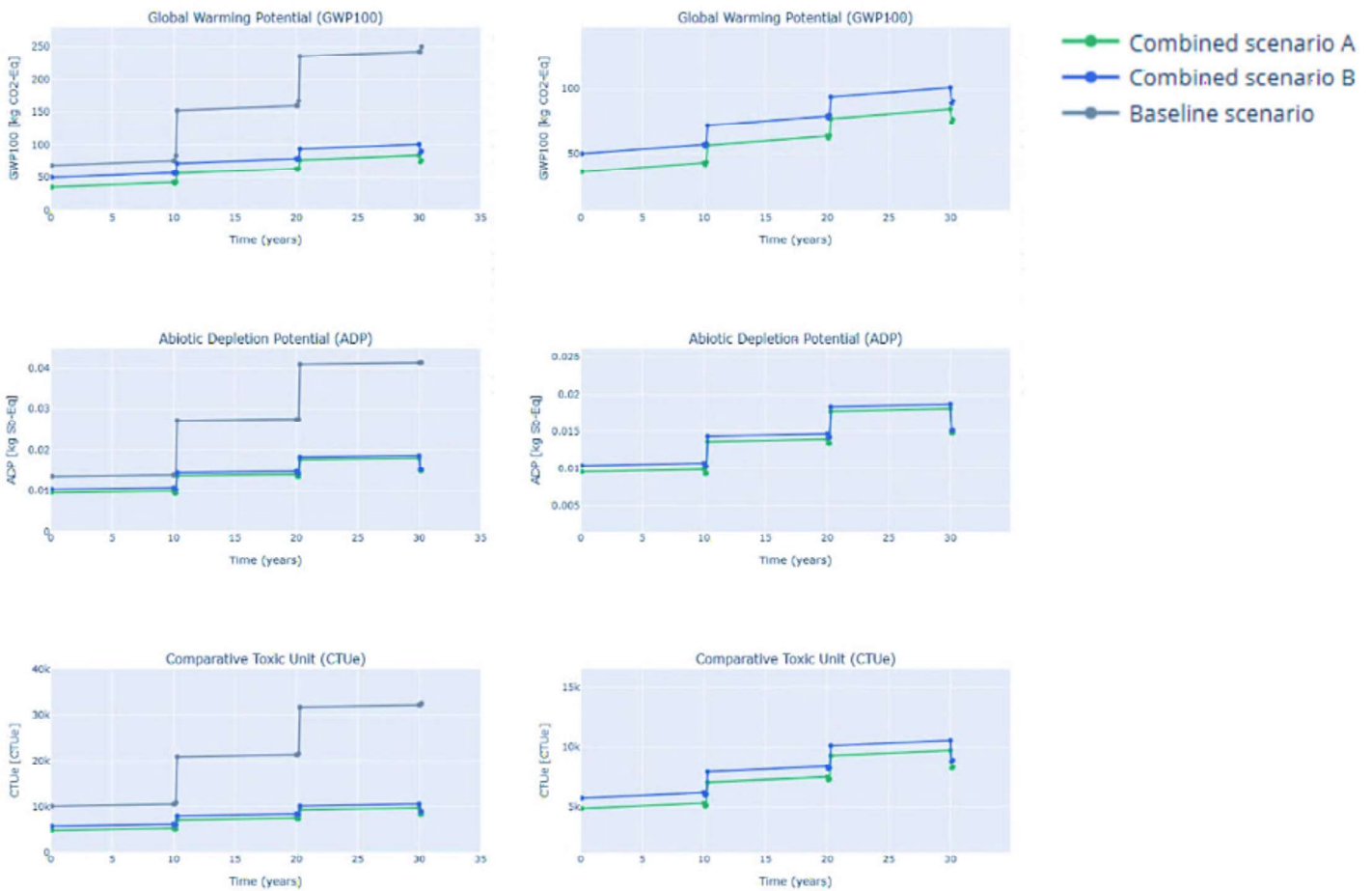


Figure 4.14-Environmental impact evolution between proposed scenarios A and B

The evolution along time in Figure 4.14 depicts the reduction of the impact on Climate Change (measured with Global Warming Potential, two first graphs at the top), on Resources Use (measured with Abiotic Depletion Potential, two graphs in the middle) and on Ecotoxicity (measured with Comparative Toxic Unit for ecosystems, two graphs at the bottom). With respect to the Baseline scenario (in grey), both Scenario A (in green) and Scenario B (in blue) are largely reduced. Comparing both scenarios, the impact is slightly lower in Scenario A than in Scenario B.

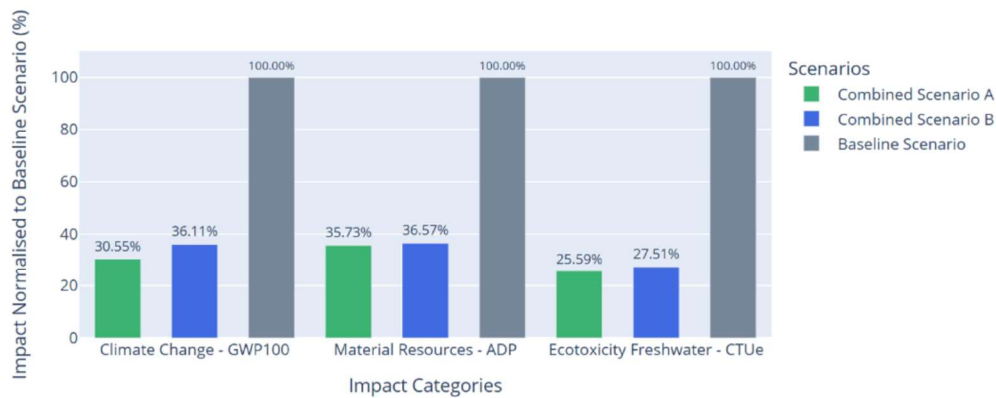


Figure 4.15-Normalized impacts of proposed scenarios across impact categories

Normalizing the impacts of the three categories and comparing the results to the Baseline Scenario (Figure 4.15), it is again seen how Scenario A (in green) achieves a slightly greater reduction in each impact than Scenario B (in blue).

Optimization: detail design

Finally, the prioritized parameters from **Scenario A** are integrated in the detail design (Figure 4.16). It should be noted that a sensitivity analysis and a heatmap are also carried out to select with more precision the components specifications. The load resistor is removed, the aluminium plate is replaced by PMMA, the CPLD step generator is removed, the size of the capacitors and inductors is reduced, the MOSFET-Si is substituted by the HEMT-GaN transistor, the DSP is introduced, the gate drivers and the PCB size are adapted, and a connectors and test points are added for improving repair.

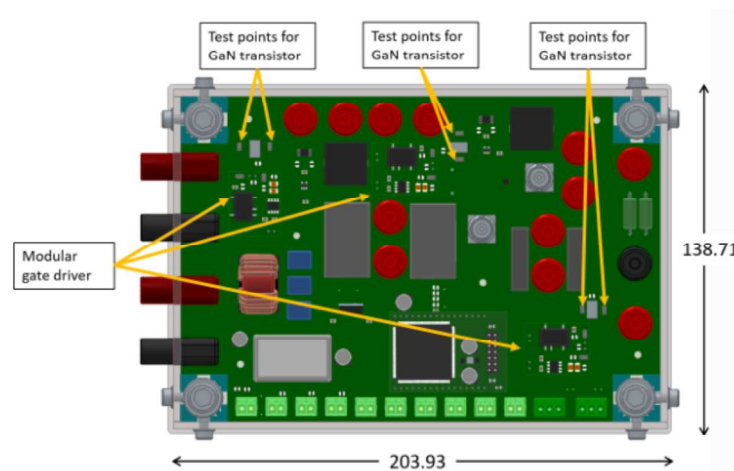


Figure 4.16-3D layout of implemented ecodesign scenario



The detailed design scenario includes optimizations in filter size and hardware selection, as well as the implementation of design-for-repair guidelines to achieve 73% repairability, as performed by the PE engineer. In addition, the lifecycle engineer provided more accurate environmental data for the DSP, gate driver and GaN transistor.

To conclude, this final delivery is compared to the initial baseline scenario. As it includes the exact data from the optimization and more precise environmental data, the LCIA results of detail design show significant reduction of the targeted impacts (blue in Figure 4.17, compared to the green case of conceptual design of Scenario A, and grey of the baseline scenario).

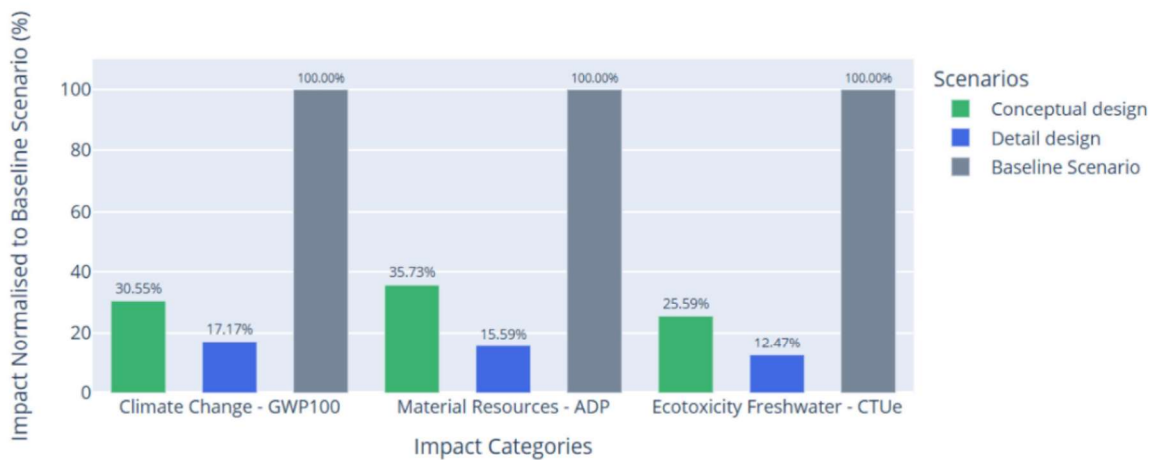


Figure 4.17-Final LCIA result comparison, distinguishing between conceptual and detail design

In conclusion, the whole meta-model process allows to integrate the circular cycle to the relevant environmental indicators, guiding eco-design decisions through the strategies development. It can be seen how eco-design is supported through graphical results, leading to a high reduction of the environmental impacts by the end of the process.

4.3.- Critics and conclusion of the PLCA meta-model and the Buck case

The objective of this chapter has been to address the limitations of traditional Life Cycle Assessment (LCA) by introducing the Parametric Life Cycle Assessment (PLCA) as a complementary methodology. In the context of Power Electronics, LCA is mainly used as a post-evaluation tool, focuses on already-designed products, follows a linear life cycle model, and does not support the early integration of eco-design strategies to reduce environmental impacts.



The PLCA shares common structural elements with the LCA—including the definition of a functional unit, the construction of an inventory, and the application of a Life Cycle Impact Assessment (LCIA) using standard impact categories such as those from the Product Environmental Footprint (PEF) method. However, unlike traditional LCA, which is applied retrospectively, PLCA is designed to support iterative and pre-evaluation design processes. Thanks to the parametric model implemented in Python, eco-design strategies can be proposed, and the environmental impact reduction can be measured.

One of the main limitations of the PLCA lies in the quality of its inventory. Because the method is applied during design, the data is less complete than in a conventional LCA and involves a higher number of assumptions. Furthermore, this case study used only the Ecoinvent database, whereas the LCA by Baudais relied on three different data sources. This highlights a general issue with life cycle methods: their results depend heavily on the databases used and the quality of the available data, which can impact the precision and reliability of the outcomes.

Despite these limitations, PLCA offers a broader and more realistic view of the product's life cycle. It includes all major phases—raw material extraction, component manufacturing, system assembly, use, end-of-life treatment, recycling, and disposal.

Regarding the results, in the Buck converter case study the manufacturing phase was once again the most critical in terms of environmental impacts, especially concerning **Freshwater Ecotoxicity (FET)** and **Material Resource Depletion (MRD)**—a similar result to that of the inverter analysed previously, where Mineral Resources Depletion (MRD), Freshwater Ecotoxicity (FET), and Human Toxicity (HT) were the three main ones in the manufacturing phase. However, the use phase had a much lower impact due to the educational context of the product, which involves fewer operating hours and lower energy consumption.

On the other hand, the Buck case also exemplified the ability to translate circularity principles into specific engineering decisions. The methodology goes beyond general strategies—such as refuse, rethink, reduce, repair, and reuse—by implementing technical changes still in the design phase. In the Buck case, these changes included removing the load resistor, replacing aluminium with PMMA, eliminating the CPLD step generator, reducing the size of passive components, and substituting the Si-MOSFET with a HEMT-GaN transistor. Other improvements involved integrating a DSP, adjusting gate drivers, and adding test points to improve repairability. These design choices resulted in a final scenario optimised not only for



performance and resource efficiency but also for maintainability, achieving a repairability rate of 73%. The environmental impacts of the final detail design showed a significant reduction with respect to the baseline scenario.

