30 Sept. & 1 Oct. 2025

Graz, Austria

Submission to the Call for Presentations and Posters

Corresponding topic (please tick)	☐ Power Electronics in Automotive & Charging Applications ☐ Power Electronics in Medium Voltage Applications ☐ DC Industry ☒ Sustainability & Circular Economy in Power Electronics
Proposed presentation title (you can indicate a preference for oral or poster presentation in the submission form)	Sustainability of Power Electronics: A Material-Centric and Life Cycle Assessment Approach
Authors (please highlight corresponding author / speaker)	**Daiyi Hu**, Regine Mallwitz, Paula Burfeind, Christine Minke

1. Introduction

The rapid expansion of electrified mobility has positioned power electronic systems at the heart of modern transportation technology. Driven by stringent emissions regulations, advances in battery energy density, and growing consumer environmental awareness, electric vehicles are being adopted at an unprecedented pace. This evolution not only cuts greenhouse-gas emissions and urban air pollution but also enables the broader integration of renewable energy into the transport sector. In these vehicles, onboard chargers (OBCs) and traction inverters play a critical role in determining drivetrain efficiency and overall energy performance. Yet their widespread deployment also intensifies concerns over resource depletion, lifecycle emissions, and end-of-life waste management. To address these challenges, it is imperative to incorporate life-cycle environmental impact assessments into the early design stages of automotive power electronics.

Life Cycle Assessment (LCA), as standardized by ISO 14040/14044, provides a systematic and robust methodology for quantifying a product's environmental impacts across its entire life cycle — from raw material extraction and manufacturing through use to final disposal. Accurate LCA depends on detailed material analysis and a comprehensive database of environmental indicators to capture energy consumption, greenhouse gas emissions, and recyclability potential. By applying this framework, engineers can derive key performance indicators —including global warming potential, water consumption, and resource efficiency — and compare them across both conventional and innovative design alternatives.

Materials selection fundamentally determines the environmental and economic performance of power electronic systems. From energy-intensive semiconductor substrates to critical metals with geopolitical supply risks, the composition and sourcing of materials directly influence the environmental and economic viability of the entire system. Consequently, sustainability-oriented material analysis and recycling strategies are essential tools for engineers and designers seeking to minimize environmental impacts and promote circularity.

This presentation delivers a structured, in‑depth examination of material sustainability in automotive power electronics, focusing exclusively on on-board chargers (OBCs) and traction inverters. Drawing on the material analyses, the presentation examines key environmental impact indicators, and design strategies to maximize resource efficiency and circularity. E-mobility is essential for decarbonizing the transportation sector. The study's results enable the identification of critical materials, the proposal of viable alternatives, and the promotion of circular economy principles within electric vehicle systems.

2. Material Analysis of Power Electronic Systems

2.1 On-Board Charger

OBCs convert grid AC to battery-compatible DC and involve multiple conversion stages, including power factor correction (PFC), isolation, and filtering. A detailed comparison between two OBCs highlights the material complexity and recyclability. Both OBCs have a nominal output power of up to 3.7 kW, which is common for a single-phase OBC. These are, on the one hand, a commercial device (referred to as Si-OBC) with primarily Silicon (Si) based power semiconductors. On the other hand, a research object (referred to as GaN-OBC) mainly uses gallium-nitride (GaN) power semiconductors.

The percentage mass distribution (Fig. 1) shows that construction accounts for approximately 80% of each OBC device. The mass of the "electronic section" is extremely low. Fig. 2 depicts the mass of the components of the "power section". It is no surprise that the magnets, such as PFC chokes and transformers, are the heaviest parts. Together with the DC-link capacitors, they make up almost the entire mass of this section. The GaN-OBC exhibits higher efficiency and power density, largely due to higher switching frequencies and reduced magnetic component sizes.

