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Environmental Impacts of Lithium-Ion Batteries Refurbishment for Second-life Applications: A Systematic Literature Review

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Abstract

With the accelerated adoption of electric vehicles (EV) over internal combustion engine vehicles, it is increasingly critical to ensure the sustainability of EVs. For example, the environmental impact of lithium-ion batteries (LiBs), the energy storage of choice in most EVs, is an area of concern as it requires carbon-intensive production and requires raw material with high embodied carbon. Additionally, despite retaining a high state-of-health (~70-80%) at the vehicle's end-of-life, they are commonly not accepted for direct reuse in EVs. To alleviate environmental impact and increase battery circularity, retired LiBs from EVs that are in good condition should be repurposed or remanufactured for second-life deployment. Although environmental sustainability improvement from these second-life deployments is probable, they are not guaranteed. Factors such as the condition of the retired LiBs and the resources required to prepare them for the intended deployment can all influence the environmental impact of the second-life applications. To ensure that the second-life application is not net-negative, assessing its viability is necessary. This necessitates understanding the environmental impact of the LiBs under different second-life scenarios. Unfortunately, data on the environmental performance of LiBs across these scenarios remains fragmented and limited in existing databases. To address this gap, this work aims to consolidate existing studies on the environmental impacts of second-life LiBs applications through a systematic literature review. From the review, it was evident that there is a noticeable lack of research on the environmental impact of LiB remanufacturing and second-life applications beyond stationary energy storage. Additionally, most studies only consider retired LiB with a state-of-health of 80% and do not disaggregate their activity data. This limits the usability of their reported data for secondary analysis, especially when the conditions diverge from those assumptions.

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Keywords: Life Cylce Assessment; Design for Circularity; Lithium ion battery; Electric Vehicle Battery; End-of-life

1. Introduction

The electrification of transportation has emerged as an important strategy in many nations' sustainability roadmap. Electric vehicles (EVs) offer several environmental advantages over internal combustion engine (ICE) vehicles, including the elimination of direct emissions, having higher energy conversion efficiencies (~70-90% in EVs compared to 20-30% for ICEs), and capacity to use electricity generated from renewable energy sources. To encourage EV adoption targeted government initiatives and regulatory mandates were implemented resulting in significant increase in the number of EVs over the past decade. Notably, global EVs sales exceeded 14 million units in 2023 with global EV fleet projected to reach ~250 million vehicles by 2030, quadrupling the 2023 baseline (<45 million) [1].

One of the key enablers of EVs is the energy storage system, with lithium-ion batteries (LiB) as the predominant technology choice. The manufacturing of LiB is carbon intensive, relying on raw materials with high embodied carbon and, in some chemistries, requiring scarce elements such as cobalt. While there is no universal regulation dictating the precise state-of-health (SoH) at which an EV battery must be replaced, a SoH of around 80% is commonly regarded as the practical end-of-

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life (EoL) threshold for EVs. Consequently, LiBs are often retired with the EV and not reused despite retaining substantial capacity and functionality. As the number of EVs increases, it is critical to consider the environmental implications associated with the handling of retired LiBs to promote sustainability and circularity while avoiding unintended rebound effects.

While retired EV LiBs are not suitable for direct reuse in EVs, they can be refurbished by either remanufacturing for continued usage in EVs or repurpose for other applications. These approaches help maximize the utility of LiBs that remain in good condition before eventual recycling or disposal. Such redeployment mitigates environmental impacts by delaying disposal, extract additional value from the batteries, and potentially reduce of the overall embodied emissions in the redeployed application, as remanufacturing or repurposing typically has a smaller environmental footprint than producing new LiBs from raw materials. Recognizing this potential, the European Union's REGULATION (EU) 2023/1542 introduces measures such as eco-modulated extended producer responsibility fees to encourage second-life deployment of batteries [2].

Although environmental sustainability improvement from second-life application is probable, it is not guaranteed. Battery cells and modules in EVs can degrade differently depending on the usage behavior of their users, which may lead to a difference in their SoH (between 70–80%) when the EV is retired [3]. At different SoH the remaining useful life of the LiB in second-life application will differ. In these scenarios the resource required to realise second-life might not be sustainable and economical compared to usage of first-life LiB for the same application [3]. Thus, condition of the battery along with the environmental impact of the remanufacturing and repurposing process should all be considered to determine the sustainability viability of the second-life application.

