Advanced high-temperature PEM fuel cells for heavy-duty applications: Performance, sustainability and life cycle assessment insights from the MEAsureD project

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ABSTRACT

The EU-funded Horizon 2020 project "MEAsureD" aims to enhance the performance and durability of high-temperature proton exchange membrane fuel cells (HT PEMFC) for heavyduty vehicle applications by integrating experimental research with advanced simulation-based modeling. One part of the project is to evaluate the environmental impact of existing FC technologies and explore how systems operating at higher temperatures can offer a cleaner and more sustainable alternative. To assess these benefits, a meta-study on FC sustainability, synthesizing literature on resource consumption, greenhouse gas emissions, recyclability, and circularity is performed. This study provides a quantitative evaluation of the current status of the environmental footprint of PEMFC systems. By consolidating data from previously conducted life cycle assessment (LCA) studies, the meta-study establishes benchmark values for key environmental indicators, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and abiotic depletion potential (ADP). These benchmarks together with the LCA on a reference HT PEMFC in the present study form the baseline for evaluating the sustainability advancements of Advent Technologies HT PEMFC systems during the MEAsureD project. The LCA results show high indicator

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values for GWP and EP, and low values for AP and ADP compared to the literature benchmarks. Impact reduction potentials which can be harnessed through reaching MEAsureD KPIs, including reduced platinum loading and increased power density, are found to be significant. Drawing on Advent Technologies expertise, the project will refine critical technical parameters to define a high-performance HT PEMFC that meets economic and environmental sustainability objectives. The project aims to deliver an improved system of up to TRL 4. Through these efforts, the MEAsureD project contributes to the broader adoption of FC technology, supporting its integration into sustainable mobility solutions and advancing clean energy innovations in transport.

1. INTRODUCTION

Fuel cells are a crucial technology for the decarbonisation of the transport sector (Ajanovic & Haas, 2021). They provide the opportunity for much higher gravimetric energy density than commercial EV batteries through the high energy density of compressed hydrogen (Lei, 2024). This makes them especially attractive for the heavy-duty vehicle (HDV) sector, where batteries are suboptimal due to their high weight and cost and there is sufficient room for large hydrogen tanks (Cunanan, et al., 2021). Multiple PEMFC systems are readily available on the market for a host of applications (Asif Jamil, 2022). Novel systems aim to improve on the useful lifespan, fuel compatibility and cost of these systems (Asif Jamil, 2022). The MEAsureD project aims to improve on these aspects in the context of high temperature HT PEMFC systems for the HDV sector by expanding on existing Advent Technologies' membrane electrode assembly (MEA) technology. The assessment of the environmental consequences of these novel products consists of three main steps. First, a literature review of relevant LCA studies is conducted. This review provides baseline values for environmental impact indicators that can serve as a benchmark for comparison for later assessments. In addition, valuable insights on various aspects of FC systems sustainability and circularity are gathered. Secondly, an LCA study on a current Advent Technologies HT PEMFC system is carried out. This assessment provides a reference point to show improvements along the development timeline of the MEAsureD project. Finally, an LCA study of the final product will be carried out to assess the impacts of the fully developed (TRL 4) system. The final LCA is not included in this paper as the project is still ongoing, but an outlook is provided and improvement potential of the current technology is discussed. During all stages of the assessment, crucial leverage points for impact reduction and improved circularity are identified.

2. METHODS

The LCA methodology applied in this study is based on the ISO 14040 (International Organization for Standardization, 2006) and ISO 14044 (International Organization for Standardization, 2006) norms, which establish a standardized framework for the systematic evaluation of the environmental impacts associated with products, services or firms. It comprises four interdependent phases that together ensure consistency and transparency throughout the assessment process. Additional guidance is taken from the ILCD handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and relevant documentations from the applied software and database.

2.1 GOAL AND SCOPE DEFINITION

The objective of the LCA is to quantify the environmental impacts associated with the production of a reference 1kW FC stack. The goal is to identify the main environmental hotspots related to the production of the system. The system boundaries include the production phase (raw material extraction, component manufacturing, stack assembly). The use phase and the end of life (EoL) are not included due to severe uncertainties and data constraints. The methodological framework adopted in this study enables consistent comparison with literature cases, while also supporting future scenario analyses based on MEAsureD KPIs and project objectives.