In conclusion, while the PLCA is not intended to replace conventional LCA, it represents a methodological evolution aligned with the needs of eco-design and circular engineering. Its reliance on assumptions and limited data sources remains a challenge, yet its ability to propose, evaluate, and refine circular scenarios makes it a valuable tool for advancing sustainability in power electronics. This way, this project proposes now a new case study of the PLCA, applied on a Boost converter whose environmental impacts have not been yet studied.

4.4.- PLCA meta-model application in a Boost Case

The objective of this section is to apply the Parametric Life Cycle Assessment (PLCA) methodology—previously developed for the Buck converter—to a second Power Electronics case: a Boost converter. In this project, this case study involved collecting technical data, analyzing the converter's main characteristics, developing a preliminary inventory and the Bill of Materials, and replicating the core phases of the PLCA framework.

However, the implementation of the Python code was significantly constrained by the unavailability of the Ecoinvent database. As a proprietary resource, Ecoinvent requires a paid license that was beyond the budget of this project. As a result, while the PLCA scripts were successfully written in Python by the author, they could not be executed locally due to the missing database access and the inability to import the associated library.

To overcome this limitation, a collaboration was established with Gaëtan Heller (PhD student at G2Elab) who executed the PLCA scripts and provided the resulting environmental impact data. Although this workaround allowed the environmental analysis to be completed, it caused delays and limited the ability to modify and re-run the model—making it difficult to explore multiple design iterations or optimization scenarios.

As a result, the iterative strategy development phase could not be carried out in this case. Instead, the focus remained on building the initial life cycle inventory, running a single environmental assessment, and comparing the results to previous cases.

Despite these limitations, this case study contributes to validating the methodology on a different topology and highlights its potential for adaptation under constrained conditions. It



also offers further insight into the environmental profile of a Boost converter, what lays the foundation for more informed and sustainable design practices in the field of Power Electronics.

4.4.1.1. Boost General characteristics

The Boost converter of the case study is analysed by Master's students at Grenoble INP – ENSE3 (*École Nationale Supérieure de l'Énergie, de l'Eau et de l'Environnement*). It is a Boost designed for automotive audio amplification, in a loudspeaker in hybrid vehicles [37]. Its main function is to convert the input voltage from 12V to 24V, having the following technical constraints (Table 4.1):

Technical constraints	
Input voltage	$V_i = 12 V$
Output voltage	$V_o = 24V$
Output Power	$P_o = 20 W$
Output Voltage Ripple	$\Delta V_o = 5 \%$
Input Current Ripple	$\Delta I_i = 10 \%$
Efficiency	$\eta \geq 80\%$
Duty Cycle	$D = 0.5$
Minium weight, volume and dimensions	

Table 4.1.-Technical Constraints of the Boost Converter

Figure 4.18 shows the main topology considered, while Figure 4.19 depicts schematically the functional requirements.

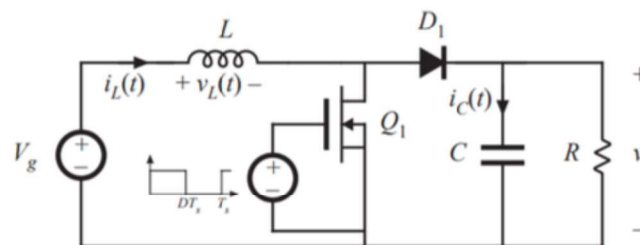


Figure 4.18-DC-DC Boost topology schematics, [37]

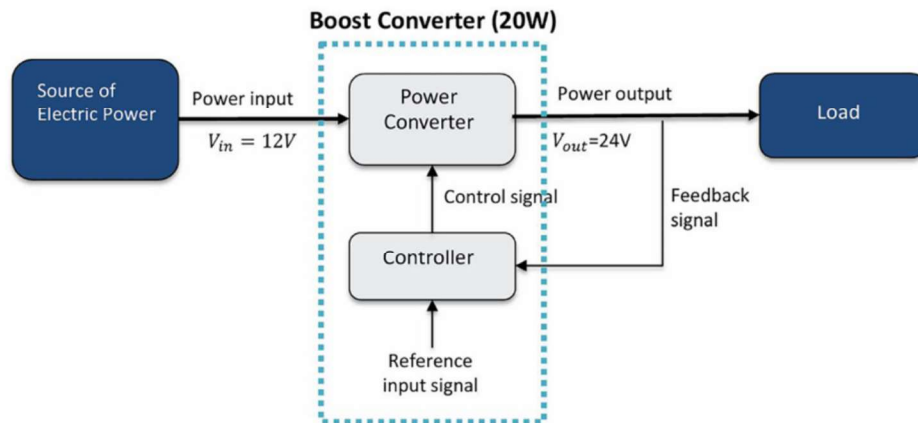


Figure 4.19-DC-DC Boost functional requirements, [33]

Once it comes to the Hardware allocation and selection, Figure 4.20 and

Figure 4.21

depict the components and its 3D routing in the PCB.

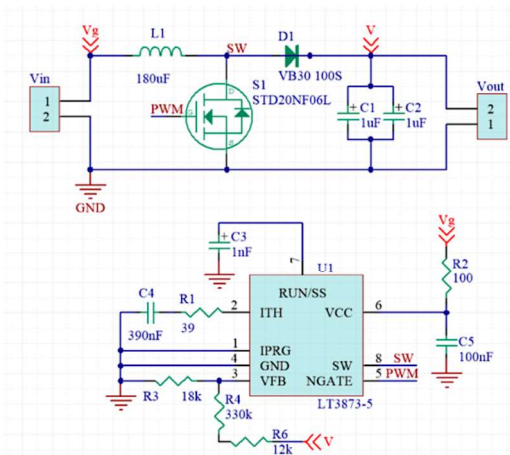


Figure 4.20-Hardware selection, [37]

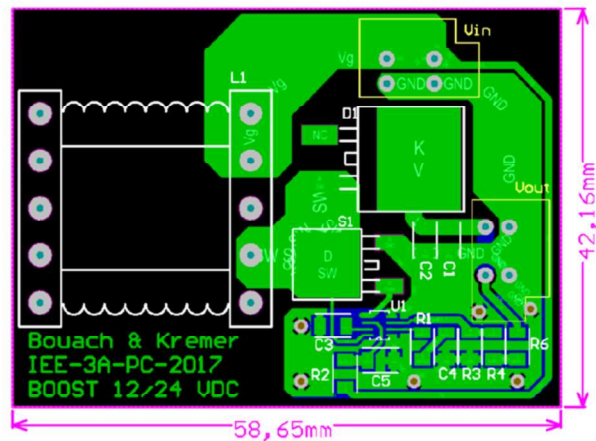


Figure 4.21-3D routing, [37]

From these specifications, the project included carrying out research on the components and its datasheets, resulting in the Bill Of Materials (BOM) of Table 4.2.



Designator	Description	Comment	Part number	Data Sheet
C1, C2	Aluminium electrolytic capacitors	2.2uF 50V	UWT1H2R2MCL1GB	Nichicon
C3, C4, C5	Ceramical capacitors		CAP SMD1206	mlcc-TDK
D1	Schottky Diode	Package D2PAK (TO-263AB)	VB30100S	Vishay
L1	Inductor	Ferrite core + copper wire (single-strand cable)	EFD 25 (N97)	TDK Electronics
S1	MOSFET Canal N, 60V	Package DPACK	STD20NF06L	ST
R1, R2, R3, R4, R6	Thick Film Chip Resistors		RCV 1206	Vishay
PWM Control	Constant frequency current mode controller	8 lead ThinSOT Package	LTC3873-5	Linear Technology
PCB	Printed Wiring Board, hybrid technology but mainly surface mounted	Dimensions of 3D routing: 58.65 x 42.16 mm ² . Thickness of 1.6 mm.	FR 4	General model

Table 4.2. BOM of the DC-DC Boost

It is interesting to mention that the choice of the components is based on the feasibility and the application at the laboratory session. The educational purpose justifies some choices such as:

- The single-strand cable made of solid copper wire to wind the ferrite core of the inductor. It is chosen so as the high Skin Effect can be measured, resulting in a resistance of 1Ω at 200kHz. Additionally, it is easier to solder and manipulate for the students.
- The transistor and the diode are over-dimensioned. This allows the design of a more robust converter that resists the periodic use in the educational field. Moreover, the package itself is enough to ensure a correct heat dissipation, without needing to include an aluminum plate or heat dissipators.
- The PCB design is based on a double-face technology, allowing a more compact routing on the top and bottom.
- The resistors and capacitors used for the PWM control are of the small model 1206, chosen because of the availability of stock.

After understanding the main characteristics of the Boost converter, the first steps of the PLCA meta-model can be applied.



4.4.2. Establishing the functional architecture coupled with environmental indicators

The functional unit that has been defined is: “to convert the input voltage from 12 V to 24 V output with an output power of 20 W for a speaker amplifier in hybrid vehicles, according to the reference usage scenario of 1 hour per day and during a Reference Service Life (RSL) of 10 years, i.e. equivalent to 3650 h of operation”.

A FAST diagram is also carried out following the schematics of Li Fang et al., in [33]: Figure 4.22.

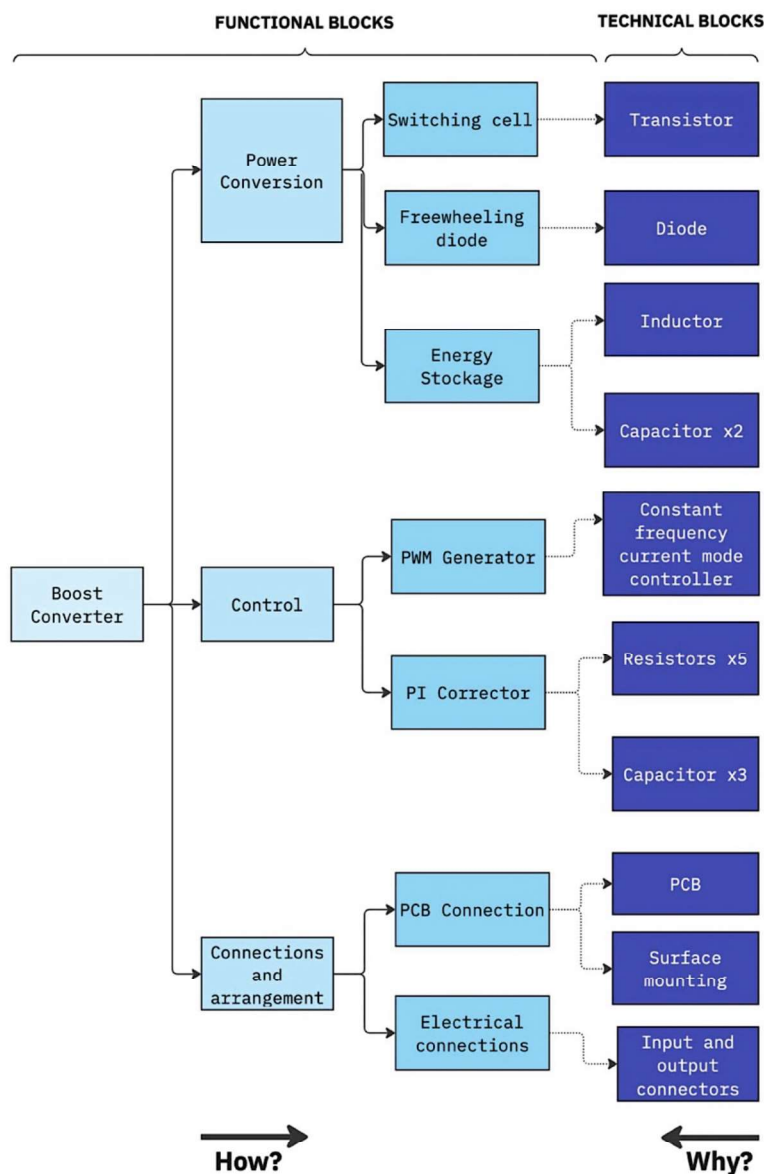


Figure 4.22-FAST diagram with functional structure of the Boost converter



Comparing the chosen functional blocks with the previous Buck diagram, the resulting FAST is largely simplified. It is noted that the converter would be ideally connected between the car battery and the audio amplifier, what allows the system to prescind of an interface supply, a step generator or an extra load. Following this reason, there is no need of a filter system or Led indicators neither. The use of the LTC3873-5 ensures the PWM Control, gathering the functions of the gate drivers, the interface switching, the control signal isolation, and a loop regulation system.

The meta-model code is written, associating the FAST to the Manufacturing phase code. Each of the technical blocks is linked to an [Ecoinvent reference](#), adapted with geography for manufacturing, and the mass of the component (data extracted from the BOM and the datasheets).

Table 4.3 summarizes the chosen Ecoinvent references with the mass of the components, the geography for the manufacturing, and the quantity.