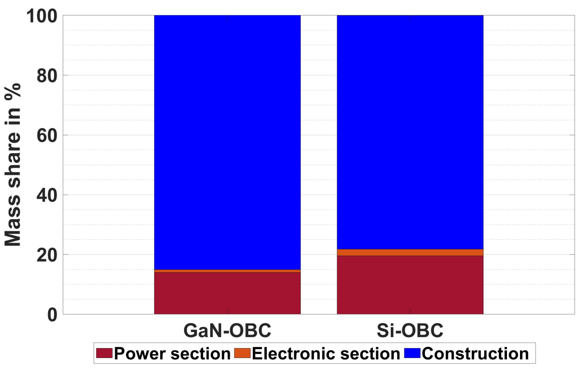

Fig. 1. Mass share of OBCs by section [1]

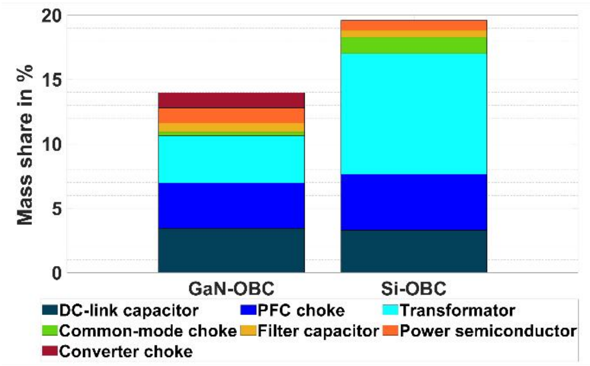

Fig. 2. Mass share by materials of OBCs' power section based on total mass [1]

Determining recycling potential requires knowing every material and its dimensions, a labor-intensive, small-scale effort when dissecting existing devices. For clarity in this presentation, materials have been grouped and summarized. Fig. 3 compares the mass breakdown of the analyzed GaN-OBC and Si-OBC into three categories:

- Metal: ca. 50 – 60 % of total mass, dominated by aluminum and copper alloys
- Polymers: ca.15 – 20 %, with silicones accounting for the largest share due to extensive potting
- Remaining: ca. 5 – 10 %, chiefly the magnetic cores

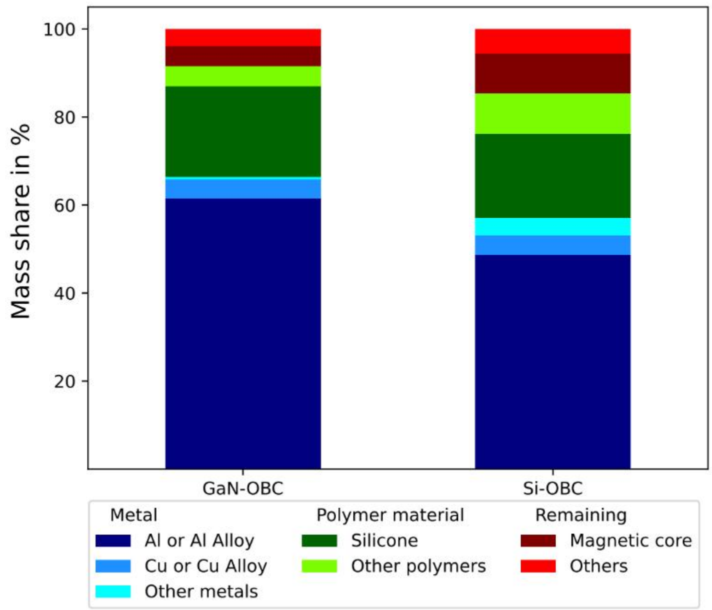

Fig. 3. Material distribution of OBCs [1]

2.2 Automotive Traction Inverter

Traction inverters, essential for electric vehicle propulsion, convert the DC power input to AC power output, controlling the electric motor. Based on [2], the composition of a general traction inverter can be classified as: Housing and heatsink; Power module; DC-link capacitor; Bus bars; Data processing, including ICs and PCBs; Others, including connectors, glands, uniting parts, and grease. The case study of an inverter, developed independently by the Institute for Electrical Machines, Traction, and Drives at TU Braunschweig. The analyzed inverter demonstrates a high level of integration, featuring aluminum housings with liquid cooling, and a B6 bridge configuration consisting of three half-bridge silicon carbide (SiC) power modules.