This requires careful consideration of the emissions associated with the remanufacturing and repurposing LiBs. However, such data is currently not widely available. Existing databases (e.g., Ecoinvent, Sphera) primarily provide life cycle assessment (LCA) for cell production and recycling processes, while emission factors related to remanufacturing and repurposing remain elusive. Therefore, this study seeks to identify and consolidate relevant data through a systematic literature review of LCA studies focused on the second-life applications of retired LiBs. In addition, the review seeks to answer the following questions:

1. What are the most commonly studied second-life LiB applications?
2. What emission factors are reported to prepare retired EVs LIB for second-life applications?
3. What are the process activities considered in these LCA studies?

The paper proceeds as follows: Section 2 will outline the methodology used for the review. Section 3 will present the findings while section 4 will discuss the insights from the analysis. Section 5 concludes the paper.

2. Methodology

This review was conducted using the systematic literature review methodology outlined by Denyer and Tranfield [4]. The schematic representation of the review process is shown in Figure 1. As of 1st September 2025, a keyword search in the Scopus database retrieved 2,218 articles. Following a series of filtering steps, 9 research articles were identified that contain LCAs of second-life LiB applications. It is important to note that during the shortlisting process, some studies related to LiB remanufacturing were excluded due to inconsistencies in the definition of the term. In this work, the definition of the remanufacturing follows Article 3 of Regulation (EU) 2023/1542, which specifies it as the process of restoring used batteries to at least 90% of their original rated capacity, thereby extending their service life [2]. Consequently, studies that labelled their work as remanufacturing but in fact described the use of recycled materials from LiBs to manufacture new battery cells were excluded.

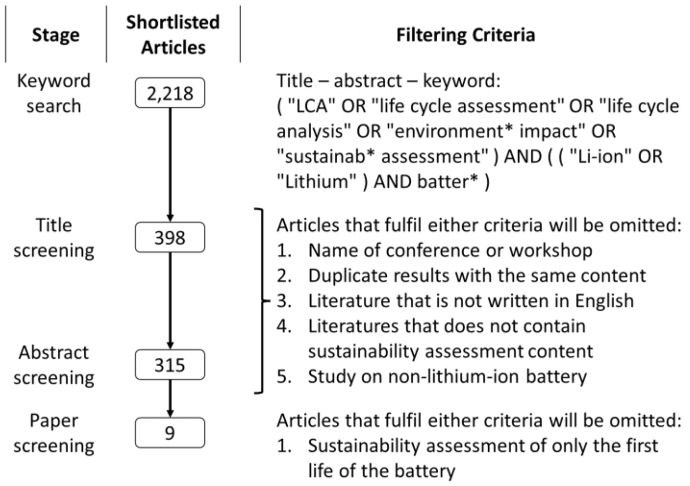

Figure 1 Overview of the systematic literature review.

3. Results

Across the 9 shortlisted articles, 11 LCA studies were reported. Some articles assessed more than one LiB technology, with each technology reported as a separate entry in this review. From the review, it was observed that all 11 studies focused on repurposing. Although some studies were labelled as examining remanufacturing, closer inspection of these studies revealed that they either described repurposing (i.e., the application of retired LiBs in a different application) or the manufacturing of new LiBs using recycled materials. Consequently, relevant studies from this group were classified under repurpose in this review while others were excluded.

Table 1 presents a compilation of the reviewed LCA studies, summarizing key information such as the functional unit, study scope, assessment model, and LCA system model. For ease of reference, each study has been assigned an index, which will be used throughout the remainder of this work. From the reviewed studies reviewed, it was observed that two LiB chemistry were commonly examined - Lithium Nickel Cobalt Manganese Oxide (7 studies) and Lithium Iron Phosphate (4 studies). Regarding the functional unit, most studies adopt 1 kWh of storage capacity, However, some outliers define their functional units differently, including: a BEV equipped with a 54.6 kWh lithium-ion battery driving 160,000 km over a 12-year lifetime; a single battery pack of 54.6 kWh; and the energy consumption of the DC grid in the production facility over a 10-year period.

Table 1 Description of LCA study pertaining to second-life application of LiB from shortlisted articles.

