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Research article

Will electric vehicle battery reconditioning succeed? – A flexible simulation approach considering stakeholders' interests

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A B S T R A C T

The increasing adoption of electric vehicles will generate substantial quantities of end-of-life batteries, necessitating effective management strategies beyond recycling. Reconditioning these batteries for reuse in vehicles or alternative applications presents a promising yet underexplored pathway. This study introduces a flexible simulation model combining discrete event and agent-based elements to estimate the long-term demand and supply of reconditioned electric vehicle batteries up to 2050. The model considers economic and regulatory factors, integrating the interests of key stakeholders, including original equipment manufacturers, recyclers, reconditioners, and consumers.

A German case study demonstrates the viability of reconditioning, highlighting its niche role compared to recycling and repurposing. Key findings reveal that original equipment manufacturer decisions, particularly the use of reconditioned batteries in warranty cases, significantly influence market dynamics. Consumers' demand for reconditioned batteries depends on their quality, price, and greenhouse gas savings compared to new batteries. The study also examines the impacts of the EU Battery Regulation's recycled content mandates.

The results underline the importance of aligning stakeholder strategies and regulatory frameworks to optimize end-of-life battery management. Promoting reconditioning can enhance circular economy practices while reducing environmental impacts, though challenges remain in aligning supply with demand and ensuring economic feasibility.

1. Introduction

The growth in electric vehicle (EV) sales will result in a substantial quantity of end-of-life (EoL) electric vehicle batteries (EVBs) in the future (Engel et al., 2019). The International Energy Agency assumes that the global stock of battery electric and plug-in hybrid electric vehicles will rise from approximately 30 million in 2022 to 250–375 million, depending on the policy scenario (IEA, 2023a). As EVBs contain both hazardous and valuable materials (Chen et al., 2019), regulations worldwide mandate the collection and ultimate recycling of these batteries (European Parliament and European Council, 2023a; Ji, 2024), i.e., reprocessing them on a material level (European Comission, 2008). In light of those regulations, the global EVB recycling market is projected to grow from 0.54 billion US dollars in 2024 to 23.72 billion US dollars by 2023 (MarketsandMarkets, 2025). However, prior to final recycling, EoL EVBs may be reused for a different application, such as a stationary energy storage system, or as spare parts for older EVs (DeRousseau et al., 2017). The utilization in an application other than the original one is generally referred to as repurposing, and different terms are common for re-utilization in the same application (Potting et al., 2017). Remanufacturing is generally used when a product is brought back to a state as-good-as-new, while reconditioning or refurbishment describe the process of restoring a product to a satisfactory working condition (Ijomah et al., 2004; Potting et al., 2017). Since EVBs cannot be restored to a like-new condition (Autocraft Solutions Group, 2023), the term "reconditioning" will be used in the following. The closed-loop system for electric vehicle batteries, including recycling, repurposing and reconditioning, is schematically illustrated in Fig. 1, and an overview of the terms is given in Table 1.

The treatment of EoL EVBs is of critical importance, as the

Abbreviations: AB, agent-based; BEV, battery electric vehicle; DES, discrete event simulation; GHG, greenhouse gas; EU, European Union; EV, electric vehicle; EVB, electric vehicle battery; EoL, end-of-life; KPI, key performance indicator; LCA, life cycle assessment LFP; lithium iron phosphate, MFA; material flow analysis, NCA; nickel cobalt aluminum oxide, not defined; NMC, nickel manganese cobalt oxide; OEM, original equipment manufacturer.

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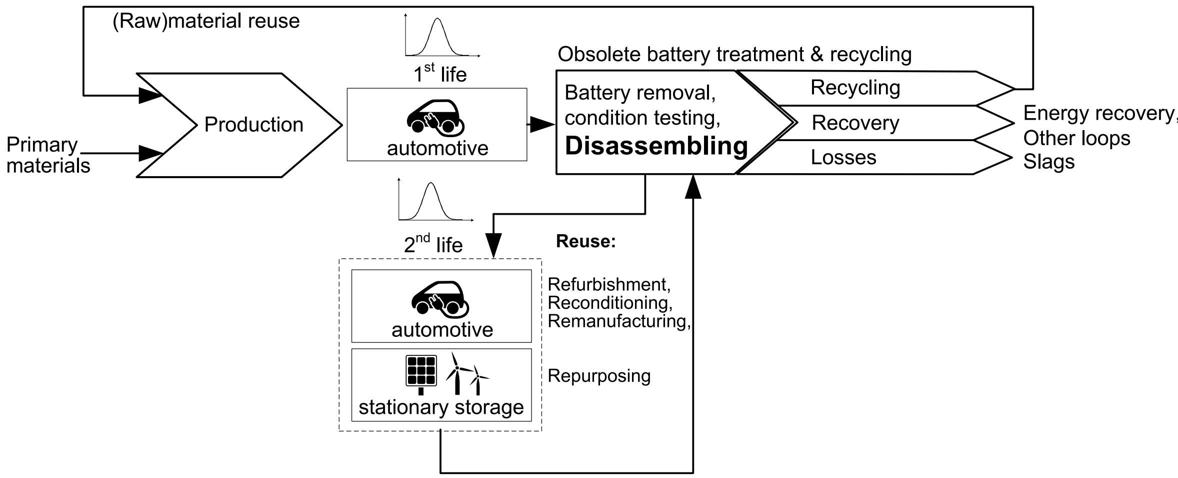


Fig. 1. Simplified closed-loop system for electric vehicle batteries. Reprinted from Glöser-Chahoud et al. (2021), with permission from Elsevier.

production of lithium-ion batteries consumes significant amounts of raw materials and energy, resulting in a high environmental footprint. For example, producing 1 kWh of a NMC622 battery (nickel, manganese and cobalt in the ratio of approximately 6:2:2) requires 104 g of lithium, 525 g of nickel, 176 g of cobalt, and 164 g of manganese (Maisel et al., 2023). For a typical EV battery of around 60 kWh, this results in the use of over 6.2 kg of lithium, 31.5 kg of nickel, 10.6 kg of cobalt, and 9.8 kg of manganese.

Recycling is an essential EoL treatment that allows the recovery of those valuable materials, which can then be used in the production of new batteries (Gaines et al., 2021). This process is especially relevant in view of the growing demand for battery raw materials. An advantage of recycling lies in the potential to produce technologically updated batteries with improved performance (Ma et al., 2021). However, recycling also entails the complete dismantling and processing of the battery, meaning that all the energy and emissions embedded in the original manufacturing process are effectively lost. From a sustainability standpoint, utilizing a battery for as long as technically feasible before recycling may be more desirable. This approach is also reflected in the European Union's waste hierarchy, which prioritizes preparation for reuse over material recycling (European Comission, 2008).