2.2 STACK SPECIFICATIONS AND DATA SOURCES

The bill of materials (BoM) for the reference HT PEMFC stack is set up based on literature, AVL expert interviews and data from Advent Technologies. The original structure of the BoM is based on Usai et al. (2020) and is adapted to represent typical material contents of a HT PEMFC system. Data for a 100W HT PEMFC system is provided by Advent Technologies and incorporated into the BoM. The system size is then scaled up to fit the chosen functional unit of 1kW FC power. Sublinear scaling is applied to specific components to reflect the requirements for some parts like housing materials, endplates and cooling fans. The specifications for the resulting stack are shown in Table 2.

Table 2: Stack Specifications

Stack Power [kW]	Stack Weight [kg]	Active Area [m²]	Pt loading [g]
1	31	0,765	1,64

The main differences compared to the original BoM from Usai et al. (2020) lies in the simplified air, water and heat management, the heavier housing and endplates, the higher platinum (Pt) load and the membrane and bipolar plate materials. The heavier housing and endplates are typical for HT PEMFC systems as they are designed for stationary application. The higher Pt load and different membrane materials are also typical for HT systems (Zucconi, et al., 2024). As many material and weight specifications as well as detailed process data and information on production locations is incomplete, the LCA model exhibits uncertainty.

2.3 LIFE CYCLE INVENTORY (LCI)

The inventory phase involves the quantification of inputs and outputs for each component. The LCI data for the PEMFC stack is based on primary and secondary data. As a proxy for data on the production processes and missing data on materials, the Ecoinvent 3.11 database is used as is common practice in recent LCA studies on FC-technologies (Gulotta et al., 2024).

2.4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The potential environmental impacts of the assessed system are quantified using the Environmental Footprint 3.1 (EF 3.1) method. This method allows a consistent and policy relevant assessment of environmental performance across 16 impact categories. In this study, emphasis is placed on the GWP indicator, expressed in kg of CO_2 equivalent emissions (kgCO_2eq.) as a key metric for climate related burdens (Sala et al., 2018). A sensitivity analysis is conducted for key parameters such as Pt loading to assess their influence on overall impact variability. Indicators for AP, ADP and EP are also evaluated.

This selection aligns with common practice of LCAs of PEMFCs and allows for direct comparison with literature benchmarks.

3. RESULTS

This section elaborates on the results of the meta-study and the LCA. The LCA results are compared to the previously determined benchmarks and crucial leverage points for impact reduction are discussed. An outlook regarding the future LCA of the novel system will be provided based on a sensitivity analysis conducted on the LCA model at hand and the MEAsureD KPIs and development objectives.

3.1 META-STUDY RESULTS

Quantitative data regarding the potential environmental impacts of FC systems was collected for four impact indicators: GWP, AP, EP and ADP. These indicators are evaluated separately for three parts of the FC life cycle: the production, the use phase and the EoL. Results regarding the production of FC systems are of the highest availability and were therefore focused upon.

The observed literature review showed an extensive amount of assessments regarding environmental implications of the production phase of FC systems. Figure 3 shows the distribution of observed GWP values for a selection of PEMFC systems.

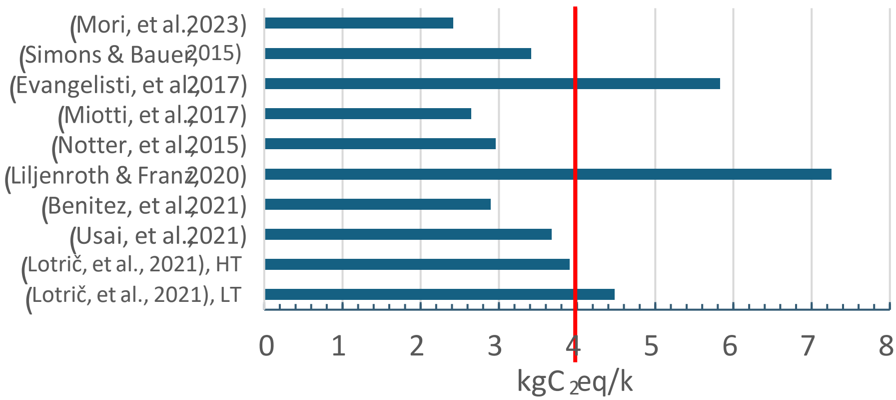

Figure 3: Distribution of the observed GWP values by source. The average of 40 $kgCO_2eq/kW$ is indicated by the vertical red line.