Designator	Ecoinvent reference	Mass (kg)	Geography	Quantity
C1, C2	<i>capacitor production, for surface-mounting.</i>	0.000167	GLO	2
C3, C4, C5	<i>capacitor production, for surface-mounting.</i>	0.00005	GLO	3
D1	<i>diode production, glass-, for surface-mounting</i>	0.00138	GLO	1
L1	<i>inductor production, ring core choke type</i>	0.0236	GLO	1
S1	<i>transistor production, surface-mounted</i>	0.00003	GLO	1
R1, R2, R3, R4, R6	<i>resistor production, surface-mounted</i>	0.00001	GLO	5
PWM Control	<i>integrated circuit production, logic type</i>	0.000015	GLO	1
PCB	<i>printed wiring board production, for surface mounting, Pb free surface</i>	Surface in m²: 0.002472098	GLO	1
Cable	<i>cable production, unspecified</i>	0.00533	GLO	2

Table 4.3.- Ecoinvent references associated to the Boost components

Figure 4.23 exemplifies the code for the Energy Stockage functional block, formed by its two technical blocks of one inductor and two capacitors. Again, the Ecoinvent reference in red and the identified mass in green.



```
energy_stockage= agb.newActivity(DB_Boost_baseline,
    "energy_stockage",
    "unit",
    exchanges = {
        agb.findActivity("capacitor production, for surface-mounting", loc="GL0", db_name="ecoinvent-3.10-cutoff"):2*0.000167,
        agb.findActivity("inductor production, ring core choke type", loc="GL0", db_name="ecoinvent-3.10-cutoff"):0.0236,

df_energy_stockage= agb.printAct(energy_stockage).sum().to_frame().T
Amount_kg_energy_stockage = df_energy_stockage.iloc[:, 1].tolist()
# print(Amount_kg_energy_storage)
```

Figure 4.23-Manufacturing phase code for the Energy Stockage functional block

It is interesting to mention that the Ecoinvent dataset has limited options of inventory, so some of the choices may not be so precise. For example, the inductor used for the Boost is a EFD 25 (N97), that is composed of two separate ferrite pieces around a coil former, having a toroidal ring core. Nevertheless, the most similar Ecoinvent inductor option is the “ring core choke type”. However, as the impact calculation is mainly based on the mass of the component (the weight of the magnetic material in this case), the approximation in the end is considered valid.

The product lifetime of 10 years and the 1 hour per day use are adjusted in the Use phase modelling. The rest of the Transport, Repair, Reuse and End of life Modelling data are not modified with respect to the Buck case, as the same hypothesis based on the PEP Ecopassport and Ademe data that Li Fang developed in [12] can be kept.

4.4.3. Identifying the main critical technical parameters

The first result of executing the code is a list of the environmental impacts with respect to the EF categories and its units, Table 4.4.

	Climate Change	Material Resources: metals/minerals	Energy Resources: non-renewable	Acidification	Ecotoxicity: Freshwater	Human Toxicity: carcinogenic	Human Toxicity: Non-carcinogenic	Eutrophication: Freshwater	Eutrophication: Marine	Eutrophication: Terrestrial	Ionising Radiation	Land use and land use change	Ozone Depletion	Particulate Matter Formation	Photochemical Oxidant Formation: human health	Water Use
	[kg CO2-Eq]	[kg Sb-Eq]	[MJ, net calorific value]	[mol H+-Eq]	[CTUe]	[CTUh]	[CTUh]	[kg P-Eq]	[kg N-Eq]	[mol N-Eq]	[kBq U235-Eq]	[kg CO2-Eq]	[kg CFC-11-Eq]	[disease incidence]	[kg NMVOC-Eq]	[m3 world Eq deprived]
EL_manufacturing	1.94089718	0.000190888	25.50937843	0.017531963	150.8362494	6.05063E-09	1.05507E-07	0.001474493	0.002267173	0.02438612	0.21240004	0.00235859	2.3519E-08	1.03552E-07	0.011679841	0.623533
EL_transport	2.787E-05	5.33948E-11	0.000356937	5.03741E-07	0.000354268	1.27824E-13	2.30979E-13	1.45405E-09	1.32584E-07	1.46507E-06	2.4201E-07	4.8857E-08	4.197E-13	1.62075E-12	4.13664E-07	1.341E-06
EL_use	21.4806772	0.001002101	2705.883111	0.145543081	1331.750356	1.07813E-07	9.38801E-07	0.008725005	0.027714559	0.230122886	121.223328	0.0197582	7.3757E-07	1.32695E-06	0.078763117	34.2564452
EL_End-of-Life	0.04314798	1.5184E-07	0.184052353	5.45163E-05	1.632883982	6.22029E-11	4.10561E-10	9.01193E-06	2.14151E-05	0.00016297	0.0005166	6.7849E-06	4.3612E-10	5.58884E-10	4.92155E-05	0.00262472
El Whole life cycle	23.4647502	0.00119314	2731.576899	0.163130064	1484.219845	1.13920E-07	1.04472E-06	0.010208512	0.030003279	0.25437896	121.436245	0.02212362	7.6153E-07	1.43106E-06	0.090492587	34.8826043

Table 4.4-Environmental impact output of each of the life cycle phases after executing the Boost code



However, the results must be normalised so that they can be compared and so that conclusions can be extracted. By dividing the values by the references given by Environmental Footprint [29], the code is modified and the following normalisation is provided in a pie chart. In Figure 4.24, the impact categories are distributed according to their weight on the total impact and depicted with the unit of the PEF framework.

In the case of the Boost converter, **Ecotoxicity of Freshwater (FET)** in blue, **Energy Resources: non-renewable, fossil fuels (FD)** in red; and **ionising radiation (IR)** in green; are the most critical impact categories. With respect to the Buck impact categories, **Material resources: metals and minerals (ADP)** that was the second most critical, is now the fourth one. **Climate change (GWP)** will be again selected because of the carbon neutrality European policies.

Normalised impacts repartition of the DC-DC Boost converter

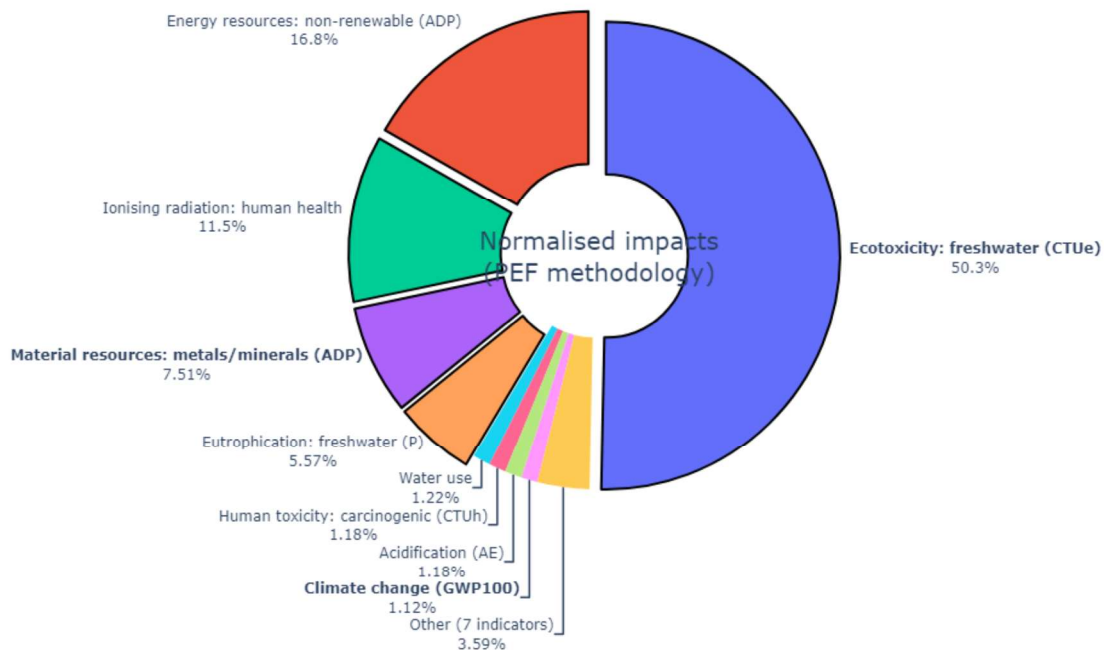


Figure 4.24-Normalised impacts repartition of the DC-DC Boost converter

Once identifying these impact categories, the analyse focuses on how **Ecotoxicity of Freshwater (FET)**, **Energy Resources: non-renewable, fossil fuels (FD)** and **Climate change (GWP)** affect each of the life cycle phases. The Python code allows the analyse such as the following results are obtained:



- **Ecotoxicity of Freshwater** accounts for 50.3 % of the total impact. It is measured in CTUe (Comparative Toxic Unit for ecosystems), and as depicted in Figure 4.25, it is mainly predominant in the use phase (89.7% of the life cycle impact in green), followed by a 10.2 % impact in the manufacturing phase.

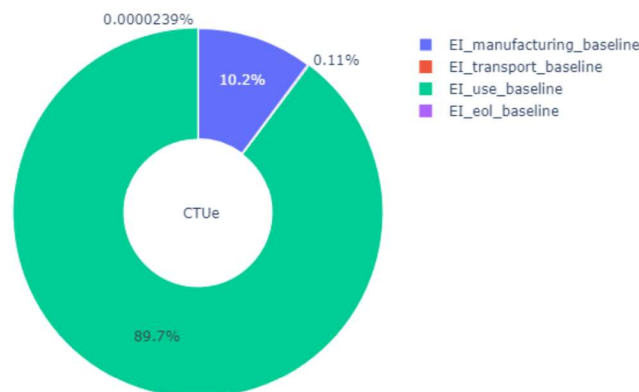


Figure 4.25-Ecotoxicity of Freshwater repartition along the whole life cycle of the Boost converter; measured in Comparative Toxic Unit for ecosystems (CTUe)

- **Energy Resources: non-renewable, fossil fuels (FD)** account for 16.8 % of the total impact. The impact is measured in MJ of Abiotic Resource Depletion (ADP), and as depicted in Figure 4.26, the use phase is responsible of almost the whole life cycle impact: 99.1% .

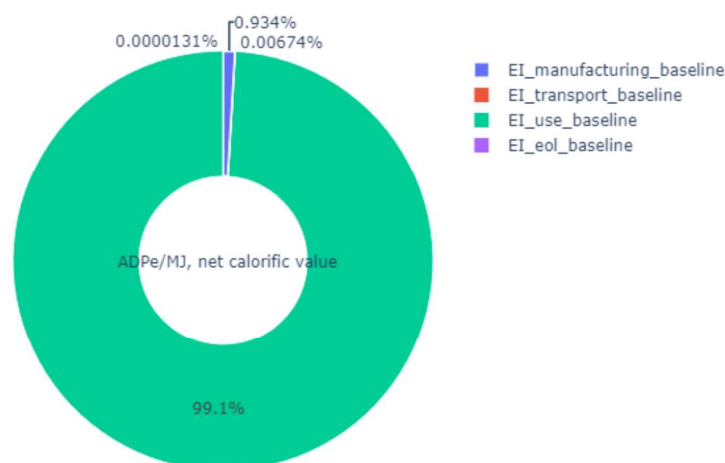


Figure 4.26-Energy Resources: non-renewable, fossil fuels; repartition along the whole life cycle of the Boost converter, measured in MJ of Abiotic Resource Depletion (ADP)



- **Climate change (GWP)** only accounts for 1.12% of the total impact, but it is analysed because of the carbon neutrality European policies. This minimal impact overall is positively enhanced, considering that even if this case study is for an automotive application, the massif deployment of PECs expected as part of the Net-Zero strategies, had as objective a climate change mitigation.

The Climate Change impact is measured in kg of CO₂ equivalent in Global Warming Potential (GWP). As depicted in Figure 4.27, the use phase is again the most critical, encompassing 91.5% of the impact; followed by 8.27 % of impact in the manufacturing phase.

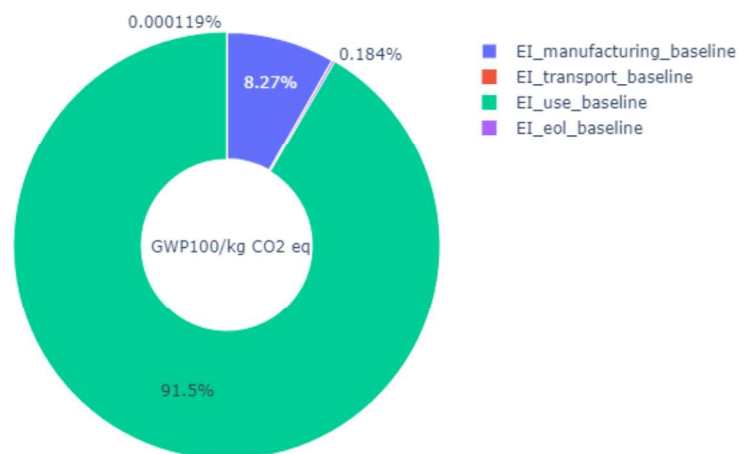


Figure 4.27- Climate Change repartition along the whole life cycle of the Boost converter, measured in Global Warming Potential (GWP), kg of CO₂ equivalent

In conclusion, in the three impacts that have been targeted, the majority of the environmental impact is concentrated in the use phase. The manufacturing of the converter is second in terms of environmental impact, while the transport and the end-of-life phases are almost negligible.

