

Influence of early-stage design choices on the environmental performance of repurposed lithium-ion batteries

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ABSTRACT

Lithium-ion batteries (LIBs) are a key technology in decarbonisation, particularly for their use in electric vehicles (EVs) and battery energy storage systems (BESS). Nevertheless, their production is associated with significant environmental impacts. Repurposing LIBs after their use in EVs for less demanding applications, such as BESS, has the potential to reduce these impacts. However, current repurposing efforts face several technical challenges, often requiring the replacement of key components. For example, the module casing might be damaged during disassembly, while the battery management system (BMS) is typically replaced because it is not programmed for stationary applications and contains sensitive data belonging to original equipment manufacturers (OEMs). This study examines how specific early-stage design choices influence the environmental impacts of second-life applications. A life cycle assessment (LCA) of a BESS equipped with repurposed LIBs was conducted, evaluating different repurposing scenarios based on the reuse or replacement of the BMS and module casing. The results revealed a superior environmental performance of second-life BESS compared to new systems in four out of five analysed impact categories. The lowest impacts were identified when both the module casing and the BMS were reused, while the highest impacts were observed when both components were replaced. These results underscore the importance of designing LIBs to enable component reuse and facilitate a more sustainable repurposing process. A “circular by design”

approach could involve avoiding adhesive connections to prevent damage to battery components, particularly the module casing, while maintaining safety. Additionally, integrating a BMS reset function, as suggested in the EU battery regulation 2023/1542, could enhance the sustainability of repurposed LIBs without compromising data confidentiality.

1. INTRODUCTION

In accordance with the European Green Deal, the European Union has formally committed to achieving climate neutrality by the year 2050 (European Commission, 2019). As part of the ongoing efforts to reduce carbon emissions, lithium-ion batteries (LIBs) are regarded as a pivotal technology. Consequently, the demand for LIBs is continuously increasing, primarily driven by the expansion of the electric vehicle (EV) fleet. However, LIBs also play a crucial role in battery energy storage systems (BESS), which facilitate the widespread integration of renewable energy sources (Bielewski et al., 2022). Despite their importance in decarbonisation efforts, the production, use, and recycling/disposal of LIBs are associated with significant environmental impacts and supply chain risks due to critical raw materials (CRMs), such as cobalt, lithium, and graphite (Buchert et al., 2017; Windisch-Kern et al., 2022).

Integrating circular economy strategies, such as repurposing and recycling at the early-design stage of LIBs, has the potential to improve their environmental performance. Repurposing end-of-life (EoL) LIBs from EVs for use in BESS extends their lifespan and reduces pressure and dependencies on CRM supply chains, before ultimately enabling the recovery of valuable materials through recycling (Kotak et al., 2021).

However, existing efforts face several technical challenges, often requiring the replacement of key components (Prenner et al., 2024b). For instance, module casings may need replacement for safety reasons due to potential damage sustained during disassembly. The battery management system (BMS) is typically replaced because it is not configured for stationary applications and may contain proprietary data belonging to original equipment manufacturers (OEMs) (Bobba et al., 2018b; Börner et al., 2022). This study investigates how specific early-stage design choices influence the environmental impacts of second-life applications.

2. METHODOLOGY

A life cycle assessment (LCA) of a BESS utilising repurposed LIBs (i.e., second-life BESS) was conducted. The goal of the LCA was to identify potential environmental benefits of second-life BESS, assuming different repurposing strategies. The system boundary is displayed in Figure 1.

Four repurposing strategies were assessed, each taking a different approach to the reuse of battery components, i.e., the module casing and BMS in the second life. All cases included the repurposing and testing of the battery cells. The summarised assumptions can be found in Table 1.

Table 1: Repurposing assumptions

	Testing	Reuse battery cells	Reuse module casing	Reuse BMS
Base case	x	x		
Case 1	x	x	x	
Case 2	x	x		x
Case 3	x	x	x	x

A BESS equipped with new batteries served as a reference scenario for comparative analysis. For both systems, a capacity of 14.4 kWh and nickel manganese cobalt oxide (NMC 111) battery chemistry were assumed. The functional unit was 1 kWh of energy delivered by the battery to meet the electricity demand of an average German household until it reaches a lower capacity than the daily household demand. A two-person household was considered with an average daily electricity demand of 8.7 kWh (Statistisches Bundesamt, 2023). The capacity loss due to ageing processes during each cycle was determined using an equation based on Han et al. (2014). More details can be found in Spindlegger et al. (2025).