The observed indicator ranges for all assessed impact indicators are shown in Table 3. The shown results are a narrowed down selection of the observed study results. A few studies where omitted due to limited comparability of the analyzed systems (e.g. SOFC or stationary systems). Even though Lotrič et al. (2021) conduct an LCA on stationary systems, the results were deemed important for the objective of the literature review. This is due to the fact that a comparison of low and high temperature systems within one LCA study is conducted in the respective study, which enables a high degree of comparability between the two systems as methodological choices are homogenous.

Apart from the system and component assessment, the impacts and criticalities that are associated with the employed materials are also of interest. The analysis in Mori et al. (2023) shows that the Pt loading of the catalyst layer is responsible for most of the environmental burden across all impact indicators which is confirmed by many other studies. The assumed Pt loads in the screened studies differ quite substantially. Benitez et al. (2021) use 0.2 g/kW for the current scenario (0.06 g/kW for the future scenario) while Miotti et al. (2015) use 0.45 g/kW. Evangelisti et al. (2017) even use 0.925 g/kW. Other, less severe environmental hotspots in PEMFC materials are found in stainless and chromium steel as well as glass fiber reinforced plastic. Criticality assessments as in Gramc (2024) and Mori et al. (2023) point towards significant criticalities concerning a multitude of materials that are typically used in PEMFC systems.

During the use phase, the majority of environmental impacts are caused by hydrogen production. An estimate of impacts from hydrogen production during the use phase, evaluating GWP and AP based on data from Acar & Dincer (2022), indicated that the respective impact indicators are much higher regarding the use phase than production. Some additional impacts arise from maintenance activities. To reduce these impacts in tandem with the FC system's expected lifespan, attention should be given to separability during system design. This is especially important regarding gasket design. Gasket design is important to limit adhesion and enable a higher degree of repairability during maintenance as well as EoL dismantling.

The EoL phase itself is currently found to be of rather low impact compared to the preceding life cycle stages. Ferreira et al. (2021) for instance find the impact of the EoL to be less than 1% of production and transport emissions. Gramc et al. (2025) report similar results, where the EoL makes up less than 2% of the combined manufacturing and EoL impacts for all assessed impact indicators apart from ADP where the EoL accounts for 7,4%. The EoL is still crucial as recycling offers an opportunity to reduce FC system's environmental footprints through the provision of secondary materials. Especially Pt recycling is found to offer the potential for significant impact reductions in all assessed impact indicators. Lotrič et al. (2021) find reduction potentials of up to 35% of production GWP (60% for ADP, 71% for AP and 65% for EP respectively) for a 76% platinum group material (PGM) recovery rate for a stationary HT PEMFC system. Without PGM recovery, the production related EoL impact reduction potential is found to be below 10% for all of the above indicators. Gramc et al. (2025) evaluate the environmental benefits of eco-design for PEMFC manufacturing and EoL. With regards to EoL, they use Pt recycling rates of 30% for their short- and long-term scenarios. The optimistic and disruptive scenarios use Pt recycling rates of 70% and 95% respectively. For the short- and long-term scenarios, 34% and 39% in potential GWP reductions through recycling are reported.

Many studies point towards significant improvement potential regarding the environmental performance of FC systems. Most studies attribute this to the potential of increased secondary material use, improved energy mixes and technological advancements regarding Pt load and system size. These potentials can be realized during the design process by following available eco-design guidelines and incorporating existing knowledge on repairability and recycling. The improvement potential pointed out in Gramc et al. (2025) is based on a host of eco-design measures including reuse and recycling of components, reductions in Pt loadings and lightweighting. In the short term they find a GWP reduction potential of 31% (52%, 74% and 85% for the long term, optimistic and disruptive scenarios respectively), with similar or higher potentials for all other impact indicators. Note that this does not consider the additional potential for avoided impacts that can be achieved through EoL recycling. The only net environmental drawback of recycling is found in the short-term scenario for EP. An increase by almost 20% is found compared to the manufacturing and EoL without Pt recovery, which originates from the recycling process of Pt. For all other scenarios, changes in EP are still negative. Based on the values used in the short- and long-term scenarios in Gramc et al. (2025), a Pt recycling rate of 30% can serve as a goal for the MEAsureD MEAs. Recyclability of other components should be considered during system design, albeit Pt recovery offering the biggest leverage point for impact reductions across most impact indicators.