Finally, these two phases were analysed more in detail, regarding the functional blocks that compose the converter. The Python code allowed for another analysis for the distribution of the target impact categories for the use (Figure 4.29) and the manufacturing phase (Figure 4.28) across the technical blocks of the Boost (the ones defined in the schematics of Figure 4.22).

Climate change (Global Warming Potential -GWP, kg CO₂eq), Ecotoxicity: freshwater - comparative toxic unit for ecosystems (CTUe); and Energy Resources: fossil fuels, (MJ of



Abiotic Resource Depletion (ADP)) are again evaluated in each of the technical blocks, with respect to the proportion of subpart’s impacts relative to the total phase impacts.

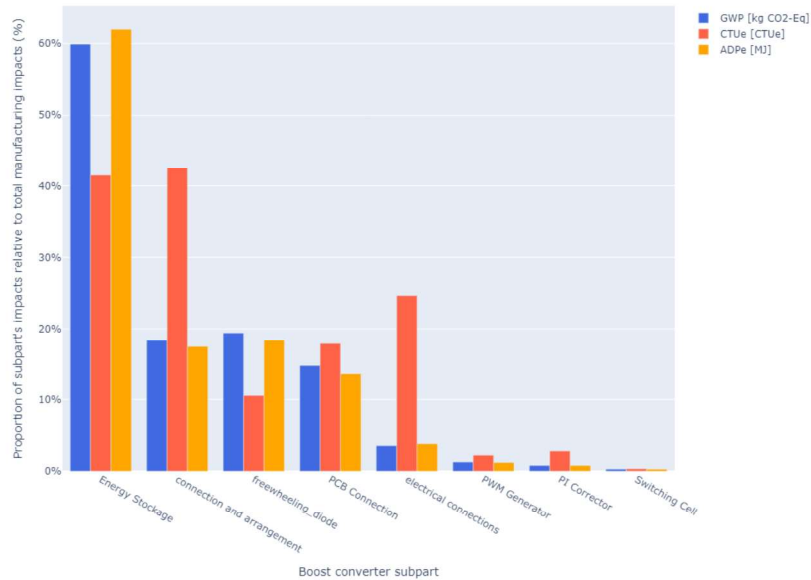


Figure 4.28- Manufacturing impacts distribution in the Boost converter's functional blocks

Use impacts distribution in boost converter's subparts, in 3 categories.

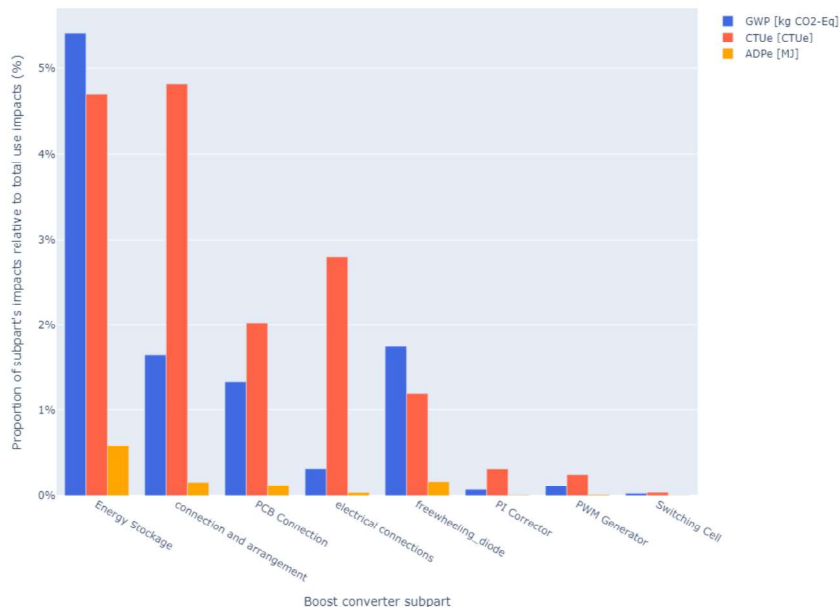


Figure 4.29-Use phase impacts distribution in the Boost converter's functional blocks

In both cases the results show that the functional block with a larger impact is the **Energy stockage** one, composed of one inductor and two capacitors. This is probably due to these



components being the bigger ones. They comprise more mass, which is finally the data that conditions the results linked to the Ecoinvent database.

4.4.4. Critics and conclusions of the PLCA meta-model for the Boost case

The next step of the PLCA meta-model would include elaborating a design strategy while identifying the key-design parameters. However, this part of the project was constrained by the unavailability of the Ecoinvent database and the difficulty of iterating multiple times through design scenarios without having a direct access to the licence. As a result, the focus was placed on analysing the obtained results and comparing them with the previous LCA and PLCA assessments presented earlier.

Figure 4.30 compares the LCA results of the three study cases, in which some similarities and general trends can be observed. Freshwater ecotoxicity is the most predominant impact in both the Buck and Boost converter. This is likely due to the manufacturing processes of printed circuit boards (PCBs) and the use of certain semiconductors, which involve substances such as lead, copper, and brominated flame retardants known to affect aquatic ecosystems [38].

Mineral Resources Depletion is also a critical impact shared between the Buck and the Inverter. This arises mainly from the use of materials such as aluminium, copper, and rare metals in passive components (inductors, capacitors) and power semiconductors, which are known to have high cumulative energy demand and scarcity concerns [39].

Interestingly, in all three converters, the Climate Change impact is relatively low compared to other categories. This is a positive outcome, especially considering that Power Electronic Converters (PECs) are instrumental in the electrification of sectors like transport and renewable energy systems—both of which are central to climate mitigation strategies outlined in Net-Zero policies. This highlights the importance of considering other environmental impacts beyond carbon emissions, and enhancing how the analysis of the whole Planetary Boundaries framework is essential.

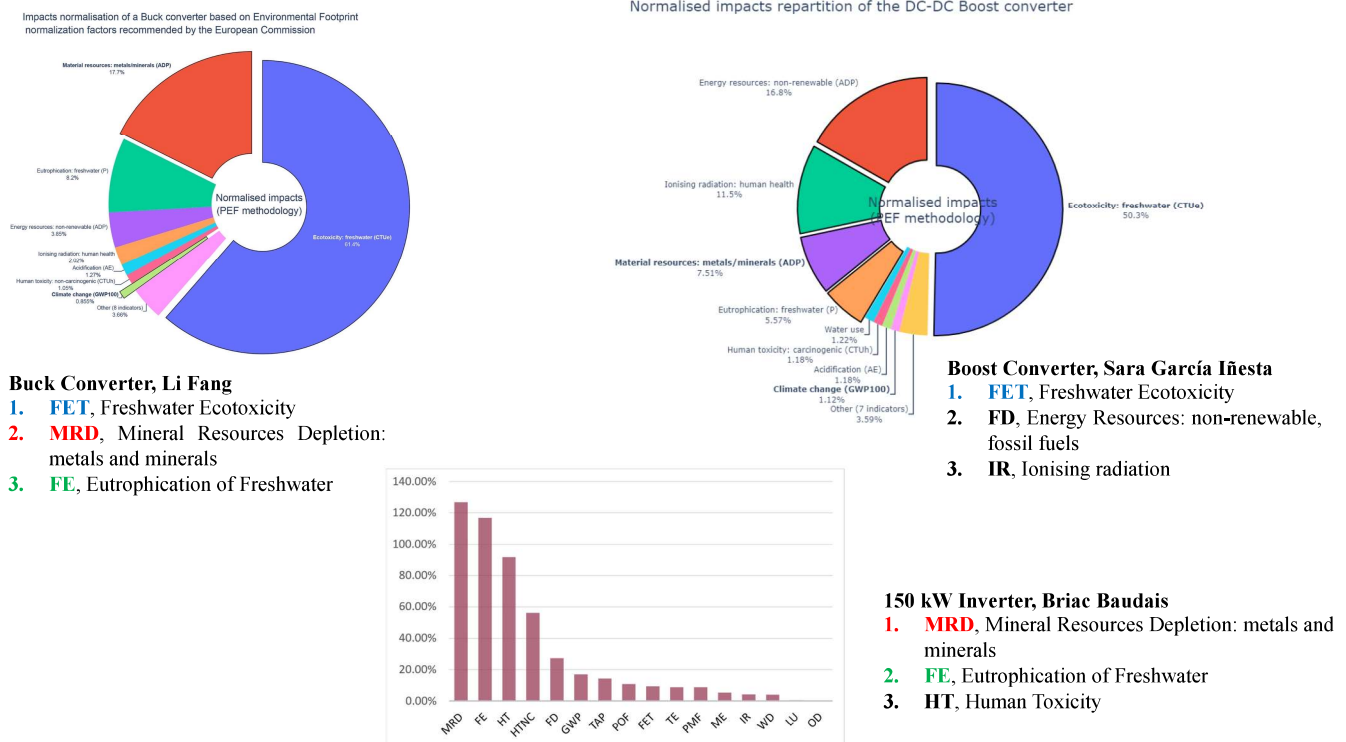


Figure 4.30–Schematic comparison of environmental impact distribution of the study cases: 150kW inverter, Buck Converter and Boost Converter

Figure 4.31 provides a summary of how the most critical impacts are distributed across the life cycle phases of the converters. Both the Boost and the Inverter show that environmental impacts are concentrated during the use phase, primarily due to electricity consumption. As expected, the results are highly dependent on the energy mix, what means that the LCA outcome is closely tied to geographical and temporal energy scenarios.

On the other hand, the Buck converter concentrates most of its environmental impact in the manufacturing phase. This is explained by its design for educational purposes: it includes a much larger inventory with a greater number of components and materials compared to the Boost, which was optimized for automotive application. As a result, the increased Bill of Materials (BOM) contributes to higher impacts during component production and assembly.

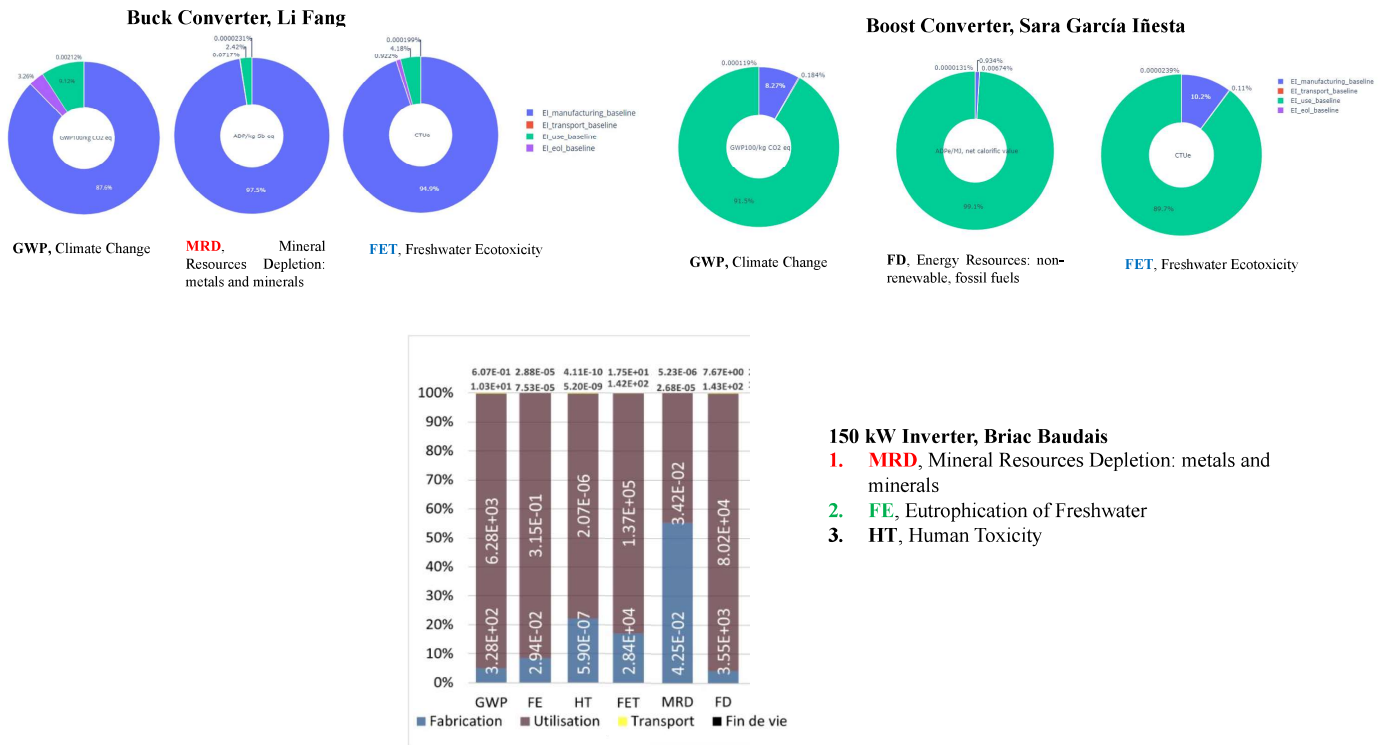


Figure 4.31-Schematic comparison of the life cycle phases the most affected by the environmental impact of the study cases: 150kW inverter, Buck Converter and Boost Converter

The key conclusion from this comparative analysis is that the environmental profile of Power Electronic Converters is strongly influenced by their functional purpose and design choices. Nevertheless, rather than focusing on the specific numerical results— which are highly dependent on the case study—attention should be placed on how both LCA and PLCA methodologies enable a structured evaluation of environmental impacts.