LCA for Experts (Sphera, 2024) was used as a software, *Ecoinvent 3.8* (Wernet et al., 2016) served as a database, and *ReCiPe 2016* (Huijbregts et al., 2017) was chosen as an impact assessment method. The results are presented for five selected impact categories: Climate change (CC), Ecotoxicity freshwater (ET_{fw}), Human toxicity, cancer (HT_c), Metal depletion (MD) and Terrestrial acidification (TA). By choosing these categories, a comprehensive

coverage of all three endpoint categories (damage to human health, ecosystems, and resource availability) was ensured.

To address the multifunctionality of the repurposed components, allocation was applied to distribute the environmental impacts of production and EoL treatment between their first life in an EV and second life in a BESS. It was assumed that 25% of the impacts were allocated to the battery's second life and 75% to its primary function in the car, in accordance with the literature (e.g., Bobba et al., 2018a; Wilson et al., 2021).

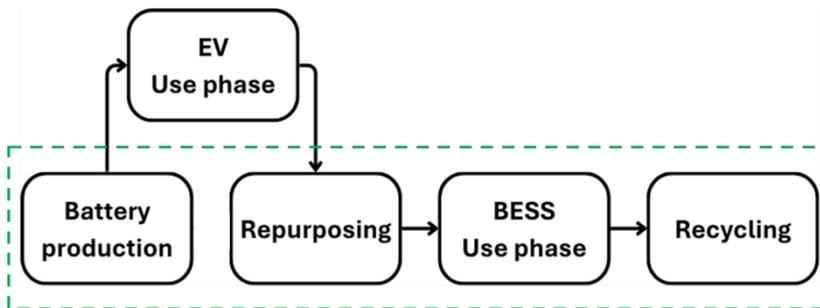


Figure 1: System boundary

3. RESULTS

The results highlight the substantial environmental benefits of second-life BESS across various impact categories and repurposing scenarios. Figure 2 presents the normalised LCA results for the second-life BESS across the assumed cases. Compared to a BESS with new LIBs, the second-life BESS consistently demonstrates superior environmental performance for MD, CC, HT_c , and TA. The most favourable outcome is observed in Case 3, where both the module casing and BMS are reused, achieving the highest reductions of 61% for MD. For HT_c and MD, reusing only the module casing (Case 1) proves more advantageous than reusing only the BMS (Case 2), with savings of 32% for HT_c and 61% for MD. This is attributed to the significant environmental impacts associated with steel production for the module casing. Conversely, Case 2 is more beneficial for CC and TA with reductions of 40% and 50%, respectively. For ET_{fw} , environmental benefits are only observed in the Base case and Case 1. In contrast, Case 2 and Case 3 result in higher impacts, with increases of 22% and 20%, respectively, compared to the new BESS. This is primarily due to reduced recycling credits from BMS treatment in the EoL phase, as a portion of these credits is allocated to the battery's first life. A

sensitivity analysis demonstrated that fully allocating the EoL impacts, including the environmental credits, to the battery’s second life eliminates these drawbacks and significantly enhances environmental savings (Spindlegger et al., 2025).

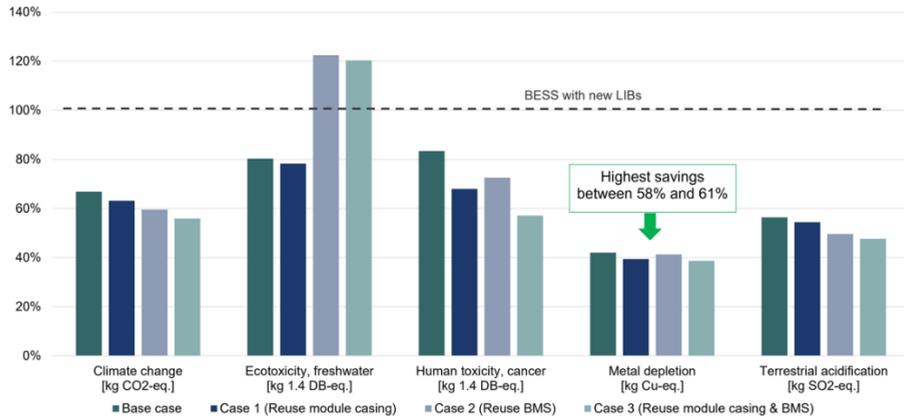


Figure 1: Normalised environmental life cycle impacts of a second-life lithium-ion battery storage system compared to a new lithium-ion battery storage system, which is the reference scenario