Name	Idx	Battery chemistry	Circular pathway	Functional unit	Scope of LCA study	Assessment model	LCA system model
Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies [5]	B1	Lithium Iron Phosphate	Repurposing	Nominal capacity of a 1 kWh battery pack	Cradle-to-cradle LiB production, first-life usage phase in an EV, repurposing (assumes parts and components are replace while modules/cells are not), secondary use in energy storage system, recycling by hydrometallurgy (Scenario 1 and 3), direct physical recycling (scenario 2), and pyrometallurgy (scenario 4).	CML2001	Unavailable
	B2	Lithium Nickel Cobalt Manganese Oxide					
Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management [6]	B3	Nickel Manganese Cobalt (NMC 111)	Repurposing	BEV equipped with a 54.6 kWh LIB for 160,000 km over a lifetime of 12 years	Cradle-to-cradle BEV production, BEV usage stage, EoL treatment of BEV and rejected LiBs , LiB refurbishment (assumes 50% cell conversion rate), avoided LiB emission, LiB recycling.	ReCiPe 2016 (H) v1.04 midpoint	Unavailable
Environmental Benefit Assessment of Second-Life Use of Electric Vehicle Lithium-Ion Batteries in Multiple Scenarios Considering Performance Degradation and Economic Value [7]	B4	Lithium Iron Phosphate	Repurposing	1 kWh of energy storage capacity	Gate-to-gate Repurpose of retired LiB (electricity for diagnostic, disassembly, cell/module replacement) * Study is conducted at scenarios with requiring no replacement, and those that require module and cell replacement at different replacement rate.	CML 2001	Unavailable
	B5	Lithium Nickel Manganese Cobalt Oxide (NMC-811)		1 kWh of energy storage capacity			
Life cycle assessment of PV-battery systems for a cloakroom and club building in Zurich [8]	B6	Lithium Nickel Cobalt Manganese Oxide	Repurposing	Battery system with 1 kWh storage capacity	Cradle-to-gate Production of battery system (allocated one seventh of battery production environmental impact in LiB repurpose application), repurposing of LiB (Includes production of battery managaemnt system, cool system, battery cells, packagaing).	Unavailable	Unavailable
Reuse of Lithium Iron Phosphate ($LiFePO_4$) Batteries from a Life Cycle Assessment Perspective: The Second-Life Case Study [9]	B7	Lithium Iron Phosphate	Repurposing	1 kWh of battery capacity	Gate-to-cradle Shipping of retired LiB to installation site, the usage phase of repurpose LiB, recycling by hydrometallurgy (scenario A) and pyrometallurgy (scenario B)	Recipe 2016 MidPoint (H)	Unavailable
Life-cycle environmental impacts of reused batteries of electric vehicles in buildings considering battery uncertainty [10]	B8	Nickel-manganese-cobalt (NMC811)	Repurpose	1 kWh energy capacity	Cradle-to-cradle LiB produdction (include material extraction and processing), transportation, first-life usage in EV, repurposing of retired LiB, second-life application of LiB in ESS (assumes direct usage), recycling by hydrometallurgy (scenario A) and pyrometallurgy (scenario B) *Study omits emission contribution from repurpose process	MidPoint (H)	Unavailable
Carbon emission assessment of lithium iron phosphate batteries throughout lifecycle under communication base station in China [3]	B9	Lithium Iron Phosphate	Repurpose	1 kWh battery capacity	Cradle-to-gate LiB production (allocated base on price ratio between second-life and new batteries), refurbishment of retired LiB, second-life application of LiB in a cascaded battery system.	Unavailable	Unavailable
Life Cycle Assessment of Lithium-ion Battery Pack: Implications of Second-life and Changes in Charging Electricity [11]	B10	Nickel Manganese Cobalt	Repurpose	1 battery pack of 54.6 kWh	Cradle-to-cradle LiB production, first-life usage in EV, LiB refurbishment (assumes 50% cell conversion rate), second-life usage, avoided LiB production, EoL recycling	ReCiPe 2016	Unavailable
Integration of energy flow modelling in life cycle assessment of electric vehicle battery repurposing: Evaluation of multi-use cases and comparison of circular business models [12]	B11	Lithium Nickel Manganese Cobalt Oxide	Repurpose	Energy consumption of the DC grid in the production facility over a period of 10 years	Gate-to-gate LiB repurposing, SLBESS production, second-life usage in a SLBESS, disposal of secondary material of SLBESS (exclude LiB EoL) Emission from the perspective of BESS, with LiB repurposing (testing, calibration, shipment to assembly site), and BESS production (manufacturing of additional part, shipment and setup at final site)	ILCD handbook	Allocation at point of substitution

Table 2 Consolidation of process emission associated with the circular pathway extracted from the shortlisted articles.