The main limitation remains being the quality of the inventory, which misses complete data and involves multiple assumptions. However, early-stage application of LCA or PLCA can effectively guide decisions on material selection, component sizing, and topology, helping to identify and reduce the most critical environmental burdens. This approach lays the foundation for more informed and sustainable design practices in the field of Power Electronics.



5. Digital Product Passport

5.1.- Accessibility to information for improving circularity

In the technological sector—and particularly in electronics—it has been proved how the implementation of circularity principles encounters significant barriers largely due to the structural and functional complexity of the systems. The electronics industry is vast and highly intricate. Due to longstanding industrial practices, access to essential information is often restricted. As a result, the current economic model remains predominantly linear, with key circular economy strategies such as repair, reuse, and recycling hindered by a lack of accessible information on the "how" of these processes [40].

The previous LCAs and PLCAs also highlight the urgent need for accurate, comprehensive and accessible data. Additionally, when it comes to circular strategies such as repairing electronic devices, it becomes unfeasible if technical procedures and component details remain inaccessible or encrypted. High-quality data is often scattered, and there are insufficient mechanisms and routines for effective data sharing. Additionally, frequent data losses along value chains—due to poor documentation practices or a reluctance to share information—further exacerbate the issue.

To address this lack of transparency throughout product life cycles, the EU introduced the Eco-design for Sustainable Products Regulation, which came into force on 18 July 2024. As part of both the EU Circular Economy Action Plan and the EU Green Deal, this regulation includes a major innovation: the Digital Product Passport (DPP). Its primary objective is “to simplify digital access to relevant product-specific information in the areas of sustainability, circularity, and legal compliance” [41], [42].

Under this regulation, an electronic register is expected to be implemented by 2030, applying to all relevant products traded within the European market. The DPP is envisioned as a digital mechanism to register, process, and share product-related data among producers, businesses, authorities and consumers. It is designed to serve as a centralized repository for critical product information, with each passport uniquely tied to a specific item. Supply chain stakeholders—



from component suppliers to third-party recyclers—would be able to both consult and contribute to this digital record [41], [43].

To ensure traceability throughout a product's lifecycle, each item would be assigned a Unique Operator Identifier and a Unique Facility Identifier, enabling the tracking of manufacturers, importers, repairers, and distributors, as well as the geographic location of their operations. This global, product-level identification is expected to significantly improve value chain transparency and help assess the environmental impact of manufacturing processes. Ultimately, this could enhance the sustainability and circularity performance of products [43].

The overarching aim is to facilitate efficient and reliable access to product information, thereby strengthening traceability in support of a circular economy. Despite the detailed principles outlined in the GSI Regulation, the initiative is still in its early stages of development. Initially, the prioritized product categories include iron and steel, aluminium, textiles, and other categories that also comprise electronics. Notably, electric vehicle batteries will explicitly require a Digital Product Passport [27].

Regarding the character of the information, research has identified three key elements of concern that should be considered when determining the types of data to be included in the Digital Product Passport, [43]:

- Perceived importance: the extent to which the data is critical for informed decision-making across the value chain.
- Data availability: although large volumes of data are generated, they are often fragmented and stored across various isolated data management systems, limiting their accessibility.
- Data sensitivity: the degree to which the data is confidential, ranging from information suitable for public disclosure to business-critical and proprietary data.

Given these concerns, it may seem unrealistic to expect industries to openly share commercially sensitive information. Therefore, robust access control mechanisms should be implemented to ensure that only authorized stakeholders—through means such as authentication protocols or verifiable credentials—could access specific types of data. In addition, security measures should also be reinforced to safeguard against data corruption or unauthorized alterations [27].



5.2.- Proposal of a DPP for PE

The specific information to be included in the DPP is not yet fully defined, and researchers continue to debate which data categories and supply chain actors should be involved [40], [43], [28]. Moreover, the relevance of the data depends greatly on the type of product under consideration.

In this project, a proposal is developed by the author aiming to outline a potential **DPP structure tailored to the Power Electronics** field. Beyond technical datasheets, there is a clear lack of organized, open-source information on PE devices, which hinders their repair, disassembly, and end-of-life management. As a result, performing accurate environmental impact assessments becomes difficult—or even impossible—due to the absence of necessary data.

The digital nature of the DPP would allow information to be structured hierarchically according to class, subclass, and instance, which helps manage content efficiently. After identifying these main characteristics, it was decided that in the proposal, for example, data about individual components within a converter should ideally link directly to their own respective DPPs. This would prevent redundancy and would avoid overly long entries. In alignment with the GS1 Standard [41], general product information would be asserted as the uppermost class level, with all items in the same batch inheriting the data from higher levels.

In consequence, after exchanging with the G2Elab team, the author proposed the categories structured in Figure 5.1, which are intended to be relevant for a wide range of PE devices: from individual components to larger systems like converters. Nevertheless, regarding the character of the information, the three elements of concern previously mentioned would limit the selection of data: perceived importance, availability and sensitivity.

This structure is inspired from the general structure provided by Berger et al. for Electric Vehicle Batteries [40], as well as from the Product Category Rules for Electrical, Electronic and HVAC-R Products published by PEP Ecopassport [28]. The detailed structure (Figure 5.1) is presented and developed in Annex II. Below is a brief justification of the selected categories, with further information provided in the annex.



DPP for PE Structure

Digital Product Passport for Power Electronics devices	2
Structure	4
General information	4
Product name	4
Serial and product number, trademark	4
Product DataSheet	4
Enterprise/Research group specialised and Geographical Area	4
Product classification/category	4
Description and picture	4
Key features or specifications	4
Electrical parameters and constraints:	5
Electrical layout	5
Intrinsic variables	5
External environment	5
Efficiency	5
Manufacturing	5
BOM: including referencing, and datasheet directly	5
Geometry	6
Manufacturing files	6
Gerber and NC Drill	7
Designer	7
Manufacturer	7
Data and operation points, system description	7
Data curation	7
Outcomes	7
Setup	8
Failure	8
Disassembling: how, instructions if possible	8
Reparation	9
End of life	9
Environmental Impact	9
Scope	9
Product Environmental Profile	9
Life Cycle Assessment (LCA)	10
Environmental Impacts/ Footprint	11
Hazardous substances	11
More product related information	11
Related experts	11
Standards, product-specific regulation	11
Other models	11
Articles	12
Future improvements or modifications	12

Figure 5.1-DPP proposed structure for PE

To start with, the **general information** section ensures clear identification and contextualization of the device. It is followed by **electrical parameters and constraints**, which offer a deeper understanding of the intrinsic variables or the device’s electrical layout. The next category, **manufacturing**, is expected to provide information on product designs, components, assembly processes, or manufacturing files, as well as the actors involved. **Data and operation points** should offer performance-related properties and details about the device’s expected behaviour. The main objective is to illustrate the functioning of the device for future users,



showing, for instance, how some variables may depend on specific setup parameters. Theoretical simulations and real measurements could be included to fully characterize the device's performance. The **failure** category aims to support maintenance, diagnosis, and the identification of possible defaults; while providing disassembling and repair instructions where available. It should also include end of life information to improve the safety of disposal, whether for second life applications or recycling. Furthermore, the **environmental impact** category seeks to assess the device's environmental performance, supported by Life Cycle Assessment (LCA) results and impact evaluations. To conclude, the **additional product-related information** section is intended to list contacts of value chain actors (those involved at any stage of the device's development), relevant regulations, and other similar models that may be of interest to the user.

Finally, each DPP should include technical information about the passport itself, such as a Registration Number, verifier accreditation, date of issue, validity period, and the DPP version. The implementation of a Digital Product Passport in Power Electronics offers a concrete source of reliable key information. By structuring and centralizing data -from components, performance or maintenance- it contributes to sustainability, democratizing access to essential technical insights, promoting reparability and engaging through the whole product's life cycle.

5.3.- DPP of the CSCGM20V5A

The proposed DPP structure for Power Electronics has been applied to the modular bidirectional converter CSC GM20V5A, selected for its modular design that supports reparability, reuse, and maintenance—key enablers of circular design. The author conducted a research process to compile and analyse the converter's key characteristics, which were later analysed to complete the DPP structure.

5.3.1. Modular approach and generic characteristics

Modularity is a core eco-design strategy (Section 2.2.4) and part of broader circular design approaches [26]. In Power Electronics, it is implemented through Power Electronics Building Blocks (PEBB): standardized modules that can be assembled, removed, or replaced based on technical requirements like input/output voltage ratio, power ratings or efficiency [44]. These



modules are connected via power clips—miniaturized copper busbars (Figure 5.3)—that enhance both heat dissipation and current conduction.

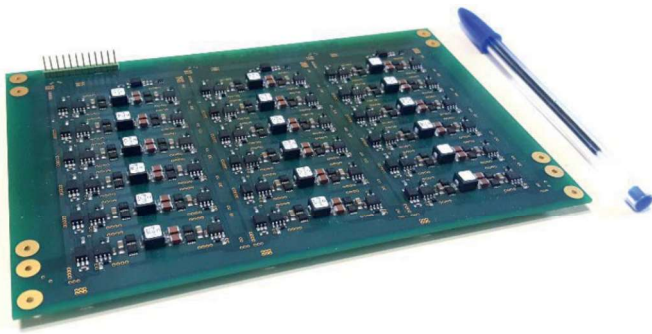


Figure 5.2-Multi-Cell Converter built with 18 Power Conversion Blocks, [44]

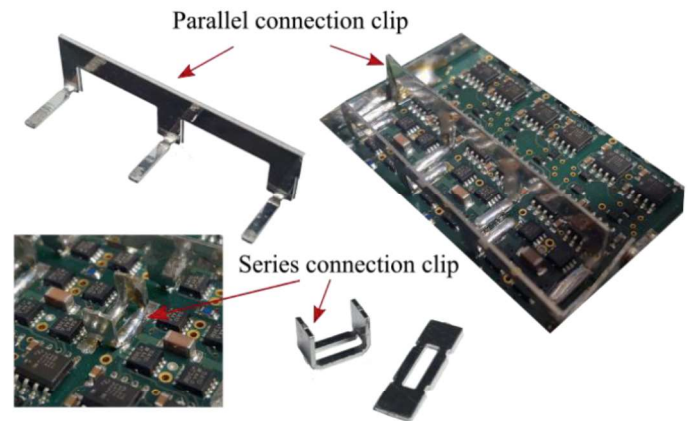


Figure 5.3-Interconnections among elementary power conversion blocks through copper bars, [45]

Several models of PEBB were developed in the G2Elab PE team [44], [46], [47], [45]. In particular, the CSC GM20V5A⁵ is the main structure under study, a high step-up current bidirectional DC-DC converter, with high voltage gain (up to 9 times, up to 200 V voltage output), high efficiency (higher than 95 %), and high-power density (higher than 9 kW/L). Its modularity enables constraint distribution, scalability, and voltage gain flexibility through block associations, adapting to the required technical specifications.

5.3.2. Technical contributions to the DPP of the CSC GM20V5A

The CSC GM20V5A converter offers a strong example of modular design in Power Electronics, yet much of its technical information remains dispersed or difficult to access. This project aimed to consolidate, generate, and structure key data to improve the accessibility and usefulness of this knowledge—particularly in the context of sustainability and circular design.

For that, between June and August 2024, the author retrieved and analyzed Altium files, generated the Bill of Materials with datasheets, conducted LTSpice simulations, took experimental measurements, and organized datasets concerning the converter. The results have

⁵ CSC stands for *Cellule Standard de Conversion*, Standard Conversion Cell; term referring to the elementary power conversion blocks or modules.



been analyzed and structured to complete the Digital Product Passport, organizing the technical findings under the previous categories of Figure 5.1. All the detailed information can be found in Annex II, in which after presenting the proposal of the DPP structure, it is applied to the CSC GM20V5A. Below are part of the main findings, with more results explained in the Annexes.

To start with, Table 5.1 summarizes the main entries that would appear at the beginning of the DPP of the CSC GM20V5A. After analyzing the available publications, technical information about the components, the operating mode, the duty cycle and the control of the phase shift was retrieved, exposed in Annex II, (Table 5.2 and Figure 5.4 as examples of the localized content).