Repurposing is one such EoL strategy that aims to maximize the utility of used EVBs. From a life cycle assessment (LCA) perspective, repurposing is beneficial: it avoids the energy-intensive processes of material processing, resulting in minimal additional environmental burdens (Koroma et al., 2022). Moreover, by substituting the need for newly manufactured stationary battery systems, repurposing indirectly lowers pressure on battery production supply chains (Aguilar Lopez et al., 2024). One limitation, however, is that materials in repurposed batteries remain tied up in use and are therefore not immediately available for recycling and re-entry into battery manufacturing (IEA, 2020).

Reconditioning offers a similar set of advantages. Like repurposing, reconditioning requires little energy and new material input (Kampker et al., 2020). In addition to prolonging the life of the battery, reconditioning may provide cost-effective spare parts for aging EVs, thereby extending the useful life of the vehicles themselves (Huster et al., 2022). This in turn reduces the need for new EVs and new EVBs, leading to further environmental benefits. Furthermore, reconditioned batteries can be used in warranty cases by OEMs, reducing their costs significantly (Sainz, 2023). Battery reconditioning is for example already performed by Stellantis or Autocraft Solutions (Autocraft Solutions n.d.; Stellantis, 2023).

Although recycling may be more or less profitable or costly depending on the cathode material and the recycling location (Lander et al., 2021), it remains the default option and is mandated by law as the final treatment for waste batteries. Repurposing or reconditioning, conversely, necessitate active decisions to pursue this alternative. For repurposing, these decisions primarily involve business entities, such as the original equipment manufacturer (OEM), which may receive old EVBs as part of the mandatory take-back system, and energy providers who operate power plants requiring energy storage systems (Schulz-Mönninghoff and Evans, 2023). These business entities are likely rational economic actors whose actions are governed by economic considerations and legal requirements. Reconditioning, however, involves additional stakeholders, including private customers who can opt for or against a reconditioned spare battery and who may have a more personal attachment to their vehicles than business entities (Gauer et al., 2023), as well as workshops that may or may not offer reconditioned spare parts. Given the multitude of stakeholders involved in EVB EoL treatment decisions, predicting market trends proves challenging, particularly in the reconditioning sector.

Nevertheless, it is imperative to obtain accurate estimations of EoL EVB streams, as the construction of treatment facilities is capital-intensive, and the optimal development of capacity is heavily dependent on the quantities of EoL EVBs (Rosenberg et al., 2023). These quantities, however, are influenced by multiple factors. For instance, the sales figures of new EVs play a significant role (Huster et al., 2023a), but

Table 1
Overview of circular economy terms.

Term	Definition
Recovery	„Incineration of materials with energy recovery" (Potting et al., 2017)
Recycling	„[Any] recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (European Comission, 2008)
Repurposing	„Use discarded product or its parts in a new product with a different function" (Potting et al., 2017)
Reconditioning/refurbishment	„The process of returning a used product to a satisfactory working condition that may be inferior to the original specification" (Ijomah et al., 2004)
Remanufacturing	„The process of returning a used product to at least OEM original performance specification from the customers' perspective" (Ijomah et al., 2004)

they can fluctuate rapidly, such as when subsidies are discontinued, as observed in Germany (Crownhart, 2024), or when competitors enter the market and acquire market shares (Dau et al., 2022). Furthermore, legal requirements that affect EoL treatment options can be subject to change, as exemplified by the EU Battery Regulation.

There are estimates about EoL quantities from consulting firms (e.g., Breiter et al., 2023; Haas et al., 2023) and scientific institutions (e.g., Sanclemente Crespo et al., 2022; Skeete et al., 2020). However, the assumptions are often only partially disclosed, and frequently these estimates focus on EoL quantities for recycling and omit other EoL pathways. Notably, estimates that include battery reconditioning are infrequent (c.f.Section 2 for a more detailed overview). To date, no model adequately captures the complexity of the environment for EoL pathway selection, particularly with regard to stakeholders' interests. This paper aims to address this gap by introducing a flexible, parameterizable simulation model to estimate the demand and supply of reconditioned EVBs in the long term (up to 2050). The model primarily adheres to the discrete event simulation paradigm, but also incorporates agent-based elements. It considers the economic interests of OEMs, recyclers, repurposers, and reconditioners, and consequently also estimates battery quantities for recycling and repurposing as a by-product. Customer preferences towards reconditioned spare batteries are taken into account, as well as recycling quotas as imposed by the EU Battery Regulation. By offering a comprehensive view of the supply and demand dynamics within this ecosystem, the study also investigates potential market mismatches and the influence of key players, such as OEMs, consumers, and policymakers, in shaping the future of battery reconditioning. This approach is novel in its inclusion of diverse stakeholder interests, making it one of the first studies to holistically evaluate economic, social, and regulatory factors that could drive the adoption of reconditioned EVBs. The model is intended for OEM use and encompasses parameters that can be controlled by OEMs, as well as those that are beyond their control.

The remainder of the study is structured as follows: First, an overview of literature concerning reconditioning supply and demand estimation is given. Afterwards, in Section 3, the stakeholders and the discrete event and agent-based simulation model is described. Additionally, a case study examining the German BEV market is introduced. In Section 4, the findings of the case study are presented, followed by a discussion in Section 5. Finally, Section 6 provides concluding remarks.