Fig. 4 focuses on the relationship between the mass distribution of components and of the materials of the analyzed inverter. The inner section of the pie chart illustrates the mass share of the six component categories. The legend on the right side of the pie chart shows the color coding for the six components represented. The outer part presents the mass fraction of materials used for the corresponding components depicted in the inner part. The legend on the left side of the pie chart provides the color coding for the various materials represented.

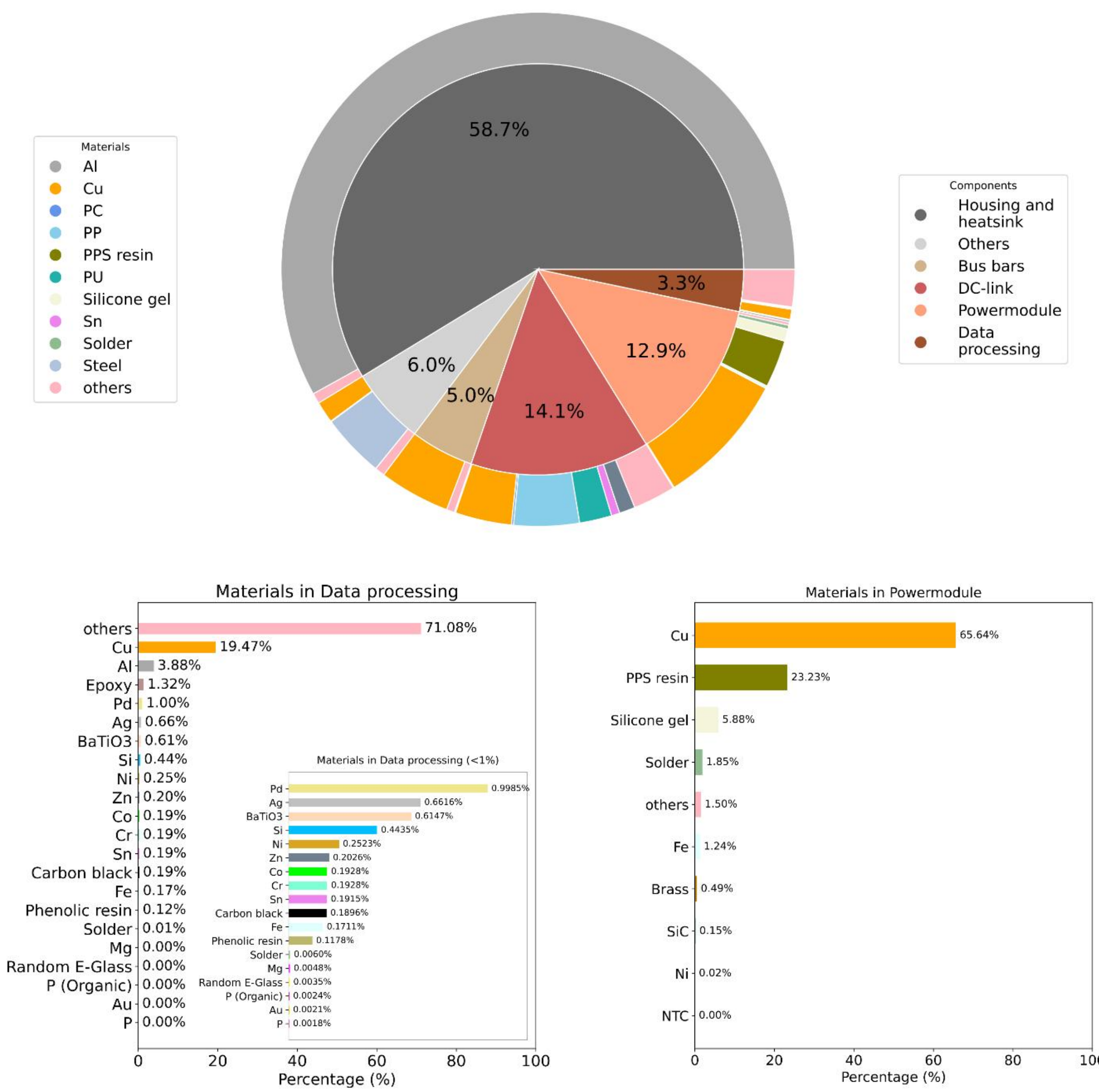

Fig. 4. Mass distribution by components (inner circle) and by materials (outer circle and bar diagrams) of the analyzed inverter [3, 4]