<i>GENERAL INFORMATION</i>	
Product name	<i>CSC GM20V5A</i>
Serial and product number, trademark	Research module
Enterprise/Research group specialised and Geographical Area	G2ELab, PE Team, Grenoble (France)
Product classification/category	Converter, DC/DC, Dual Active Bridge
Description	<ul style="list-style-type: none"> • High step-up current bidirectional DC-DC converter • High voltage gain: up to 9 times, up to 200 V voltage output. • High efficiency: > 95 % • High power density: >9 kW/L • Benefits: constraints distribution, improved thermal management and scalability

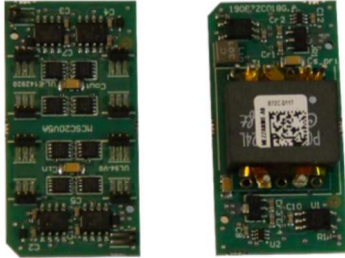
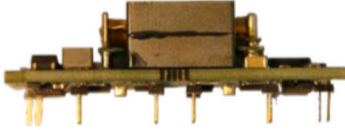
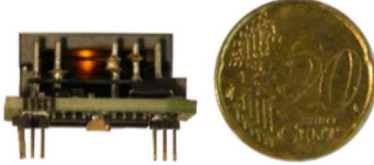




Table 5.1- General information of the CSC GM20V5A belonging to its DPP, Annex II



Component name	Function and description
8 Si MOSFETs	These MOSFETs are arranged in two active bridges connected back to back
Input/output capacitors	These capacitors filter the DC voltage in the input and the output of the DAB
L_{ac}	This inductance is composed of a discrete inductor and the leakage inductance of the transformer
4 Gate drivers	Each one responsible for driving 2 MOSFETs in a leg forming a switching cell,
2 dual inverter buffers	Responsible for generating a complementary logic signal to drive the two legs of a full bridge with one single signal
2 Optocouplers	Used to isolate the control neutral point from each CSC neutral point.
2 Linear regulators	One on each side of the DAB converter to supply the adequate voltage to each electronic component.
Auxiliary passive components	Filtering capacitors, bootstrap capacitors and bootstrap diodes.

Table 5.2.- Components present in the CSC GM20V5A, Annex II [44]

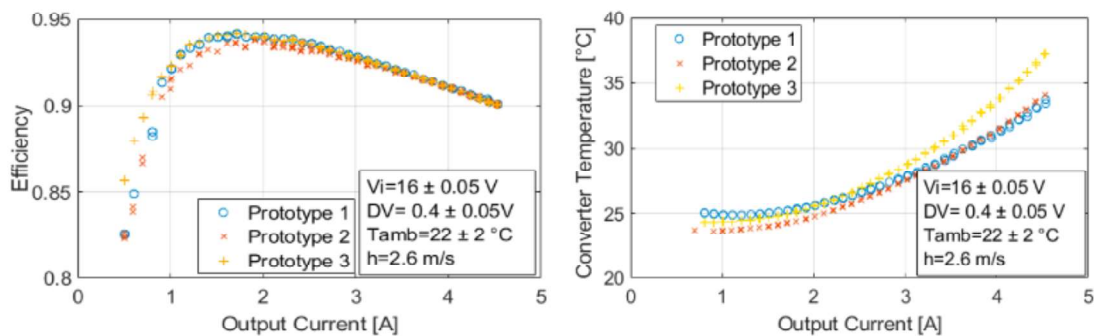


Figure 5.4-Output current versus efficiency (left) and versus converter temperature (right) for three prototypes of the CSC GM20V5A, Annex II [44]

Altium and manufacturing files

As a second step, the original Altium files in which André Andreta based his PhD research [44] were retrieved. From these, the author of this document generated schematic PDFs and Gerber files for both the CSC GM20V5A converter and its microcontroller-based control board. Representative examples are presented in Figure 5.5 and Figure 5.6, while the complete



documentation is included in Annex III. This annex also provides the conclusions of the analysis, with further details on component functions and interconnections.

In the DPP structure these files correspond to *Electrical parameters and constraints*, concerning specifically the *Electrical layout*.

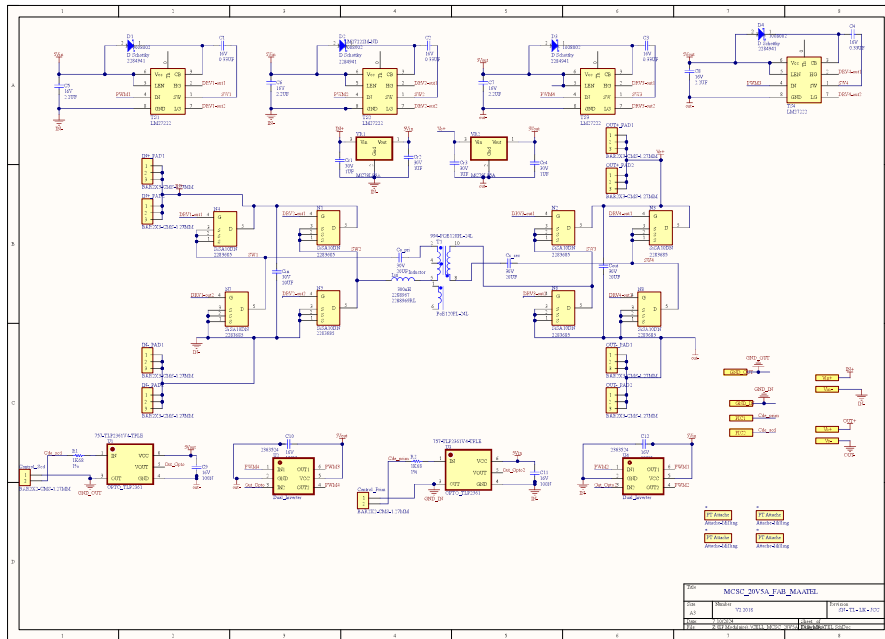


Figure 5.5- Altium Schematics of the CSC GM20V5A

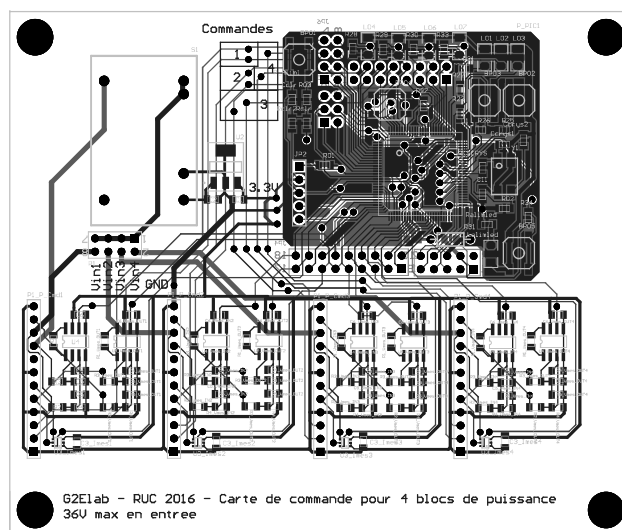


Figure 5.6- Altium Schematics of the Control board of the Microprocessor



BOMs and Datasheet gathering

Once the Altium files were analyzed, the Bill Of Materials (BOM) of the CSC GM20V5A (Table 5.3) and the Control Board were generated by the author, associating the components codes to its reference, footprint and other designators. Further, a direct identification of each Datasheet of the components was carried out (found in Annex IV), with the purpose of identifying all the available information and characteristics of the components.

In the DPP this belongs to the **Manufacturing** category, concerning the **BOMs** as well as **Suppliers of components**.

Comment	Description	Designator	Footprint	LibRef	Quantity	Data Sheet
0.33uF 16V		C1, C2, C3, C4	CAPC1608X09N-0603	CC0U33-16V-0603-X5R-10%	4	Kemet
1uF 30V		Cr1, Cr2, Cr3, Cr4	CAPC1608X09N-0603	CC1U-30V-0603-X7R-20%	4	Kgm -series
2uF 16V		C5, C6, C7, C8	CAPC1608X09N-0603	CC2U2-16V-0603-X5R-10%	4	kgm x5r series
20uF 20V		Cs_pri, Cs_sec	CAPC3216X16N-1206	CC20U-30V-1206-X7R-20%	2	kgm series
20uF 30V		Cin, Cout	CAPC3216X16N-1206	CC20U-30V-1206-X7R-20%	2	kgm series
100nF 16V		C9, C10, C11, C12	CAPC1608X09N-0603	CC100N-16V-0603-X7R-20%	4	kgm series
Attache-Milling			Attache_Milling	Attache-Milling	4	
BAR2X2-CMS-1.27MM		Control_Prim, Control_Scd	BAR1X2-1.27mm- SAMTEC-OK	BAR2X2-CMS-1.27MM	2	Samtec-Low Profile Dual Wipe Socket
BAR2X3-CMS-1.27MM		IN-_PAD1, IN-_PAD2, IN+_PAD1, IN+_PAD2, OUT-_PAD1, OUT- _PAD2, OUT+_PAD1, OUT+_PAD2	BAR1X3-1.27mm- SAMTEC	BAR2X3-CMS-1.27MM	8	Samtec-Low Profile Dual Wipe Socket
D Schottky	Schottky Diode	D1, D2, D3, D4	SMini2-F5-B SMD Zener Diode	D Schottky	4	Panasonic-D2Z1075
Dual_Inverter	Dual Inverter NC7WZ04	U2, U4	SOT65P210X110-6N	Dual_Inverter	2	Onsemi-NC7WZ04P6X
Inductor	Inductor	Lin	Coilcraft - XEL4030	Inductor	1	Coilcraft-xel4030
LM27222	Gate Driver LM27222	TS1, TS2, TS3, TS4	SOIC8_N	LM27222	4	Texas-Im27222
MC78L05A	IC, LDO, 5V, 100MA, SOT-89	VR1, VR2	SOT89-150P360X170- 3N	MC78L05A	2	Onsemi-MC78L00A_D-2315651
OPTO_TLP2361	Optocoupleur Toshiba	U1, U3	11-4L15 - TLP2361	OPTO_TLP2361	2	Toshiba-TLP2361
PoE120PL-24L	Transformer-CoilCraft, PoE120PL-24L	T1	PoE120PL-24L-TL	T-CoilCraft	1	Coilcraft-poe120pl
R1K68-1%-0603		R1, R2	RES01608X05N-0603	R1K68-1%-0603	2	Yageo Resistors
SISA10DN	MOSFET Canal N, 30V	N1, N2, N3, N4, N5, N6, N7, N8	1212-8 PowerPAK	NMOS_Gery	8	Vishay-sisa10dn

Table 5.3.- BOM of the CSC GM20V5A

The process included localizing fifteen datasheets for the GM20V5A and twenty-seven for the Control Board. As in some cases the references from the BOM were not precise enough, it was decided to associate a colour code depending on the reliability of the attached datasheet. The specific components that were correctly identified were highlighted in “green”; but in those



cases, in which the values were standardized and the reference was general, the identified datasheets were associated a “yellow” category. It was the case of components largely produced (such as capacitors or resistors), that were associated to just general standard values. Finally, there were some components whose reference was too vague, so a possible datasheet was associated but in a “red” category. For example, according to the Altium file, the headers were female type or pin sockets, but manufacturer specifications would be required for correctly identifying the specific models.

LTSpice simulations

The main topology of the module is a Dual Active Bridge (DAB) circuit, which was also reproduced in LTSpice (the electric layout depicted in Figure 5.7). Annex VI includes the technical decisions for the chosen impedances or transistors, as well as the working procedure and the outcomes.

In the DPP the corresponding category is *Data and operation points*, particularly *Theoretical simulations: LTSpice*.