2. Literature

The literature about EoL EVB forecasting predominantly focuses on recycling as the sole viable option. For instance, Shafique et al. (2023) used material flow analysis to estimate the recovery potential of materials from nickel manganese cobalt oxide (NMC) batteries globally up to 2038; while Wasesa et al. (2022) evaluated the lithium-ion battery recycling supply chain up to 2035 in Indonesia with a combination of system dynamics and an agent-based approach. Literature incorporating repurposing options is less prevalent and primarily employs material flow analyses. For example, Wu et al. (2020) estimate the EVB return quantities for recycling and repurposing for different provinces in China. The repurposing supply is determined by assuming that all lithium iron phosphate (LFP) batteries are suitable for repurposing (Wu et al., 2020). Yang et al. (2024) also estimate EVB return quantities for recycling and repurposing on province level in China. They assume a certain proportion of the EoL LFP batteries to be suitable for repurposing, evolving from 25 % in 2022 to 80 % in 2030. Fallah et al. (2021) determine the useable repurposing capacity of EVBs in Ireland as a proportion of EoL returns, commencing with a rate of 0 % in 2010 and increasing this rate by +10 % or +20 % in a low or high scenario, while assuming a remaining battery capacity of 80 %. In their estimation, they consider that repurposing increases the remaining value of an electric vehicle, thereby altering the costs. They examine the effect of repurposing on the demand for new electric vehicles under changing political conditions with regard to motor and vehicle registration tax, grants, and the ban of internal combustion vehicles (Fallah et al., 2021). Sanclemente Crespo et al. (2022) employ a product flow analysis for estimating EVB repurposing quantities and secondary material supply from recycling in Catalonia, Spain. For estimating repurposing quantities, they also assume certain rates of the collected EoL EVBs, starting from 10 % in 2017 and rising to 25 %–75 % in 2030, depending on the scenario. Demand for secondary storage is not considered. Pratap et al. (2024) utilize a system dynamics model to determine the raw material recovery potential from EoL EVBs in India while considering repurposing as an EoL option that delays recycling. They incorporate the financial aspect of the repurposing-vs.-recycling decision by setting repurposing and recycling costs and prices dynamically based on the collection quantities, and deciding on capacity expansion or contraction based on those costs. Demand is assumed to be a fixed value, corrected by a compound annual growth rate of 30 % (Pratap et al., 2024). Similarly, Seika and Kubli (2024) use system dynamics to estimate recycling and repurposing EVB quantities in Switzerland, considering the costs and profits of recycling and repurposing for decisions about capacity expansions or contractions. They investigate how the mandatory recycled materials shares imposed by the EU Battery Regulation affect those quantities.

A limited number of studies provide predictions regarding reconditioning quantities. Table 2 presents an overview of these studies. Notably, most research utilizes material flow analysis to estimate reconditioning quantities and focuses on determining supply. Supply is predominantly estimated as a fixed percentage of either all returning EVBs (e.g., Busch et al., 2014; Standridge and Corneal) or of those returning during the warranty period (Abdelbaky et al., 2020) or up to a certain use time (Kastanaki and Giannis, 2023). Only some of the studies consider demand (five out of eight, cf. Table 2). Busch et al. (2014), Duarte Castro et al. (2021) and Standridge and Corneal assume that reconditioned batteries are utilized in new electric vehicles, therefore substituting new battery demand. Huster et al. (2022) estimate demand based on the lifetime mismatch between vehicles and batteries. They assume that reconditioned batteries are only used as spare parts for vehicles up to a certain lifetime, whose battery failed prematurely. Tao et al. (2022) also incorporate consumers' preferences in their demand estimation. Based on survey results, they concluded that 57 % of customers prefer to replace their faulty EVB with a new one, 26 % with a reconditioned one, and 17 % prefer a direct reuse battery. In a high circularity scenario, they assume an increased demand for reconditioned and reused batteries, and also posit that reconditioned batteries can be utilized in new vehicles. However, it remains unclear how batteries are deemed suitable for reconditioning in their simulation model. Apart from private consumers, the only stakeholders included in one of the studies is politics, by considering legislation in the form of recycling efficiency targets set by the EU Battery Regulation for lithium, nickel, cobalt and copper (Kastanaki and Giannis, 2023). This refers to the recycling efficiencies for EoL EVBs, not to the minimum recycled content mandated by the same regulation for lithium, nickel and cobalt from August 2031 onwards.

It can be concluded that the supply of reconditioned EVBs is predominantly considered a technical issue, wherein a specific percentage is deemed suitable for reconditioning, and demand is either disregarded or assumed to be virtually unlimited if it substitutes demand originating from new vehicles. While the technical challenge undoubtedly exists (Kampker et al., 2020), decisions about reconditioning should also incorporate stakeholders' perspectives (Akano et al., 2021; Lieder et al., 2017). Tao et al. (2022) initiated this approach by including consumers' preferences concerning the replacement of a faulty battery with a new, reconditioned or directly reused battery. However, these preferences are represented as fixed proportions and are independent of the characteristics of the alternatives.

Qualitative studies have explored stakeholder perspectives regarding EV battery reconditioning and remanufacturing. For instance, Chirumalla et al. (2022) and Olsson et al. (2018) examine the roles of key

Table 2
Studies estimating EVB reconditioning quantities.

Publication	Method	Description	Determination of reconditioning supply	Determination of reconditioning demand	Stakeholders	Different cathodes
Abdelbaky et al. (2020)	MFA	Estimate EVB recycling potential in the EU up to 2040, considering remanufacturing and repurposing	Fixed percentage of failures during warranty (30 %–70 %, depending on the scenario)	n.d.	n.d.	No
Bobba et al. (2019)	MFA	Estimate stocks and flows of EVBs after their removal from electric vehicles in Europe up to 2035	Fixed percentage of returning EVBs (20 % in a high-reuse scenario)	n.d.	n.d.	Yes
Busch et al. (2014)	MFA	Estimate stocks and flows of EVBs and other vehicle parts in the UK up to 2050	Fixed rate of 95 %	Remanufactured EVBs are used like new ones → reman demand equals new demand	n.d.	No
Duarte Castro et al. (2021)	MFA	Estimate stocks and flows of EVBs in Brazil up to 2030	80 % of all EVBs that return because of vehicle failure, not battery failure.	Remanufactured EVBs are used like new ones → reman demand equals new demand	n.d.	Yes
Huster et al. (2022)	DES	Estimate EVB reconditioning potential in Germany, considering recycling and repurposing up to 2040	Fixed percentage of returning EVBs	Vehicles up to a certain age with a failed battery after the warranty period (→ reconditioned batteries are only used as spare parts)	n.d.	No
Kastanaki and Giannis (2023)	MFA	Estimate EoL EVB quantities for reconditioning, repurposing and recycling in the EU up to 2040	50 % of the batteries that fail after five or less years of use	n.d.	EU Battery Regulation (recycling targets)	Yes
Standridge and Corneal	MFA	Estimate EoL EVB quantities for reconditioning, repurposing and recycling up to 2030	Fixed percentage of returning EVBs (scenarios from 0 % to 85 %)	Remanufactured EVBs are used like new ones → reman demand equals new demand	n.d.	No
Tao et al. (2022)	Life cycle and market simulation	Estimate EoL EVB quantities for direct reuse, reconditioning, repurposing and recycling in Japan up to 2050, quantified by CO_2 emissions	Unclear	26 % of the replacement cases are fulfilled with reconditioned batteries and 17 % with direct reuse batteries. In a high scenario, reconditioned EVBs are also installed in new vehicles	Consumers (preference for battery replacement with new, direct reuse or reconditioned batteries)	No
This study	DES and AB	Estimate EoL EVB quantities for reconditioning, repurposing and recycling in Germany up to 2050	Dependent on demand and on financial viability for OEM, considering the alternatives recycling and repurposing, and reduced demand for new replacement batteries. Fixed percentage of batteries is unsuitable for reconditioning	Dependent on car workshops and on consumers' preferences, which in turn depend on the price, quality and environmental footprint of reconditioned batteries. Demand can also stem from OEMs' warranty cases	Consumers (preferences for battery replacements with new or reconditioned batteries or replacement of the whole car) OEM (also in the function of a repurposer and reconditioner) Recycler EU battery regulation (recycling targets and recycled materials in new batteries targets)	Yes