3.2 LCIA RESULTS FOR THE REFERENCE PEMFC SYSTEM

The total GWP associated with the production of the 1 kW system amounts to 179.37 kgCO_2eq. The analysis reveals distinct impact contributions across component groups, highlighting critical hotspots primarily associated with material intensity and upstream processing emissions.

The largest share of emissions originates from other stack components contributing 87.35 kgCO_2eq which represents 48.7% of the total impact. This category includes non-core components such as aluminium and cast alloy housings, electronic control units, steel structures and cabling. The dominant impacts within this category stem from the use of aluminium cast alloys and wrought aluminium, which are associated with high embodied energy due to electrolysis based primary production. The catalyst is the second largest contributor with 74.90 kgCO_2eq, which equates to a 41.8% share of the total impact, primarily due to the use of Pt, as well as chemical inputs like formaldehyde, cobalt salts and fluorinated solvents. Despite its minor mass share, the upstream impacts from Pt mining, refining and chemical synthesis processes result in a disproportionately high environmental footprint. The membrane accounts for 6.35 kgCO_2eq (3.5% share of total GWP), linked mainly to the production of phosphoric acid and benzimidazole compounds used in polybenzimidazole (PBI) based membranes. While its share is modest, the membrane remains a hotspot due to the embodied energy of specialty chemicals. Bipolar plates (BPPs) contribute 4.27 kgCO_2eq (2.4%) and are typically based on coated graphite substrates. Graphite is a durable but highly energy intensive metal, requiring high temperature smelting and machining which is reflected in the upstream impacts. The gas diffusion layers, including carbon paper and microporous coatings, account for 1.97 kgCO_2eq (1.1%), with main inputs being graphite and carbon black. Auxiliary subsystems, such as fuel and heat management, together contribute less than 1%, with emissions of 0.64 and 0.22 kgCO_2eq, respectively.

In addition to the GWP, the environmental footprint assessment revealed critical contributions across ADP and EP indicators. Figure 3 presents the normalized environmental profile of the assessed HT PEMFC system, across six key EF 3.1 midpoint indicators: GWP, AP, ADP, freshwater eutrophication potential (FEP), marine eutrophication potential (MEP) and terrestrial eutrophication potential (TEP). The results highlight significant differences in component level contributions depending on the environmental mechanism under consideration. The Catalyst consistently emerges as the dominant contributor across most categories particularly in AP, MEP and TEP, where it accounts more than 75% of the normalized impacts. This is attributable to the use of Pt, inorganic salts and fluorinated compounds, which are linked to acidifying emissions and aquatic nutrient loading during mining and chemical synthesis (Liu et al., 2023). In contrast, other stack components dominate in GWP and FEP, contributing 41.7% and 55.1% of the total impact in these categories respectively. This reflects the embedded emissions of aluminium, steel and electronics, as well as phosphate related discharges during upstream processing. The ADP shows a more distributed profile, while the catalyst still contributes a majority share (58.7%), auxiliaries and membrane components also have visible impacts (17.4% and 1.9%), likely due to the use of phosphoric acid, specialty polymers and metallic fittings. The ADP of fossil resources totals 2.34 MJ, mainly reflecting the embodied energy of aluminium and graphite production, as well as polymer processing. In parallel, the depletion of mineral resources (0.0006 kgSbeq) is driven by Pt, cobalt and copper inputs, all materials that carry high depletion factors due to intensive extraction requirements. BPP and GDL components consistently show a minimal contribution (<2.5%) across all categories, indicating their relatively low mass. The system's TEP, calculated at 6.88 molNeq, is largely attributable to upstream NO_x and NH_3 emissions, particularly from combustion related processes in aluminium and membrane precursor supply chains. FEP and MEP values are found to be 0.16 kgPeq and 0.51 kgNeq respectively, mostly arising from nitrate and phosphate rich emissions associated with chemical processing in the catalyst and membrane subsystems. Lastly, the AP, amounting to 6.69 molH$^+$eq, is primarily caused by SO_2 and NO_x emissions originating from fossil fuel-based electricity and industrial processing of base metals and electronics.