The "housing and heatsink" are primarily made of aluminum. Copper is the main construction material for the "bus bars." The component category "Others" encompasses relatively simple materials, primarily consisting of common metals and coatings. In the component categories "DC-Link", "Power module", and "Data processing", most materials contribute only a small proportion to the overall composition. The term "others" in the left legend accounts for materials with insignificantly low distributions and materials for which no data is available in the LCA database. This category primarily consists of polymers used in DC-link and a small subset categorized as proprietary materials, as specified in the material content data sheets of integrated circuits (ICs) used in Data processing.

In the DC link, a significant portion comprises plastics, such as polypropylene (PP) and polyurethane (PU), followed by copper. The components "Power module" and "Data processing" are represented separately. Copper is the primary material used in the power module for its conductivity and heat dissipation properties. Resin is used for insulation and protection against moisture and dust. Although silicon carbide (SiC) has a minimal weight percentage, it is a crucial semiconductor material. Data processing revealed a high level of complexity in the material's composition, despite its very low mass fraction, with nearly three-quarters of the material types being undefined.

3. Recycling Rates and Environmental Impacts

3.1 Recycling Performance of Power Electronics

To evaluate the circularity potential of power electronic systems, quantifiable recycling rates (RRs) serve as essential indicators. In the field of recycling, recycling rates are classified into two primary categories based on distinct perspectives within the product life cycle: the end-of-life recycling rate (EOL-RR) and the end-of-life recycling input rate (EOL-RIR) [5]. The EOL-RR measures the amount of material from discarded products that is successfully recycled. It focuses on the portion of collected waste that is functionally recycled. Functional recycling restores materials to their original quality, while non-functional recycling results in downcycling and loss of properties. On the other hand, EOL-RIR indicates the share of recycled material used in production compared to total material input. In the context of the present study, the focus lies on the EOL-RR, as it more directly relates to the recoverability of materials from power electronic components at the end of their operational life.

To ensure more accurate and representative assessments in future research, it is imperative to (1) obtain more granular life cycle inventory (LCI) data for electronic components, (2) include a broader range of non-metallic materials such as ceramics, potting compounds, and fiber-reinforced substrates, and (3) validate recovery assumptions with data from real-world disassembly and recycling processes, especially in the context of automated vs. manual treatment scenarios. Moreover, greater transparency in the supply chain and standardization of product data (e.g., through IMDS) will support higher fidelity in recycling rate estimations and environmental impact modeling.

3.2 Life Cycle Assessment: Framework and Relevance

Evaluating the environmental performance of power electronic systems requires a holistic, life-cycle-based approach. LCA provides a framework that enables the structured analysis of environmental impacts, from the initial extraction of raw materials through manufacturing, operational use, and end-of-life (EOL) treatment. It comprises four key stages:

(1) definition of the goal and scope, which sets the boundaries and objectives of the study;

(2) life cycle inventory (LCI), which involves the collection of data on material and energy inputs and emissions;

(3) life cycle impact assessment (LCIA), which quantifies the potential environmental impacts associated with the inputs and outputs;

and (4) interpretation, where the results are evaluated to support decision-making.

Together, these stages enable a comprehensive assessment of material flows, energy consumption, emissions, and resource depletion.