AB: agent-based simulation; DES: Discrete-event simulation; EoL: End-of-Life; EVB: electric vehicle battery; MFA: material flow analysis; n.d.: not defined.

stakeholders in the EV battery value chain, emphasizing the importance of collaboration across industries such as OEMs, recyclers, and energy storage providers. Wrålsen et al. (2021) identify governments and vehicle manufacturers as the most critical stakeholders, while also discussing the regulatory and financial barriers that impact circular business models for lithium-ion batteries. Kadner et al. (2021) extend this by including repair shops and logistics providers, highlighting the complexity of the roles these actors play in battery end-of-life management. Slattery et al. (2024) focus on the EV battery reuse and recycling network in North America. They discuss the role of various stakeholders, including manufacturers, remanufacturers, and policymakers, and the challenges in creating a closed-loop value chain for EV batteries. Their study emphasizes the importance of collaboration between these stakeholders to overcome barriers such as safety, transportation, and access to critical information.

Besides EV batteries, Abdul-Kader and Haque (2011) have examined stakeholder relations in the remanufacturing of tires using an agent-based simulation approach. Their study models the economic implications of remanufacturing processes and the involvement of different stakeholders such as tire manufacturers, recyclers, and consumers. Akano et al. (2021) explore decision-making factors in remanufacturability, focusing on the needs of primary stakeholders like OEMs and consumers. Kalverkamp and Raabe (2018) examine the automotive remanufacturing system, analyzing stakeholder interactions within the reverse logistics framework and highlighting the challenges faced by remanufacturers in balancing economic, environmental, and societal objectives. Their work adds to the broader understanding of the remanufacturing market, which could be useful in the context of EV battery reconditioning.

The present study extends existing quantitative approaches by including the consumers' and car' workshops' interests for or against reconditioned batteries in the demand estimation. Consumers' preferences are contingent upon the characteristics of reconditioned batteries with respect to price, quality, and environmental impact. Additionally, warranty cases may contribute to the demand for reconditioned batteries. The supply of reconditioned batteries considers the profitability for the OEM, the recycler, the reconditioner, and the repurposer, as well as potential lost sales of new spare batteries from the OEMs' perspective, in the event that reconditioned batteries are also supplied. Legislation is partially incorporated by considering recycling efficiencies and minimum recycled content of new batteries, as mandated by the EU battery regulation. To the best of the authors' knowledge, this study is the first to comprehensively examine the supply and demand of reconditioned batteries within the network of stakeholders with partially conflicting interests. The approach contributes to environmental management literature by expanding the technical focus of reconditioning research to include an economic perspective (OEM, recycler, repurposer, reconditioner) and a social perspective (consumers).

3. Materials and methods

To gain insights into stakeholders' interests, a comprehensive literature review was conducted, supplemented by 19 interviews and two surveys. Utilizing the information obtained from these sources, a flexible simulation model incorporating discrete event and agent-based elements was constructed. The model's flexibility is attributed to its 49 input parameters, enabling comprehensive depiction of future scenarios.

3.1. Stakeholders

The interview participants comprised representatives from automotive OEMs (2), recycling companies (2), scrap yards (5), and workshops (10). The OEMs, recyclers, and one of the scrap yards were also involved in repurposing activities. The surveys were conducted among workshops (58 complete responses, cf. Huster et al., 2024a) and with potential customers of reconditioned batteries (837 complete responses in a discrete-choice experiment, cf. Huster et al., 2024b). For the literature review regarding legal requirements, the European Union (EU) battery regulation served as the primary source, thereby establishing the regional focus of the study on the EU.

The stakeholders can be categorized into four distinct groups: business entities, workshops, customers, and legislative bodies.

3.1.1. Business entities

These encompass the OEMs, recyclers, reconditioners, and repurposers. The primary finding from the interviews was that, within the constraints of legal requirements, economic viability is the principal objective. Environmental sustainability was also identified as a decision criterion, albeit with the limitation that environmental and economic sustainability should be congruent.

3.1.2. Workshops

Although workshops are also business entities, they are categorized separately. The interviews and the survey indicated that the attitude regarding reconditioned spare parts for some workshops is influenced by opinions about those parts rather than factual information (Huster et al., 2024a). Consequently, factors beyond economic considerations may influence a workshop's decision to offer or not offer reconditioned spare EVBs.

3.1.3. Customers

Data regarding customers' spare battery preferences were obtained through a discrete-choice experiment involving 837 participants, with the results published in Huster et al. (2024b). The choice options presented were “buy a new battery”, “buy a reconditioned battery” or “buy a new car”. These options varied in terms of price, life expectancy, and the greenhouse gas (GHG) intensity of new and reconditioned batteries, as well as the new vehicle price. As a result, the utility functions of the three options was retrieved (Huster et al., 2024b).