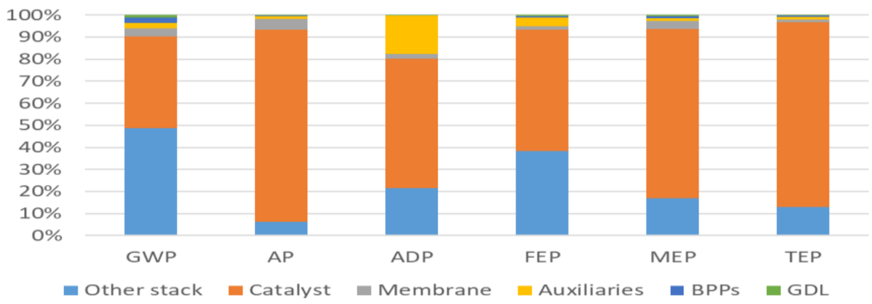

Figure 3: Normalized results of the LCIA of the HT PEMFC for the assessed indicators (EF 3.1).

3.3 BENCHMARKING

This section elaborates on the benchmarking of the LCA results against literature values which were obtained in the meta-study. The observed ranges from literature for all selected indicators are shown in Table 3. All values are scaled to the functional unit of 1 kW of FC power.

Table 3: Benchmark values and ranges for the selected impact indicators. *Original high value of the GWP range was at 724 kgCO2eq/kW before narrowing down the results. **Values from Gramc et al. (2025).

Indicator	This Study	Literature Benchmark	Unit
GWP	179	24 – 73*	$kgCO_2eq/kW$
AP	6.7	0.8 – 23	$kgSO_2eq/kW$
ADP	0.006	0.0008 – 0.06	kgSbeq/kW
EP		0.09 – 2.7	$kgPO_4eq/kW$
TEP	6.88	0.34**	molNeq/kW
FEP	0.16	0.0001**	$kgPO_4eq/kW$
MEP	0.51	0.03**	kgNeq/kW

The benchmarking shows that the GWP of the reference product exceeds the narrowed down range of the literature results. Significant reductions in GWP will be necessary to reach the benchmark average of 40 $kgCO_2eq/kW$. However, compared to the original high end of the range, the result is still well sat inside the range. In terms of AP and ADP, the reference product places on the mid to lower end of the range. To enable a meaningful comparison with regards to EP, the results from Gramc et al. (2025) are chosen as a reference point. This is due to the fact that different indicators are used to express EP which makes comparison between the EF 3.1 method and the meta-study results impossible in this regard. Compared to the chosen reference, the reference product performs significantly worse in all three measures of EP. Additional challenges arise when comparing this study to literature results. Many studies assess different FC technologies and system applications, like focusing on LT PEMFC or stationary systems. LT PEMFCs do not use steel as housing material but rather plastics, as there is no need for heavy housing. The Pt loading is also generally lower for LT systems (Zucconi, et al., 2024).

This explains largely, why this reference HT PEMFC LCA shows much higher GWP values than the literature baseline.

3.4 OUTLOOK AND IMPROVEMENT POTENTIAL

The upcoming LCA of the novel HT PEMFC system will build upon the baselines that are established in the meta-study as well as the results presented in this paper. This LCA not only assesses the environmental impacts but also reflects on how technical advancements in the MEAsureD project can potentially contribute to their reduction.

Several improvements are expected to help with impact reduction as defined by the KPIs of the MEAsureD project. The new system is designed to last 20000 hours and deliver greater power density of 1.2 W/cm² at 0.65 V, both of which directly influence the environmental performance of the FC by extending its operational lifetime and improving energy output per unit of material. In addition, the Pt load shall be reduced to 0.3 mg/cm². This planned Pt reduction addresses one of the major environmental hotspots identified in this study. Lower Pt use reduces the environmental burden associated with resource extraction and catalyst production. Furthermore, the manufacturing process is being streamlined to use less energy and produce less waste, while ensuring consistent batch-to-batch quality.