To address this, researchers have begun incorporating mass-based methods and component-level breakdowns into LCA practice. For example, the IMAB studies (2023PC18) provide a detailed disaggregation of traction inverter systems into functional groups—power section, electronic section, and construction section—followed by material-specific analysis linked to “Ecoinvent database” entries. This enables a more accurate attribution of environmental indicators such as carbon footprint, water use, and resource depletion at the subcomponent level. Similarly, the CIPS 2024 study applies a flow-based modeling approach to estimate recycling rates and environmental impact potentials, using actual measured data from dismantled OBC units.

These efforts reflect a shift toward more accurate and application-specific LCA models for power electronics. They also highlight the importance of integrating LCA with material analysis and recycling data to support eco-design and policy-making. However, challenges remain, particularly in acquiring high-resolution LCI data for embedded components (e.g., integrated circuits, capacitors), understanding the impacts of potting and composite materials, and modeling realistic EOL scenarios. Future work should also focus on enhancing access to databases, such as the International Material Data System (IMDS), and on validating assumptions through empirical studies of actual recycling processes. Only with such enhancements can LCA realize its full potential as a tool for advancing the sustainability of power electronic systems.

3.3 Environmental KPIs: Carbon, Water, and Resource Use

Building on the component-level material analysis presented in Section 2.2, environmental key performance indicators (KPIs), such as carbon footprint, water consumption, and resource depletion, were assessed for the IMAB inverter. Using Ecoinvent database entries for primary materials, the environmental burdens of each component group were estimated.

Figure 6 provides a comparative overview of mass share and environmental impact contributions (carbon footprint, water use, and resource depletion) for each inverter component group. It highlights that the environmental burdens are not directly proportional to component mass. Despite accounting for the most significant mass share, the housing and heatsink (primarily aluminum) did not dominate all impact categories. They contributed 47% of the carbon footprint and 65% of the water footprint, but only 16% of the resource depletion. In contrast, the data processing unit, although representing only 3% of the mass, accounted for 36% of the total carbon footprint and 46% of the resource depletion, primarily driven by the use of gold and other critical materials. Power modules and DC-link capacitors showed more balanced profiles, contributing proportionally across all indicators. These findings confirm that environmental impacts are not only mass-dependent but also tightly linked to material criticality and process intensity.

The environmental impact analysis assumes the use of primary materials and idealized recycling pathways. Future work should enhance these models by incorporating real-world recovery rates and secondary material flows. Further insight into the reduction potential of material substitution is provided in Figure 7. This figure illustrates the environmental benefits that can be achieved by replacing primary materials with their secondary (recycled) counterparts in the IMAB inverter. Specifically, switching aluminum and copper to their secondary equivalents results in reductions of over 90% in carbon footprint and water use, and more than 70% in resource depletion. These findings underscore the substantial sustainability gains that can be achieved through material loop closure.

Complementing this, Figure 8 compares the absolute environmental impacts of key raw materials in both their primary and secondary forms. The figure reveals that aluminum, copper, and zinc exhibit drastic reductions in environmental burdens—up to 99% in carbon and water footprints—when sourced as recycled materials. This comparative view underscores the importance of increasing recycled content in future product generations, particularly for metals with high environmental impact during primary extraction.

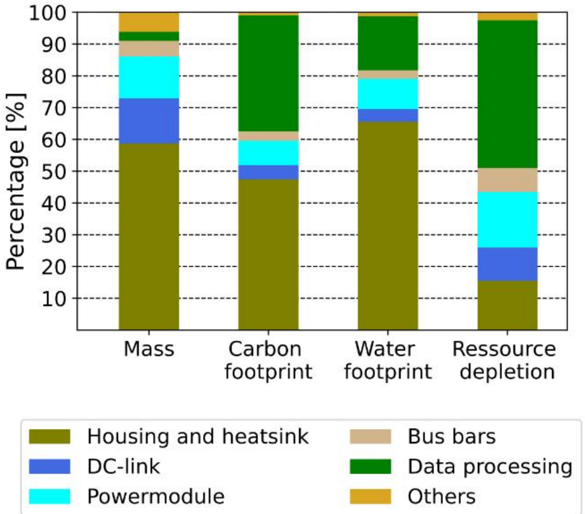

Fig. 6. Environmental impact for primary materials vs. mass share [Report ECPE 2023PC18]