Idx	Process emissions	Circular pathway	Second-life application	Remarks
B1	-	Repurposing	Energy storage system	Emission reported covers LiB first and second use. Repurposing assumed only part and components of LiB were replaced, not modules or cells.
B2	-			
B3	9.475 kg CO2e/kWh	Repurposing	Stationary energy storage application	Study assumes a 50% conversion rate of LiB cells in refurbishment and 50% conversion rate of used LiBs. Emission is normalized by remaining capacity of the battery (SoH 80%)
B4	4.61 kg CO_2e/kWh	Repurposing (Pack diagnosis)	Energy storage system	Repurposing equation for second-life LIBs where R represents the component replacement rate.
	$\frac{4.62}{1-R} + 7.37$ kg CO_2e/kWh	Repurposing (Module replacement)		
	$\frac{4.62}{1-R} + 8.16$ kg CO_2e/kWh	Repurposing (Cell replacement)		
B5	2.73 kg CO_2e/kWh	Repurposing (Pack diagnosis)		
	$\frac{2.73}{1-R} + 4.18$ kg CO_2e/kWh	Repurposing (Module replacement)		
	$\frac{2.73}{1-R} + 4.65$ kg CO_2e/kWh	Repurposing (Cell replacement)		
B6	80.6 kg CO_2e/kWh	Repurposing	Energy storage system for PV system	Through allocation include one seventh of battery production environmental impact
B7	0.816 kg CO_2e /kWh	Repurposing	Stationary Energy storage system	Emission encompasses reverse logistic and usage phase only.
B8	-	Repurpose	Energy storage system	Study omits emission contribution from repurpose process
B9	3.57 kg CO_2e/kWh	Repurpose	Cascaded battery system in a communication base station	Assumes retired LiB at 80% SoH.
B10	3.59 kg CO_2e/kWh	Repurpose	Stationary application	Study assumes 50% cell conversion rate in the refurbishment.
B11	87.38 kg CO_2e/kWh	Repurpose	Battery energy storage system (BESS)	Emission from the perspective of BESS, with LiB repurposing (testing, calibration, shipment to assembly site), and BESS production (manufacturing of additional part, shipment and setup at final site)

Table 2 presents key information on the second-life application of retired LiB reported in the reviewed studies. The analysis of the process emissions focuses specifically on extracting carbon dioxide equivalent (CO_2e) emissions associated with the processes required to prepare LiBs for second-life use (emissions from activities occurring after the end of first-life usage phase and before deployment in the second-life system). In cases where process emission cannot be disaggregated (e.g., B1 and B2), or where such emissions are excluded from the study (e.g., B8), no process emission is extracted. When analyzing the second-life application of retired LiBs across the reviewed studies, it is evident that, despite the contextual differences, the primary use is in energy storage system, predominantly for stationary applications.

Figure 2 illustrate some of the common activity reported to prepare a retired LiB for repurposing and remanufacturing. While the activities listed are commonly discussed in practice, they are not all covered in the reviewed LCA studies. Table 3 consolidates the activities that are included in the studies reviewed. Among the studies, B5 did not explicitly describe the activity in the repurpose process providing an amalgamated value of the process, while B8 is the only study that omits the contribution of repurpose process choosing to only focus on the usage phase of the repurpose application in its LCA.

Analyzing the activities considered across the reviewed studies, reassembly is the only activity not considered. While reverse logistics is addressed in only 2 studies: B3, which relies on secondary source for transport distance data, and B7, which bases its LCA on data provided by Nissan. Its omission in other studies likely reflects the absence of valid case studies, as most were conducted in academic settings without access to industrial data.