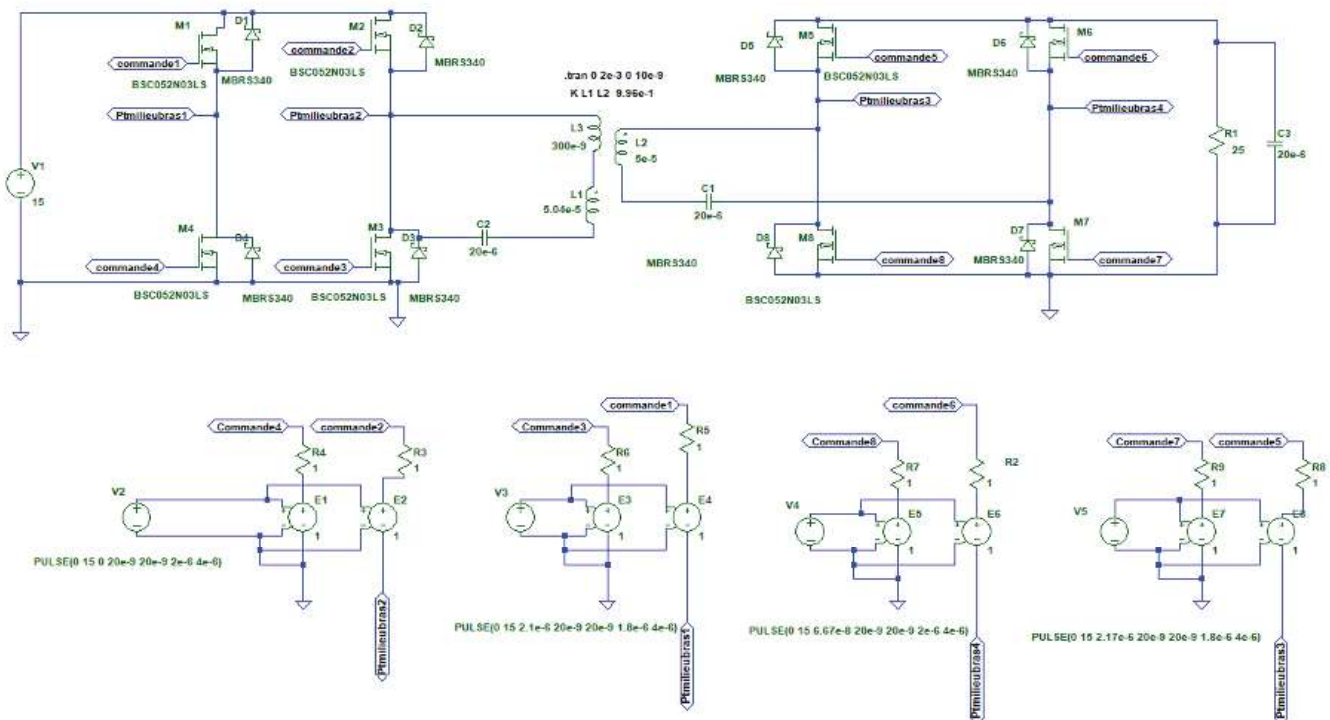


Figure 5.7-LTSpice DAB electric layout



From the simulations, the transistors switching and the input current at the inductance L3 were generated. The objective was to study the internal behaviour of the converter with the switching and different phase shifts, as well as the current that would get in the transformer through the inductance. However, the model would still need to be completed in the future, as some of the outputs do not still match the expected waveforms.

Experimental measurements

To complement the LTSpice simulations, real measurements were carried out by the author from a physical prototype of the CSC GM20V5A at G2Elab. This effort contributes to improving the understanding of the converter's behavior under practical conditions. The results belong to the DPP category of *Data and operation points*, particularly to *Real measurements: Oscilloscope*.

The main objectives were to observe the general operation of the converter, analyse transistor switching behaviour, and measure input/output voltages at the transformer. Special focus was placed on identifying hard and soft switching patterns, allowing comparison with the simulated waveforms. Figure 5.8 and Figure 5.9 show part of the procedure as well as an example of the results.

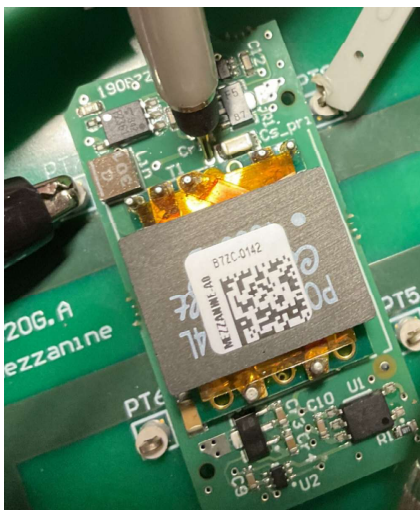


Figure 5.8- MCSC20V-5A top view for Vds N7 measurement

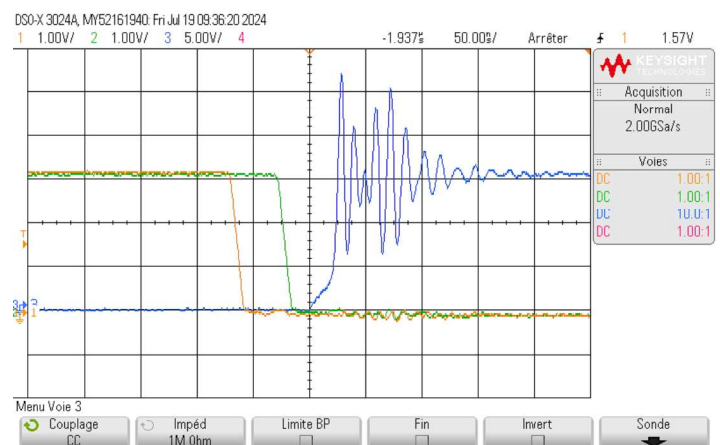


Figure 5.9- Transistors commutation for a phase shift of 3,4°: hard switching

For the transformer measurements, the output voltage and current were adjusted for specific values, varying the phase shift and the resistor at a constant input voltage.



Further, with a thermal camera, thermal pictures were also provided, depicting the increase of temperature in the CSC as the current increases (Figure 5.10). All measurement procedures, required equipment, results, and supporting images are detailed in Annex VII.

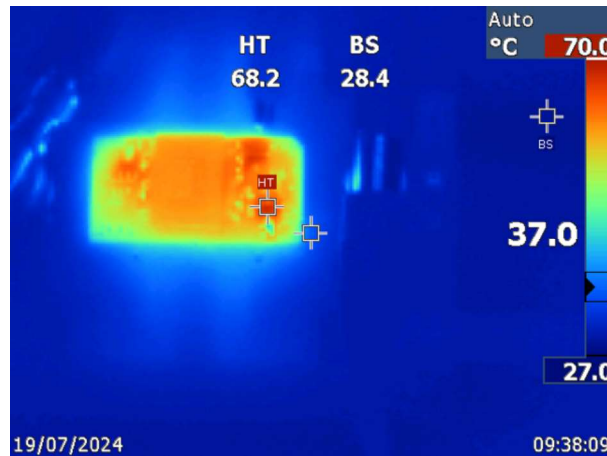


Figure 5.10-Example of one of the thermal camera pictures

Data Curation – Characterisation Tool in Excel

To enrich the *Data and Operation Points* section of the DPP—specifically the *Data Curation* field—the author contacted CSC GM20V5A experts to gather additional operational insights. André Andreta [PhD] shared a comprehensive Excel file developed during his PhD at G2ELab-MAATEL, documenting the converter's characterization across various configurations and operating ranges.

Then, this project included processing and structuring this raw data, categorizing over 2400 test cases into two main sheets: one detailing multiple converter associations and another focused on a single CSC unit (see Annex V and Figure 5.11 for the categories selected). Although experimental conditions may vary, the Characterisation Tool offers high added value for the DPP. Not only illustrating how different modular configurations affect performance, but also serving as a practical and structured reference for understanding the converter's operational behaviour. By making this data more transparent, reusable, and methodologically framed, it significantly strengthens the DPP's role as a centralised, accessible knowledge database.



5.4.- Critique and conclusion of the study case

The CSC GM20V5A has served as a representative example to apply and test the Digital Product Passport structure in Power Electronics. Through the classification and generation of technical content, this case study demonstrates how the proposed DPP categories can be completed. Additionally, this study case is particularly interesting as illustrates the characteristics of a modular approach, a key design regarding circularity.

Despite this, significant limitations remain—particularly in terms of missing or incomplete data. For that, Annex II includes a colour code to indicate the accessibility of the information, underlining the challenge of obtaining comprehensive technical data. Although the theoretical and technical analysis allowed useful information to be located, there are still several categories of the DPP in which information is neither localised nor generated.

One key gap is the absence of a Life Cycle Assessment (LCA) specific to the CSC GM20V5A. While the analysis improves knowledge of the converter's behaviour and provides insights into its structure, it does not quantify its environmental impacts. Without such data, the sustainability potential of modularity cannot be fully validated. This highlights the broader challenge of accessing comprehensive information in Power Electronics and the need to incorporate LCA metrics early in product development.

Nevertheless, the case does include valuable data on repairability, which is increasingly recognized as an important dimension of sustainable design [8],[48]. In particular, the work of Simon Chabanne [48] was added to this DPP, as provides a detailed methodology for assessing and guiding repair of the converter. Figure 5.12 shows a repair guidance tool that evaluates components based on reliability, accessibility, soldering type, materials, and cost, yielding a disassembly difficulty score.

In summary, this study reinforces the need to structure and centralize data from the early stages of development, outlining three keyways:

- It illustrates how the DPP structure can be concretely applied in Power Electronics.
- It identifies current information gaps—especially the lack of LCA—while showing that repairability data is also available and valuable.
- It underscores the benefits of modular design, not only for flexibility and customization but also for making maintenance and upgrading more accessible.



Comment	Description	Designator	Footprint	LibRef	Quantity	Ref	Datasheet	MTBF ou MTTF (hours)	Prix (pour 1000)	Nomb re de pattes	Type de soudure	Taille des pins	Accessibilit é physique (entre 1 et 0 > 0 sans rien)	Materiel nécessaire au déssou dage (texte)	Materiel nécessaire au déssou dage (note)	Durée de déssou dage air pince chaud	Déssou dage pince	Note de difficulté de déassemblage des composants
Con*	connecteur on T 5 contacts 1,27mm de pitch	M_A, M_B, M_C, M_D, M_E, M_G2_A, M_G2_B, M_G2_C, M_G2_D	PCBComponent_1	M50-3630642	8	M50-3630642	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,281	0,65	5	Stone CMS on op	0,65	0,3	impossible à déssou dater sans endommager irrevérables	5	impossible sans endommager	x	5,34
CC1U-30V-0603-XTR-20%		CC_G11, CC_G12, CC_G11, CC_G12, CC_G11, CC_G12, CC_G11, CC_G12, CC_G11, CC_G12, CC_G11, CC_G12	CAPC608X09M-0603	CC1U-30V-0603-XTR-20%	14	CL04A03KX38MUMC	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,011	0,3	3	CMS classique	0,3	0,7	pince à déssou dater	3	00:10	00:05	3,15
CC20U-30V-1206-XTR-20%		CC_H11, CC_H12, CC_H11, CC_H12	CapacitorAC	CC20U-30V-1206-XTR-20%	8	FA6PCTR1M06K250A	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,391	0,6	3	CMS classique	0,6	1	pince à déssou dater	3	01:30	00:10	3,14
4x4x1-CC20U-30V-1206-XTR-20%		CCP_H11, CCP_H12, CCP_H11, CCP_H12	CapacitorAC	4x4x1-CC20U-30V-1206-XTR-20%	8	FA6PCTR1M06K250A	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,391	1,2	3	CMS classique	1,2	0,5	pince à déssou dater	3	00:26	00:05	3,13
LDO SV Richtek RT3068	LDO SV Richtek RT3068 LDC5V Richtek RT3068; RT3065-33ZFP	LDO_V1, LDC_V2	SOIC1PFS3X175-3N	VoltageReg5V	2	RT3068GSP	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	1,411	0,3	4	Petit DIP	0,3	0,7	déssou dage à l'air chaud	4	00:30	x	4,45
CC220N-60V-1206		CC_M_V1, CC_V2, COM_A, COM_B, COM_A, COM_B	CAPC3216X16N-1206	CC220N-60V-1206	6	CTB06C224MRECT21	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,071	0,6	3	CMS classique	0,6	1	pince à déssou dater	3	00:24	00:05	3,14
T-CoilCraft		T1	POE120PL-24L-TL	T-CoilCraft	1	POE120PL-24L	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	14,101	2,03	4	CMS complexe	2,03	0,5	déssou dage à l'air chaud	4	00:30	x	4,37
3SA100N		NA_H1, NL_H2, NL_H1, ML_H2, NL_H1, ML_H2, NL_H1, NL_H2	1216-8 PowerPAK	MMOS_Gery	8	S1S862ADM-T1-GE3	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,451	0,25	4	sorte de petit DIP	0,25	0,7	déssou dage à l'air chaud	4	00:23	00:30	4,45
Inducteur XGL4040	Inducteur coilcraft XGL4020 300mH	LJ_H1, LL_H2, LJ_H1, LL_H2	Coilcraft - XGL4040	Inducteur XGL4040	4	XGL4040-41MEC	https://www.coilcraft.com/magnetics/218351b2-421-4-43-a232-080b8717d4262a9d040.pdf	0,651	3,4	3	MS pad on dazoo	3,4	0,7	pince à déssou dater	3	01:18	00:15	3,10
RIK1R-0603		RDT_G1, RDT_G2, RDT_G1, RDT_G2, RFB_V2, RHL_V1	REC608X05M-0603	RIK1R-0603	8	CECCV0503K1DFKEE	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,011	0,8	3	CMS classique	0,8	0,7	pince à déssou dater	3	00:15	00:05	3,14
UCC21520ADV	UCC21520ADV	U_G1, UL_G1, U_G1, UL_G1	SOIC1P1030X26-5-16N	UCC21520ADV	4	UCC21520ADV	https://www.ti.com/lit/ds/zh/tidz022	5,161	0,3	4	Grand DIP	0,3	0,7	déssou dage à l'air chaud	4	00:30	x	4,85
D Schottky 60V	Diode Schottky Mxpeps 60V 200mA	D_G1, D_G2, D_G1, D_G2	SOD-323FL SMD Diode Panasonic	D Schottky 60V	4	PMEG6002EJ	https://www.mouser.fr/ds/2/131/050-3632-1103536.pdf	0,091	0,032	3	CMS type diode	0,032	0,7	pince à déssou dater	3	00:23	00:08	3,15

Figure 5.12-Reparation criteria applied on the components of the CSC GM20V5A, resulting on a disassembly score based on criteria such as reliability, accessibility or soldering characteristics [48].