4. DISCUSSION AND CONCLUSIONS

LCAs can be a versatile tool for decision-making in battery design, enabling the consideration of environmental aspects in the early development stage. However, from a methodological perspective, our LCA study highlights the substantial influence of allocation procedures on overall environmental impacts, underscoring the need for more explicit methodological guidance on how to allocate environmental burdens between different life cycle stages. In other words: How should the credits be distributed among the different sectors (e.g., cell producers, car manufacturers, repurposing companies, recyclers, etc.)? To address this, the Circular Footprint Formula (CFF) represents a harmonised method for calculating a product’s environmental footprint and provides a structured approach to allocating environmental burdens and credits in the EoL phase (European Commission, 2021). However, applying the formula to second-life batteries remains challenging due to its methodological complexity and numerous parameters involved. Alternatively, multifunctionality problems in LCAs could also be addressed through system expansion.

This approach provides a more comprehensive view of environmental effects by considering all battery life stages in one LCA model.

From a practical standpoint, the results provide actionable recommendations for improving the environmental performance of BESS and offer valuable input for integrating repurposing strategies early in the innovation phase of new LIB systems. Furthermore, these findings show the potential of early-stage design considerations to improve the environmental impacts of LIBs by extending their lifespan and contributing to their circularity. Specifically, re-using both the module casing and BMS proved to be environmentally beneficial. However, implementing such strategies requires a change in battery design practices. Current battery designs are highly diverse and often rely on adhesives and welding techniques, which pose substantial challenges to the disassembly process. Likewise, enabling the reuse of the BMS requires safeguarding OEM data (Prenner et al., 2024b). To address such challenges, the battery regulation (Regulation 2023/1542) recommends developing standards for design and assembly techniques that facilitate repurposing. For instance, a modular design would improve repairability, reuse and repurposing. Moreover, the replacement of adhesive connections with mechanical options, such as screws, would improve manual or automated disassembly processes. Incorporating a reset function in the BMS, as suggested in the battery regulation, could provide a practical solution to ensure OEM data protection while allowing for reuse. Such standards could provide guidance for battery manufacturers in designing LIBs that are optimised beyond their first life, enabling more efficient resource utilisation and supporting circular economy actions. To ensure the feasibility and acceptance of design standards, without imposing overly restrictive design constraints, their development should involve relevant stakeholders, including OEMs, policymakers, repurposing operators, and researchers (Prenner et al., 2024a). Incorporating these early in the design phase can help overcome technical barriers and, consequently, reduce the costs associated with LIB disassembly and component replacement (Prenner et al., 2024b). This, in turn, renders repurposing and recycling more technically and economically viable.

Overall, battery design choices should not be limited to the initial application but should instead embrace a life cycle perspective in the sense of the 9R strategy of the circular economy (Potting et al., 2017). Such “circular by design” approaches, similar to eco-design principles, could effectively integrate repair, refurbish, reuse and repurposing considerations into the design phase, ultimately supporting the transition to more sustainable battery value cycles. However, future research is still required to evaluate the economic feasibility,

as well as the suitability across different battery types and applications of the proposed design strategies.

ACKNOWLEDGEMENTS

The authors acknowledge the Austrian Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology, the Bundesanstalt für Materialforschung und -prüfung (BAM), and the Institut National de l'Environnement Industriel et des Risques (Ineris), for their financial support of the transnational funding programme SAFERA, which has enabled the realisation of the project 'SafeLiBatt' (FFG project no. 880683). This study was also supported by the Austrian Research Promotion Agency (FFG), which has funded the project 'MoLiBity' (FFG project no. 899505). Ricardo Gabbay De Souza acknowledges the São Paulo Research Foundation (FAPESP) (grant#2023/03698-0).

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