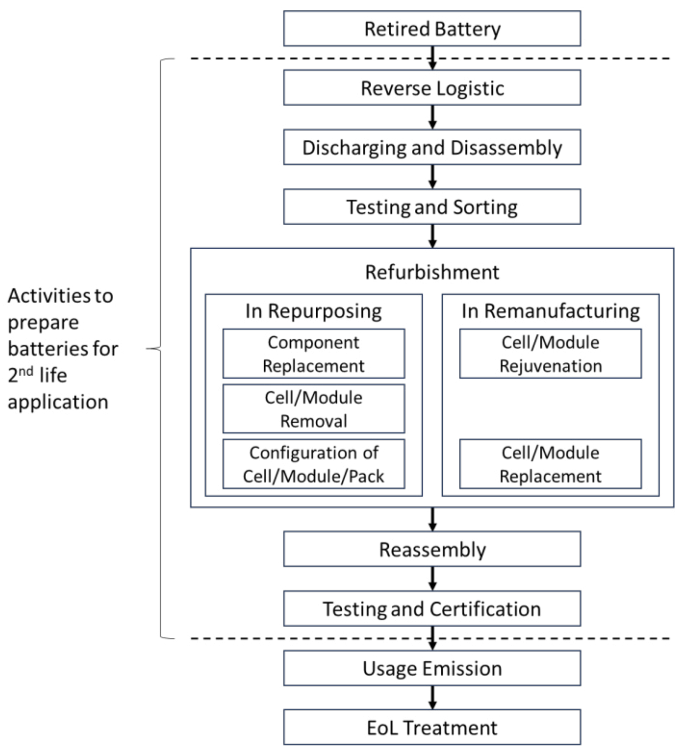

Figure 2 High level compilation of activities in the LCA of LiB second-life application

Table 3 Consolidation of emission contribution of activities indicated from the reviewed studies. *No detailed breakdown is selected for studies that did not describe the activities considered.

Idx	Reverse logistic	Discharging and disassembly	Testing and sorting	Refurbishment	Reassembly	Testing and certification	No detailed breakdown
B1							✓
B2							✓
B3	✓	✓	✓	✓			
B4		✓	✓	✓		✓	
B5		✓	✓	✓		✓	
B6							✓
B7	✓						
B8	Study omits contribution of repurpose process						
B9							✓
B10							✓
B11			✓	✓			

4. Discussion

Synthesizing the findings, current LCA study on second-life application lack diversity. Among the repurpose pathways, stationary energy storage is the most widely examined. This focus is likely due to the less demanding operational requirements of stationary energy storage applications, where the SoH of LiBs is less critical [13]. Additionally, energy storage systems, particularly at grid-scale, require a large number of battery cells and modules, and using second-life LiBs can potentially reduce both environmental impact and cost in such deployment. Despite this, there are other second-life applications areas, including industrial vehicles (e.g., forklifts and transport trolleys) and light electric mobility (e.g., e-bikes, e-scooters, and battery swapping systems) [14]. Understanding the environmental impact of preparing and integrating retired LiBs into these alternative applications could help assess their overall viability and identify threshold performance levels below which second-life use is no longer beneficial. Therefore, studies exploring the deployment of second-life LiBs across a broader range of applications are needed, as such research can provide decision-makers with the necessary data to evaluate a wider portfolio of repurposing options, which would be critical in scenarios where stationary energy storage is not feasible. The lack of diversity in the investigated LiB chemistry was also observed. Current studies center around only two types of LiB, despite the diversity of LiB chemistry. To enable environmental sustainability assessment of second-life application for a wider range of LiB, additional studies should be conducted beginning with other types of commonly used LiB such as Lithium Cobalt Oxide, Lithium Manganese Oxide, and Lithium Nickel Cobalt Aluminum Oxide.

In terms of processes, there is a notable lack of studies on LiB remanufacturing. While remanufacturing and repurposing pathways have similar activities (Figure 2), the scope of the refurbishment activity differs between the two, making their results non-substitutable. In repurposing, refurbishment of the LiB include replacement of broken component, removing cells/modules that does not meet the requirement, and preparing the cells/module/pack into the configuration to meet the requirement of the second-life application [15]. While in remanufacturing, at a module or pack level, refurbishment can either be rejuvenation of existing cells and/or replacement of the battery components, including cell, so that the resulting battery is restored to a capacity to at least 90% of the original rated capacity with the state of health of individual cells that does not differ by more than 3% between them and can be used for the same purpose or application [2]. Due to the requirements of remanufacturing, the process is inherently more dynamic compared to repurposing as the extent of intervention depends on the condition of the LiB module or pack. Furthermore, emission factors of remanufacturing process can vary significantly depending on the strategy deployed, such as rejuvenation versus component replacement. The dynamic nature of the pathway and lack of commercial proliferation of LiB rejuvenation technology are potential factors contributing to the lack of studies. The scarcity of data from the lack of studies poses challenges for robust decision-making in selecting pathways for second-life applications of LiBs. To bridge this gap further study of different remanufacturing strategies needs to be commissioned.