To quantify the impacts of expected improvements the LCA model is adapted to evaluate potential scenarios. As the MEAsureD project KPIs aim to reduce the impact of the materials significantly, the inputs are downscaled to assess the impact of these goals. Reducing the Pt loading from 1.64 g to 0.27 g lowers the GWP by about 35%. Changing the employed electricity mix to wind energy from Greece lowers the overall GWP result by less than 1%. The energy consumption during production is however subject to uncertainties. Increasing the power density to 1.2 W/cm² reduces the overall GWP by about 44%, assuming that the cell related material demand is reduced accordingly. Changing the BPP material from synthetic graphite to stainless steel reduces the overall GWP by about 1.2%, albeit the weight of the stainless steel BPPs being slightly higher.

As emphasized by Gramc et al. (2025), embedding LCA early in the design process supports the proactive identification of environmental hotspots and guides targeted improvements in material choice, durability and recyclability. Their eco design framework demonstrates how integrating life cycle thinking during technology development can significantly lower cumulative environmental burdens across all product life cycle stages. Finally, the MEAsureD project aims to develop a PEMFC system in the 80 kW range. Comparatively speaking, the larger system size will most likely lead to an improved environmental performance with regards to a 1 kW functional unit due to sublinear scaling advantages.

All together, these improvements are expected to yield significant reduction in the overall environmental impact of HT PEMFCs, offering a cleaner and more sustainable option for HDV applications. Regarding to the critical material issues, a next generation HT PEMFC with Ion Pair technology, offering higher power density and lower Pt use, needs to be analyzed and conducted. The upcoming novel HT PEMFC LCA will capture these advancements, showing optimised design and production options for future FCs. In addition, the upcoming LCA should also take the use phase into consideration, as significant environmental advantages could be found with regards to the HT PEMFC systems capability to operate on less pure hydrogen which potentially benefits impacts from the use phase.

4. CONCLUSION

This paper presents an environmental assessment within the broader scope of the MEAsureD project, which aims to improve the performance, durability and sustainability of HT PEMFCs for HDV applications. Through a combination of a literature review and an LCA study, this paper evaluates both the current environmental impact of an Advent Technologies HT PEMFC system as well as the improvements expected through ongoing research and development.

The meta-study revealed that reported potential environmental impacts vary widely across published PEMFC LCA studies and ranges for the impact indicators GWP, AP, ADP and EP were derived as a benchmark for the LCA studies in the context of the MEAsureD project.

The LCA conducted on the current PEMFC stack is based on a 100 W laboratory-scale system which is scaled up to 1 kW for comparability to the meta-study. The results for GWP are 179 kgCO_2eq/kW, which is above the identified benchmark average. Indicators for EP are found to be higher than the established benchmarks. Indicator values for AP and ADP on the other hand are placed on the lower end of the benchmark ranges. Notably, the highest contribution to the GWP value stems from the stack housing and endplates. Another hotspot are the catalyst layers due to the Pt loading. In addition, the inefficiencies and high material intensity resulting from small-scale systems, as well as data uncertainties coming from limited primary data and necessary modelling assumptions explain the high results. These findings should therefore be interpreted as estimates, rather than being representative of the system's potential at higher TRL.

Despite the environmental challenges observed in the LCA, the outlook for the novel HT PEMFC system is highly encouraging. The upcoming LCA will reflect the benefits of key technological advancements, including an improved stack lifetime and reduced Pt loading, which directly improves the environmental performance. Additionally, the enhanced power density leads to more compact and efficient designs and optimized ionomer formulations reduce energy use, improve batch consistency and enhance recyclability. Lastly, the capability to utilize hydrogen of lower purity is not part of the LCA at hand, despite it being one of the expected key advantages of HT PEMFC systems in environmental terms compared to current high TRL systems when considering their full life cycle.

In summary, while the HT PEMFC LCA highlights the environmental challenges associated with early stage, small-scale FC stacks, it also provides a valuable baseline for identifying key points for improvement. The results of the upcoming LCA on the TRL 4 system are expected to show substantial reductions across several environmental indicators, demonstrating the MEAsureD project's potential to deliver cleaner, more efficient FC solutions for the HDV sector. This supports the broader project goals of climate-neutral mobility, circular design and resource-efficient energy technologies.

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