Annexes provide additional technical data, repair tools, and classification tables to support this analysis. Looking forward, future work should prioritize integrating LCA data with modular architectures to move beyond theoretical assumptions and toward evidence-based sustainability in Power Electronics.

5.5.- Insights and perspectives from Expert Interviews

To support the data collection process, three interviews were conducted with researchers who developed their PhD theses on the CSC GM20V5A: André Andreta [44], Glauber De Freitas Lima [49] and Hugot Pichon [50]. The objective of these interviews was to gather technical insights relevant to the DPP, as well as to better understand the converter's operation and the potential challenges future users might face. While the responses were primarily qualitative rather than quantitative, they led to shared reflections that underline the importance of accessible, well-structured information as a foundation for sustainability and the implementation of tools like the DPP.

The importance of modularity, repairability, and standardization emerged as central themes across the interviews. The researchers highlighted the technical and practical trade-offs inherent in Power Electronics design, especially in balancing performance with long-term maintainability. Failures in components such as gate drivers or PCAs often led to time-consuming diagnostics and redesigns, particularly when working with highly integrated or miniaturized parts. Decisions about connectors and sourcing strategies further illustrated the tension between practical assembly, robustness, and supply chain constraints.

These challenges illustrate the broader need for structured and accessible documentation throughout the design process. Much of the technical knowledge developed during prototyping remains unwritten, scattered across informal channels such as lab notes, internal conversations, or online tutorials. As a result, expertise is often acquired through hands-on experience rather than through centralized or curated resources. In this context, a framework like the Digital Product Passport could provide a practical means of capturing design logic, facilitating collaboration, and ensuring that knowledge is traceable and reusable across successive projects and users.

The interviewees also emphasized the need to democratize technical knowledge. All three researchers advocated for developing multiple modes of communication—from rigorous



technical documentation aimed at specialists to more educational formats like books and video tutorials. Open-source initiatives were seen as promising models for collective knowledge sharing, as long as they were supported by adequate organizational structures that could coordinate contributions, ensure continuity, and recognize the value of collective work. The DPP, if implemented with these aspects in mind, could serve as a unifying tool to bridge these different layers of communication and access.



6. Conclusions

The Earth is currently facing an environmental planetary crisis reaching a non-return point, with climate change, loss of biodiversity and pollution representing some of the biggest threats to humanity. International commitment focuses on climate change mitigation, aiming to achieve a Net-zero system cutting down carbon emissions. For that, decarbonization strategies focus on transitioning from fossil fuels to renewable energy, increasing electrification, and improving energy efficiency. In this context, Power Electronic Converters play a major role, being the backbone of all electrified systems—from electric mobility and renewable energy to industrial automation.

However, while PECs support climate change mitigation, their environmental impact extends beyond carbon emissions. The drive for electrification, if not critically assessed, risks increasing the volume of e-waste, intensifying raw material extraction, and impacting other planetary boundaries such as land-system change, biosphere integrity, and chemical pollution.

Therefore, the environmental impact of PECs must be addressed holistically—not just from a climate perspective, but across the full spectrum of environmental challenges. This requires considering the framework delimited by the Planetary Boundaries Theory to avoid catastrophic consequences on Earth.

The objective of this project was to explore how to integrate “Sustainability” into technology and Power Electronics—through strategies such as **circular economy**, **Life Cycle Assessment** and **eco-design**. These three inputs were analyzed through both theoretical study and applied case studies, offering a multi-faceted perspective on their benefits and limitations.

- **Circular economy** serves as the guiding framework for sustainable resource use, emphasizing strategies such as reuse, repair, remanufacturing, recycling, and extending product life cycles. However, the implementation of circular strategies in Power Electronics is challenged by system complexity and limited access to consistent technical and environmental data across the value chain.
- **Eco-design** reinforces the importance of the design phase in determining environmental impacts. It is estimated that up to 80% of a product’s environmental impacts can be determined at the design stage. This underscores the need to embed sustainability



considerations early in the product life cycle. However, to effectively guide eco-design decisions, there is a need of reliable methods to accurately evaluate environmental impacts. Regarding the application of eco-design through eco-optimisation, the lack of accessible, detailed environmental data and the oversimplification of environmental modelling are among the major obstacles identified.

- **Life Cycle Assessment (LCA)** is a key methodology that allows for the quantification of environmental impacts from raw material extraction to the product's final disposal. The case studies presented here confirm that the use phase—particularly energy consumption—often dominates the impact profile and is highly dependent on the electricity mix. In contrast, the manufacturing phase reveals greater potential for design intervention. Despite its robustness, traditional LCA is a post-evaluation tool and often fails to integrate circular economy principles such as reuse or remanufacturing. Its linear structure and dependence on comprehensive data also limit its usefulness in early design stages.

Having identified key limitations—such as system complexity, restricted access to information, and the lack of environmental data specific to Power Electronics—three strategies were analyzed to enable a more holistic approach, each addressing specific challenges.

The **LCA** case study demonstrated the potential of the methodology, but also highlighted difficulties in interpreting results and the absence of a circular life cycle model with indicators tailored to Power Electronics. To overcome these issues, the **Parametric Life Cycle Assessment (PLCA)** meta-model tailored to Power Electronics was analyzed and tested. The PLCA approach supported iterative design by simulating the environmental impacts of design choices through parametric modeling in Python. This method allowed designers to measure the effect of proposed modifications, making it suitable for early-stage eco-design.

In this project, the application of the PLCA model was constrained by licensing limitations, revealing that despite its advantages, the tool is not fully accessible. For the Boost converter, a structured design strategy would be required to identify key design parameters. Nevertheless, environmental impact results at the early design stage were obtained, while the Buck converter case study served as an illustrative example of the whole methodology.

Rather than focusing on specific numerical results—which are highly dependent on each case study—emphasis should be placed on how PLCA methodology enables a structured evaluation



of environmental impacts. However, it is important to note that their accuracy is limited by the quality of the input data (i.e. component inventories and environmental information). This highlights a long-standing issue in environmental assessment: the limited availability and reliability of environmental data at the component level.

To address this recurring issue of data availability and to support the integration of circular economy decisions, the concept of the **Digital Product Passport (DPP)** was introduced and applied to the CSC GM20V5A converter. As a proposition of the EU Circular Economy Action Plan, the DPP is proposed for PE as a tool to enable transparency, traceability, and circularity throughout a product's life cycle. However, its success depends again on overcoming three data challenges: perceived importance of the data, data availability, and data sensitivity. A shared and standardized understanding of what data is critical, accessible, and non-confidential will be essential for operationalizing DPPs in industry.

The DPP case study—based on the CSC GM20V5A modular converter—highlighted key technical characteristics of modular applications in Power Electronics. Modularity shows clear potential, enabling product repair, reuse, and component-level upgrades—core principles of the circular economy. However, the case revealed limitations due to some missing information, particularly regarding environmental impacts. Although reports on repairability were available, the absence of supporting LCAs means that the reduction in environmental impact has not yet been fully quantified. This analysis underscores the broader challenge of accessing comprehensive information in Power Electronics—not only technical data but also environmental metrics—both of which are essential to evaluate and enhance circular economy advantages.

Nevertheless, when considered together in an iterative process, the three strategies—LCA, PLCA, and DPP—complement each other and help overcome individual limitations, Figure 6.1. The limitations of conventional LCA are addressed by the PLCA approach. In turn, the PLCA and LCA methodologies rely heavily on access to reliable and structured data—an area where the DPP plays a key role.

The Digital Product Passport can serve as a dynamic repository of technical data, which provides accessible, high-quality inventories for LCAs and PLCAs. Starting from reliable



component-level data, both methodologies generate environmental metrics that can be reintegrated into the DPP, enriching it further.

Thanks to its digital and updatable nature, the DPP should support continuous integration of new data, while the iterative modeling capabilities of PLCA would allow for ongoing design improvements.

Together, these three strategies—DPP, LCA, and PLCA—form a complementary cycle of data collection, evaluation, and refinement. As environmental impact estimates become more precise, eco-design decisions can be better informed, ultimately contributing to reduced environmental burdens. Overall, the focus should remain on ensuring the quality and accessibility of data, as these elements are key to the effectiveness and synergy of the methodologies.

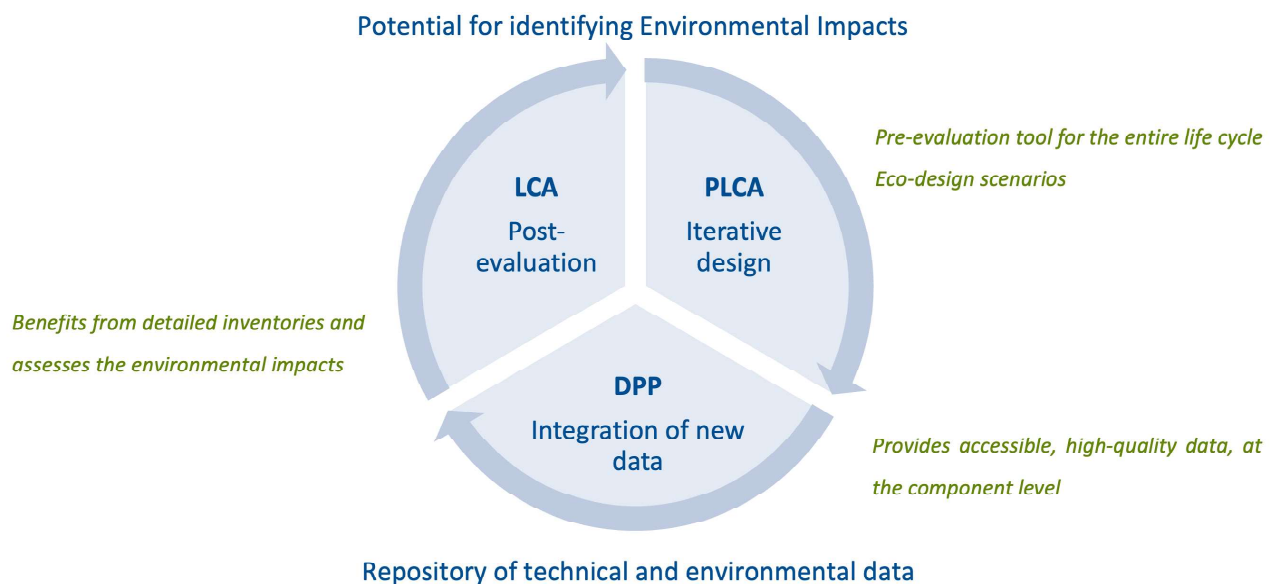


Figure 6.1-Complementary cycle of data collection, evaluation and refinement

Building on the initial objectives and after assessing the effectiveness and limitations of the identified strategies, the question arises as to whether sustainability in Power Electronics still lacks essential aspects. From this analysis, several final conclusions can be drawn:

- **A systemic shift is needed to ensure the sustainability of Power Electronic Converters (PECs).**

Tackling the environmental crisis requires rethinking technological development within a Circular Economy framework, aligned within the Planetary Boundaries theory. This



means assessing PECs across their entire life cycle using multiple indicators—not just carbon emissions. It is essential to adopt a circular approach and to fully understand how circular economy strategies can reduce environmental burdens across different system levels.

- **Eco-design is a key intervention point.**

Integrating sustainability from the early design stages—through tools like PLCA and eco-optimisation—is essential, as most environmental impacts are determined at this phase. Understanding that these impacts can be quantified and mitigated allows for informed design choices, helping to verify real benefits and avoid potential burden shifting.

- **Existing methodologies are evolving but are already essential.**

While LCA and PLCA each have limitations, they remain among the best tools currently available to quantify and mitigate environmental impacts. At the same time, the specific environmental results of each case study depend on the converter's function and context. Rather than focusing on the specific numerical results, the value lies in the methodologies' ability to identify critical impacts.

- **Technical and environmental data is indispensable.**

The environmental assessment of PECs is hindered by a lack of high-quality, standardized data. The focus should remain on obtaining detailed environmental information and developing standardised data reporting protocols, through the combination of DPPs and LCAs.

In conclusion, while challenges remain, this project shows that a more sustainable approach to Power Electronics is both necessary and achievable. By embracing circular economy principles, advancing design-stage methodologies like PLCA, and improving data transparency through tools like the DPP, the field can align more closely with the needs of the environment—and contribute meaningfully to a just and sustainable energy transition.



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