Additionally, it was observed that in studies that discuss the usage phase of second-life application, a SoH of 80% is commonly assumed as the baseline condition. Under this assumption, comparison assessment between new and second-life LiB deployed in the same application generally indicates that the latter offers greater sustainability benefits. This trend is reflected in Table 4, which summarizes representative studies featuring such comparisons. However, as highlighted in the introduction, the condition of retired LiBs is not uniform. Thus, the collective insight from these studies can only be used to conclude that second-life deployment of LiB is sustainability more advantageous when its SoH are at or above 80% for the applications and battery chemistry examined. In contrast, the sustainability of deployed second-life LiB with lower SoH (<80%) remains inconclusive in these studies. To address this gap, future LCA studies can mirror the work of Lai, et al. [3], which explicitly modeled second-life applications of LiBs with varying initial SoH levels in cascaded battery systems for communication base stations. Their findings indicate a breakeven point (SoH falls below 76.5%), when repurpose LiBs has a higher total life cycle emission than new LiBs. Alternatively, developing an evaluation models, such as that proposed by Cui, et al. [7], which enables the computation

Table 4 Comparison study of LCA between second-life and first life LiB in the same application.

LiB chemistry	Application	Circular pathway	Scope of study	Reported emissions		Ref
				First-life LiB	Second-life LiB	
Lithium iron phosphate	Cascaded battery system for communication base station	Repurposing	Entire life cycle	247.40 kg CO_2e/kWh	87.55 kg CO_2e/kWh	[3]
Lithium nickel- cobalt-manganese oxide	Battery energy storage system	Repurposing	Entire life cycle	185.00 kg CO_2e/kWh	80.60 kg CO_2e/kWh	[8]

of the environmental impact for second life use of LiBs would also be invaluable. Overall, further research is needed to systematically quantify the environmental performance of second-life LiBs across a broader range of SoH conditions, thereby establishing more robust thresholds for sustainable redeployment.

Lastly, examination of the activity data from the studies (Table 3) reveals a lack of transparency, with almost half of the studies providing only aggregated results without detailing the contributions of individual activities or specifying which activities are included. This limitation reduces the utility of the data, since processes for repurposing retired LiBs can vary considerably depending on the second-life application and the condition of the battery. Although the reviewed studies focus primarily on repurposing, the same issue is equally relevant for remanufacturing, where different strategies (e.g., rejuvenation versus component replacement) involve distinct activity profiles. Greater transparency in reporting activity-level data would therefore be highly desirable to enable more robust sustainability assessments of both repurposing and remanufacturing pathways, thereby better informing decision-making.

5. Conclusion

The rapid and accelerating adoption of EVs driven by transportation electrification will result in a substantial influx of retired EV LiBs in the following decade. Second-life application of retired LiBs has emerged as a critical strategy to manage the growing volume of retired EV LiBs by maximizing the utility of those that remain in good condition. The redeployment of retired LiBs has the potential to contribute to the long-term sustainability of electrification initiatives and contribute to resource efficiency. While there are potential for environmental sustainability improvement from second-life deployment of retired LiBs, it is not guaranteed. Factors such as battery condition, the selected EoL circularity pathway (repurpose or remanufacturing), and intended application all influence the net environmental impact of the second-life application.

To ensure sustainability in second-life applications, it is necessary to have access to emission data of LiB repurposing and remanufacturing processes to assess the environmental sustainability viability of the pathways and support decision-making. This review provides timely insights into such data as reported in the literature. The consolidated findings highlight that repurposing remains the dominant focus, particularly in applications for BESS, while studies on LiB remanufacturing are notably absent. Based on the review, several areas warrant further research attention:

1. Development of parameterized emission factors that reflect the variability in refurbishment activities across different remanufacturing and repurposing pathways.
2. Studies examining a broader range of SoH conditions to establish more robust thresholds for sustainable redeployment.
3. LCA studies of LiB second-life deployment across a wider array of repurpose applications for different LiB chemistry.
4. LCA studies on LiB remanufacturing.

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