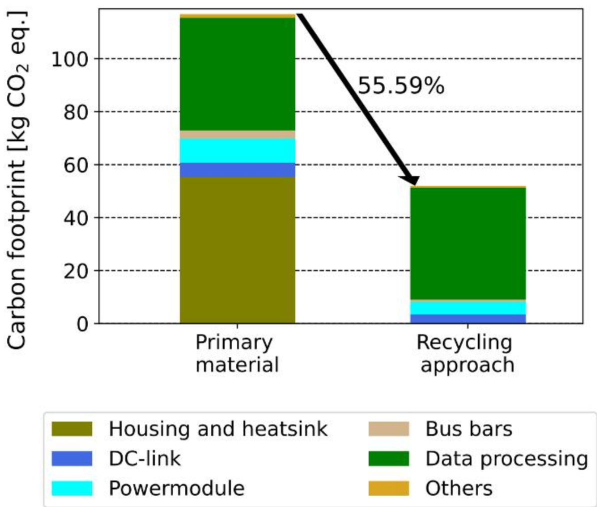

Fig. 7 Reduction potential of potential Carbon Footprint through the use of secondary raw materials [Report ECPE 2023PC18]

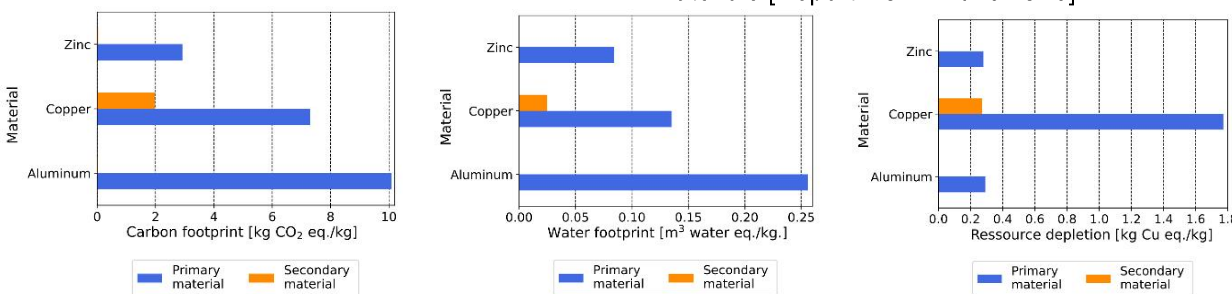

Fig. 8. Environmental gains of secondary materials [Report ECPE 2023PC18]

4. Discussion: Alternative Materials and Design Strategies

4.1 Material Alternatives

Sustainable power electronics design starts with informed material selection, especially for substrates, semiconductors, and packaging. Traditional FR4 PCBs are difficult to recycle due to their thermoset content. Alternatives, such as flexible and biodegradable PCBs, including PLA/flax composites, offer environmental benefits but face challenges in terms of thermal stability, mechanical strength, and dielectric performance. These limitations must be addressed before they can be reliably used in high-temperature or high-voltage applications. [3]

Additionally, vitrimer-based packaging presents another promising sustainable solution. Vitrimers combine the durability of thermosets with the reprocessability of thermoplastics through dynamic covalent bonds, enabling reshaping and recycling under heat. They also provide self-healing properties and strong mechanical performance. However, high processing viscosity, limited thermal stability, and a narrow reprocessing temperature range currently limit their industrial scalability and long-term reliability. Overcoming these challenges is crucial to unlocking their full potential as eco-friendly alternatives to conventional thermoset composites. [3]

4.2 Design for Sustainability

Beyond material selection, modular designs, standardized interfaces, and enhanced material transparency are essential strategies for promoting reuse, repair, and recycling in circular power electronics.
Early-stage design should consider disassembly, joining techniques, and the separation of materials with differing recyclability. Avoiding tightly integrated components and favoring accessible layouts increases recovery value and simplifies recycling.