3.1.4. Legislative bodies

While numerous national and international regulations may influence the EoL pathway of an EVB, the EU Battery Regulation, which was ratified in August 2023, is considered one of the most significant in Europe. This regulation applies to all types of batteries and encompasses the entire battery life cycle from production to recycling. With regard to EoL, the regulation imposes extended producer responsibility (EPR) on manufacturers, making them responsible for an adequate EoL treatment. However, it does not entitle the producers to the EoL batteries. Instead, end consumers are required to return them to certified collection points, which in turn must ensure the batteries are treated within the boundaries of the law. This treatment can be conducted by the producer or by third parties. Furthermore, the EU Battery Regulation mandates certain minimum material recovery shares from 2031 onwards, as well as minimum recycled content in new battery cells from August 2031 onwards. For EVs, the initial minimum recycled content shares are 16 % for cobalt (Co), 6 % for lithium (Li), and 6 % for nickel (Ni). These thresholds will increase five years later to 26 % (Co), 12 % (Li), and 15 % (Ni). It is noteworthy that battery manufacturers are not required to obtain recycled materials for new battery production from their own batteries. In addition to recycling quotas, the EU Battery Regulation also outlines requirements for reuse, remanufacturing, and repurposing, as well as the preparation of these EoL pathways. For instance, it transfers the EPR from the original economic operator who placed the battery on the market to the operator who places the second-life battery on the market. In return, remanufacturers are granted access to relevant information about the battery's composition and condition through the Battery Passport (European Parliament and European Council, 2023a). The significant transfer of responsibilities to the second-life operator suggests that reconditioning and repurposing are likely to be carried out by or in collaboration with OEMs.

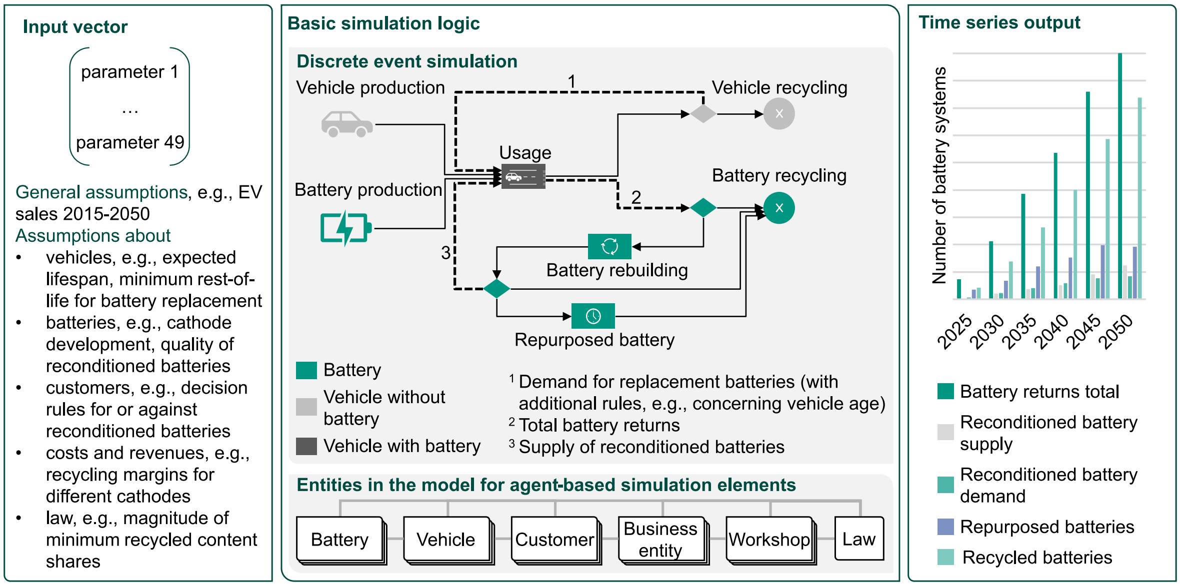


Fig. 2. General simulation logic (partially adapted from Huster et al. (2022)).

3.2. Simulation model

As stated in Section 1, the aim of this study is to create a flexible simulation model to estimate the demand and supply of reconditioned EV batteries up to 2050 under various future scenarios. For achieving this, a simulation model is constructed using the Java-based simulation software AnyLogic University 8.9.0. AnyLogic supports discrete event, agent-based, and system dynamics simulation paradigms, as well as the integration of these approaches. To capture detailed supply chain effects at an entity level, the discrete event paradigm is selected as the predominant logic. To incorporate effects arising from stakeholders' actions and interactions, agent-based elements are included. The general simulation logic is depicted in Fig. 2. A predecessor model, comprising only the entities "vehicle" and "EVB", has been published in Huster et al. (2022), and an extension including customers' preferences is presented in Huster et al. (2023b).

The model employs a 49-parameter vector as input. These parameters characterize the overall environment, including historical and anticipated EV sales data through 2050, hypotheses regarding the onset of battery reconditioning feasibility, and stakeholder-related factors. A thorough explanation of each parameter is accessible in the Supplementary Material.

The discrete event simulation methodology initiates with the production of batteries and vehicles, which are subsequently integrated to form an EV. This is followed by a utilization phase, which may conclude due to the failure of either the vehicle or its battery. The longevity of both components is governed by independent lifetime distributions, with battery lifespan further influenced by the specific battery type employed. Upon the failure of either component, both are processed through the next stage of the simulation model. At this juncture, the vehicle may receive a replacement battery or be retired, contingent upon its operational status or the user's decision regarding battery replacement. The battery may undergo recycling, be repurposed for alternative applications, or undergo reconditioning for use as a spare unit. These decision-making processes involve varying degrees of stakeholder participation.

3.2.1. Business entities and workshops

As delineated in Section 2.1, the business entities are presumed to make decisions based the economic viability of recycling, repurposing and reconditioning, each expressed as a percentage of the sales price of new EVBs. The margin and cost curves are established by values for the years 2023 and 2050, with linear interpolation for the intervening years. By setting the margins and costs in relation to the new sales price, the actual development of prices and costs, which depend on various factors including volatile raw material prices and difficult-to-predict energy costs, are excluded from consideration. Discounting thus becomes unnecessary. However, it is important to recognize both the advantages and limitations of using the "percent of new price" approach. On the one hand, this method simplifies the modeling process by providing a consistent metric that allows for easy comparisons between different EoL options, regardless of fluctuations in raw material or energy prices. By linking costs directly to the sales price of new EVBs, it also makes it easier to track changes over time without having to account for complex price dynamics. On the other hand, this approach assumes that all EoL options are equally sensitive to changes in raw material prices or other economic factors, which may not be the case in practice. For example,

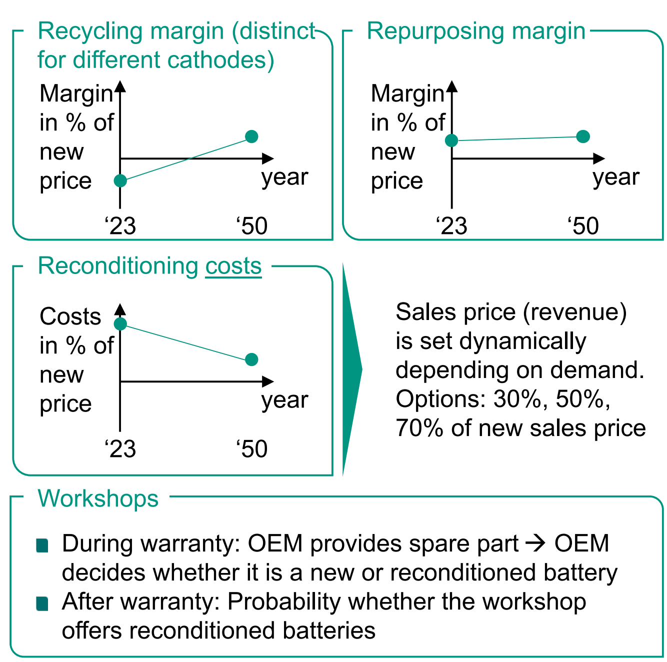


Fig. 3. Input parameters for business entities and workshops.

reconditioning may not be as directly impacted by raw material price increases as recycling, which heavily depends on the value of recovered materials.

While recycling and repurposing inputs are expressed as margins, the parameter for reconditioning is represented as costs. This distinction is made because the sales price of reconditioned batteries is a significant determinant of customer demand for replacement batteries after the warranty period (Huster et al., 2024b), and this way, the reconditioning entity can steer demand by setting the price for reconditioned batteries. As the EU Battery Regulation transfers numerous responsibilities of the original producer to the reconditioner, it seems likely that reconditioning is mainly done by OEMs or contract reconditioners. Consequently, reconditioned original EVBs compete with new original EVBs in the spare parts market. With the input parameters of new sales margin, recycling margin, repurposing margin, and reconditioning costs, the OEM can determine whether to offer reconditioned EVBs and how to establish the sales price of reconditioned batteries to maximize revenues. The considered sales prices are 30 %, 50 %, and 70 % of the new sales price, and they are determined annually based on which sales price would have been most advantageous in the previous year. This approach fully utilizes the willingness-to-pay of customers for new and reconditioned batteries while acknowledging the trade-off that occurs because some customers may not purchase a spare battery if the price is too high.

The decision regarding EVB replacement after the expiration of the battery warranty lies with the vehicle owner, while the OEMs determine the EVB selection in warranty cases. Warranty provisions typically specify that replacements should restore the vehicle to a condition appropriate for its age (Mercedes-Benz, n.d.), implying that customers are not entitled to a new battery in warranty cases, and a reconditioned battery may suffice. The simulation model allows for the option of OEMs utilizing reconditioned batteries in warranty cases when reconditioning is cheaper than manufacturing new batteries. Upon expiration of the warranty period, workshops also gain influence in the replacement decision. Given that some workshops even oppose parts that are remanufactured to a state as-good-as-new (Huster et al., 2024a), the model incorporates a specified percentage of workshops offering or not offering reconditioned EVBs as an input parameter. This approach assumes that customers do not actively seek workshops offering reconditioned EVBs but rather maintain their relationship with their trusted workshop. This assumption can be adjusted by setting the proportion of workshops offering reconditioned batteries to 100 %. The input parameters for business entities and workshops are depicted in Fig. 3.

3.2.2. Customers

Consumers determine battery replacement options in the event of EVB failure post-warranty expiration, in conjunction with workshops as laid out in Section 3.2.1. The available three alternatives are replacing the failed EVB with a new or reconditioned unit, or replacing the entire EV. Pertinent model inputs for this decision-making process encompass the lifetime loss and GHG savings of reconditioned EVBs compared to new ones, as well as the vehicle size as a proxy for vehicle price. Vehicle sizes are categorized in the model as proportions of small, medium-sized, and large vehicles. With this information, the utility of all replacement options is evaluated in each choice scenario. In instances where a reconditioned battery demonstrates the highest utility but is unavailable, a new battery may be chosen if this option provides higher utility for the specific consumer than replacing the entire EV.

Should the user of the simulation model be interested in the model outcome *without* considering consumers' utilities, it is also feasible to assume that all consumers opt for a new battery, all select a reconditioned battery, or all choose the EV replacement option.

3.2.3. EU battery regulation

The EU battery regulation requires specific minimum recycled content shares for newly produced EVBs from August 2031 onwards, as laid out in Section 2. While the regulation does not specify the source of these recycled materials, the simulation model incorporates an option to derive them from EVBs within the simulated environment. This feature necessitates the recycling of a sufficient number of batteries to obtain the requisite amounts of recycled cobalt, lithium, and nickel for new battery production. As a result, recycling may be mandated even when repurposing or reconditioning would be more economically viable.

The model also enables the assessment of increased recycled content share requirements for cobalt, lithium, and nickel in the reference years 2031 and 2036.

For assessing the impact of recycled content shares, the composition of batteries is critical. Three battery technology development scenarios are implemented in the model, from which the user can select: a scenario where NMC cathodes maintain long-term dominance (scenario name NCx); an LFP-dominant scenario (scenario name LFP); and a scenario in which solid-state batterie, namely lithium sulphur and lithium air batteries, take over significant market share from 2030 onwards (scenario name: Li-S & Li-Air) (Xu et al., 2020). The cathode scenarios are depicted in the Supplementary Information.

3.2.4. Outputs

The model outputs are of a time series nature with a five-year resolution. For the years 2025, 2030, 2035, 2040, 2045, and 2050, the total EVB returns, the EVB returns from vehicles (excluding returns from repurposing), the supply and demand of reconditioned EVBs, the quantity of repurposed EVBs, and the quantity of recycled EVBs are determined. Additionally, aggregated key performance indicators (KPI) over the entire simulated period for all the aforementioned categories are recorded. At an aggregated level, the quantity of recycled batteries is further subdivided into different cathode technologies, such as NMC111 or NMC622 (i.e., nickel, manganese and cobalt in a ratio of 1:1:1 or 6:2:2, Myung et al., 2017), to facilitate environmental analysis and resource planning.