Adopting circular economy principles—such as the R-strategies (Reduce, Reuse, Recycle, Refurbish)—requires coordination among designers, recyclers, and regulators. Only through such integration can power electronics deliver sustainability across their full life cycle, not just during the use phase.

5. Conclusion

This study examines the material sustainability of power electronic systems in electric vehicles through a detailed component analysis, assessment of recycling rates, and evaluation of environmental impacts. By comparing two OBCs and one automotive traction inverter, the work highlights the structural differences and critical material hotspots influencing recyclability and environmental performance.

The findings emphasize that mass alone does not determine environmental impact. Subcomponents, such as data processing, although small in mass, contribute disproportionately to carbon and resource burdens due to the high-impact materials they use. Recycling rates are generally high for metals like aluminum and copper, but significantly lower for precious metals embedded in complex assemblies. Life Cycle Assessment, when combined with detailed material analysis, offers a robust tool for identifying improvement opportunities across product life stages.

To advance sustainability in power electronics, future designs must adopt modular, demountable structures, integrate secondary material flows, and avoid the use of difficult-to-recycle composites. More accurate LCA modeling, supported by empirical recycling data and transparent material inventories, will be vital for guiding eco-design strategies and regulatory compliance.

By bridging design, material science, and circular economy principles, the study contributes to a deeper understanding of how next-generation power electronics can support the broader transition toward sustainable e-mobility.

6. Literature

[1] C. Minke, P. Burfeind, R. Mallwitz, D. Hu: Recycling potential of power electronics solutions – an exemplary study about on-board chargers. CIPS 2024; 13th International Conference on Integrated Power Electronics Systems, Düsseldorf, Germany, 2024, pp. 637-645.
[2] B. Baudais, H. Ben Ahmed, G. Jodin, N. Degrenne, S. Lefebvre: Life Cycle Assessment of a 150 kW Electronic Power Inverter. MDPI Energies 2023, 16, 2192
[3] D. Hu, R. Mallwitz, J. Hoffmann, M. Henke, P. Ohnesorge, N. Langmaack: Resource Requirements and Sustainability of Electric Drivetrains in Mobility Applications. ETG Kongress 2025; Kassel, Germany, Mai 2025, preliminary
[4] D. Hu, Y. Tian, P. Burfeind, R. Mallwitz, C. Minke: Method for Sustainable Analysis of a Traction Inverter Assuming Several Use Phases. ECCE Europe 2025; Energy Conversion Congress & Expo, Birmingham, United Kingdom, Sep. 2025, preliminary
[5] T. Graedel, J. Allwood, J. Birat, M. Buchert, C. Hagelüken, B. Reck, S. Sibley, G. Sonnemann: Recycling rates of metals: A status report. United Nations Environment Programme. 2011. ISBN: 978-92-807-3161-3
[6] D. Hu, P. Burfeind, R. Mallwitz, C. Minke: Sustainability Screening: materials, manufacturing and recycling of power electronics. ECPE project report; 2024

Contact details of corresponding author / speaker	Title	Sustainability of Power Electronics: A Material-Centric and Life Cycle Assessment Approach
	First name	Daiyi
	Last name	Hu
	Organisation	TU Braunschweig
	Department	Institute for Electrical Machines, Traction and Drives
	Position	Research Associate
	Address	Hans-Sommer-Straße 66 38106 Braunschweig Germany
	Email	d.hu@tu-braunschweig.de
	Phone	+49 0531 3913917
Short CV	Daiyi Hu received a master's degree in Electrical Engineering from Technische Universität Braunschweig in May 2024. Since June 2024, she is working as a Research Associate at the Institute for Electrical Machines, Traction and Drives. From 2019 to 2023, she has participated as a Student Research Associate, contributing to projects involving OBC design, power cycling tests, and reliability assessments of power electronics. Since March 2023, she has joined the sustainability of power electronics project. Currently, her primary focus is on power electronics technology, where she researches to enhance the sustainability of power electronics in various applications.	
Photo