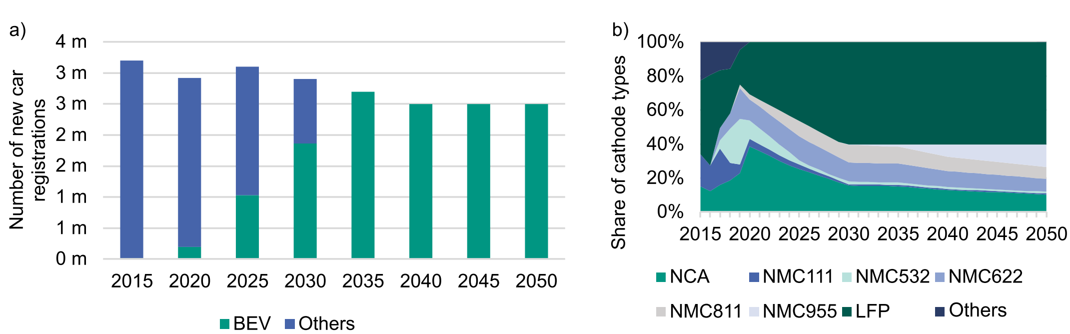


Fig. 4. a) Number of new car registrations. For 2015; 2020, the actual sales values are used (Kraftfahrt-Bundesamt, 2022). From then on, the total vehicle sales up to 2040 are assumed as predicted by Deloitte (2020) and kept constant for the following periods 2045 and 2050. From 2035 onwards, only BEVs are assumed to be newly registered due to the EU directive to only allow locally emission-free vehicles from then on (BMUV, 2023). The BEV sales values in between (periods 2025 and 2030) are linear interpolations. b) Cathode scenario, which is the LFP-dominant scenario of Xu et al. (2020), CC BY 4.0.

3.3. Case study

The model is applied to various parameter combinations for demonstrative purposes. Initially, a base case is established. Subsequently, parameters are varied for sensitivity analysis.

The base case aims to create a plausible scenario for the development of the German EVB EoL market. However, due to the lack of available data on actual values, some parameters must be estimated. The historical and projected Battery Electric Vehicle (BEV) sales data for Germany are utilized as input for the simulation model (cf. Fig. 4a). The simulation period spans 36 years, commencing from 2015. Initiating the simulation from a period when EVs began entering the market ensures that the model replicates the actual market development. Furthermore, a cathode scenario is assumed in which LFP cathodes will gain a significant market share ("LFP scenario", Xu et al. (2020), cf. Fig. 4b). The robustness of this assumption is tested later on in the parameter variation by assuming the NCx scenario and the solid-state scenario Li-S & Li-Air (cf. Section 3.2.3). Vehicles are assumed to have an average lifespan of 14 years (Oguchi and Fuse, 2015), while batteries are expected to last 10 years (NMC and NCO cathodes, Shafique et al., 2023)) and 12 years (other cathodes, based on Ding et al. (2019)). However, both for vehicles and batteries, higher and lower life expectancies can be found in the literature. For example, Ai et al. (2019) assume the lifetime of EVBs of unspecified cell chemistry to evolve from 5.5 to 12.5 years until 2035, Drabik and Rizos (2018) estimate an average EVB lifetime in an EV to be 8 years, most likely referring to NMC cathodes, and Schoch (2018) claim that with optimized charging, NMC batteries might last 25 years. LFP and more advanced battery chemistries are generally assumed to hav a higher lifespan than NMC batteries (Ding et al., 2019; Zhang et al., 2018). To account for the variability of assumptions, a longer and shorter battery life expectancy of two years for all chemistries is tested in the parameter variation section 4.2. The warranty period is set to the standard duration of 8 years (ADAC, 2022), and the production scrap is set at 10 % (Koenig, 2024), which also accounts as recycled content as it is reintroduced into production. Warranty replacements are presumed to be executed exclusively with new batteries. However, this is relaxed when varying the parameters in Section 4.2. Reconditioned batteries are unable to achieve a like-new condition (Autocraft Solutions Group, 2023). Since, to the authors' knowledge, it is not specified how much the condition of a reconditioned battery differs from that of a new battery, various lifetime reductions are tested. In the base case, a lifetime reduction of 4 years is assumed for all cell chemistries, and a reduction of 2 or 4 years is tested in the parameter variation section. The CO_2 emissions are estimated at 50 % of those of a new battery (Arnold et al., 2021), but higher and lower values (30 % and 50 %) are also tested. The sales margin for new batteries is set to 20 % in the base case (Zhang and Yang, 2023) and subject to variation in the sensitivity analysis, and the cost for reconditioning is assumed to be 40 % of the new sales price (Colledani et al., 2014). Minimum proportions of recycled cobalt, lithium and nickel from 2032 to 2036 onward are determined by the EU battery regulation (European Parliament and European Council, 2023a). For the parameter variation, cases where the recycled content is sourced from outside the system boundaries are tested, and cases where the recycled content quotas are doubled. Additional assumptions are delineated in the Supplementary Information.

4. Results

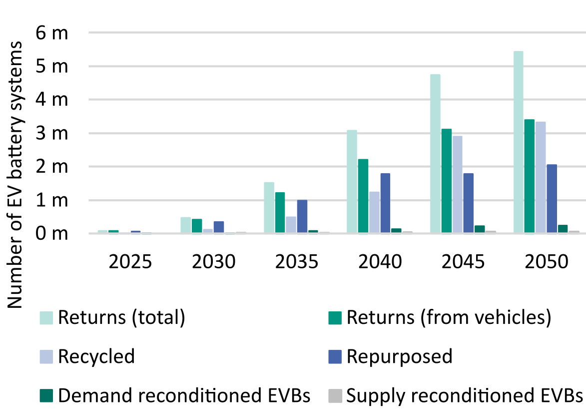
4.1. Base case

The base case of the case study, as laid out in Section 3.3 yields the outputs as depicted in Fig. 5. As expected, in 2025, only minimal quantities of EV batteries will be returned. Approximately 1.5 million EV batteries will be returned from 2035 onwards, with the number increasing to 5.4 million in 2050. This includes returning EV batteries from vehicles and after a second use phase in a non-automotive application. Return numbers from vehicle use reach a plateau from approximately 2045 onwards at about 3.1–3.4 million batteries, which equates to approximately 235–260 GWh of battery capacity, assuming 50 kWh batteries for small vehicles, 75 kWh for medium-sized vehicles, and 100 kWh for large vehicles. In the base case, repurposing is the predominant EoL strategy up to 2040, followed by recycling, and far behind, reconditioning. From 2045 onwards, more EoL batteries are recycled than repurposed, due to the high number of returning repurposed batteries. In all years, there is some demand for reconditioned EV spare batteries (up to approx. 240,000 in 2050). However, the supply peaks at approx. 50,000. It is plausible that the demand consistently exceeds the supply, as some consumers who would purchase a reconditioned battery would also consider purchasing a new spare battery with a potentially higher margin for the OEM. To mitigate cannibalization effects, it is sensible from an OEM perspective to attempt to maximize the willingness-to-pay with new batteries initially. Additionally, there may be a temporal mismatch between demand and potential supply that partially accounts for the discrepancy between supply and demand figures.

On an aggregated level of all years of the simulation (2015–2050), about 75.8 million EV batteries (5760 GWh) are manufactured, of which 65.3 million (4960 GWh) are returned in the examined time frame. Corresponding with the assumed new cathode production (Fig. 4b), the majority of recycled batteries are LFP batteries, followed by NCA, NMC622, and NMC811 cathodes.

4.2. Parameter variation

The influence of parameter changes on the demand and supply of reconditioned spare batteries varies significantly (cf. Fig. 6). While eliminating the minimum recycled content share in new batteries (Fig. 6, "Min. recycled content: 0") or doubling it compared to the



Aggregated over all years:

- Returning EV batteries (from vehicles and second-life applications: 65.3. m (4,960 GWh)
- Reconditioned EV battery supply: 0.85 m (65 GWh)
- Reconditioned EV battery demand: 3.2 m (240 GWh)
- Recycled NCA EV batteries: 9.0 m (605)
- Recycled NMC111 EV batteries: 0.7 m (50 GWh)
- Recycled NMC532 EV batteries: 1.0 m (75 GWh)
- Recycled NMC622 EV batteries: 5.2 m (395 GWh)
- Recycled NMC811 EV batteries: 2.8 m (210 GWh)
- Recycled NMC955 EV batteries: 0.35 m (25 GWh)
- Recycled LFP EV batteries: 14.2 m (1,075 GWh)
- Manufactured EV batteries: 75.8 m (5,760 GWh)

Fig. 5. Results of the base case.

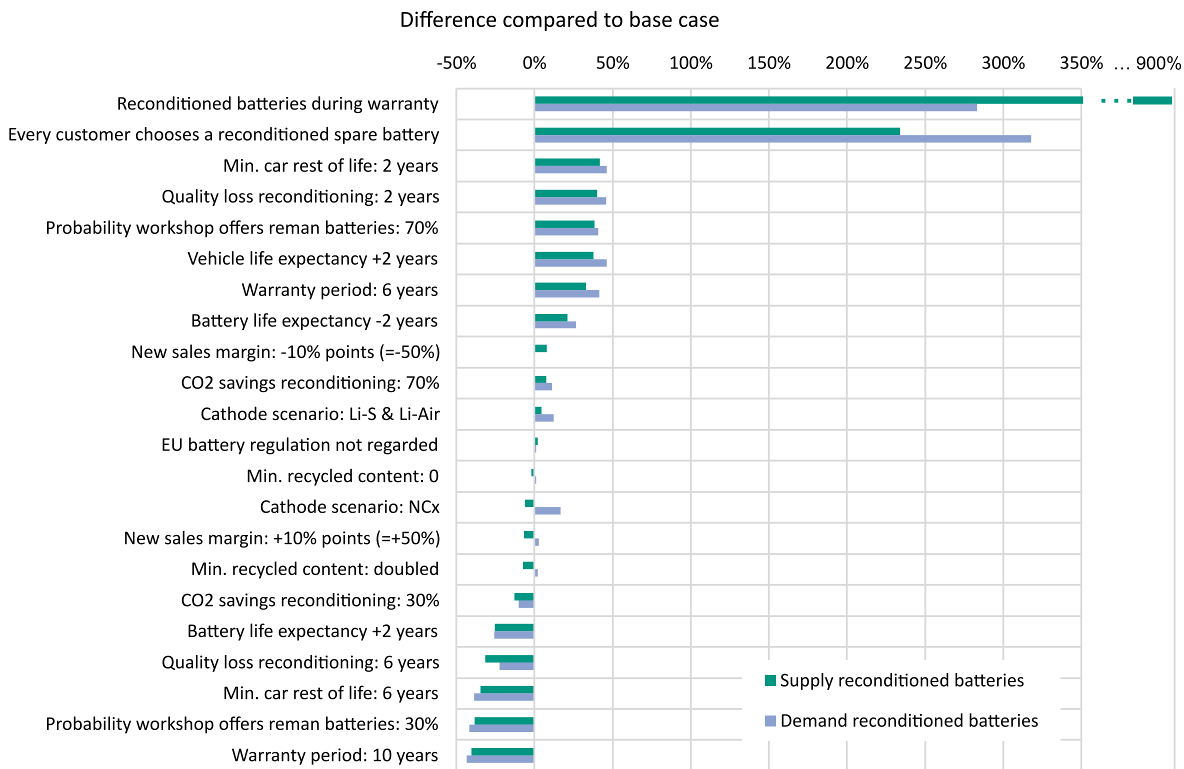


Fig. 6. Difference of supply and demand for reconditioned batteries compared to the base case for certain parameter variations.

current EU Battery Regulation requirements (Fig. 6, "Min. recycled content share: doubled") has minimal effect on the aforementioned KPIs, other parameters, such as the assumption that all consumers select reconditioned batteries as spare parts for battery replacements after the warranty period (Fig. 6, "Every customer chooses a reconditioned spare battery"), substantially increase both demand and supply (+320 % and +230 %). While, in the base case, consumer decisions follow the results obtained in Huster et al. (2024b), the assumption that all consumers opt for reconditioned spare batteries would imply a drastic change in consumer behavior toward reconditioned spare parts, potentially due to price incentives or environmental awareness campaigns (cf. Section 5). The majority of parameters fall between these extremes, ranging from hardly any effect to a large effect.

In the event that the average battery lifetime is two years longer or shorter than in the base case (Fig. 6, "Battery life expectancy +2 [−2] years"), demand and supply fluctuate by approximately 25 % in the anticipated direction, which is an increase of 25 % if the battery has a shorter lifespan, and a decrease of 25 % in the opposite scenario. In case the vehicle is more durable than expected (+2 years, 16 years in total), demand and supply increase by approximately 40 %, as the timeframe in which consumers may replace batteries after the warranty period expiration extends. Similarly, if cars are only eligible for battery replacement up to a remaining useful life of six years instead of four years (Fig. 6, "Min. car rest of life: 6 years"), supply and demand of reconditioned batteries decreases by about 35–40 %, while they increase by 40–45 %, if vehicles with a remaining useful life of two years remain eligible for battery replacement (Fig. 6, "Min. car rest of life: 2 years"). An extension of the warranty period by two years results in approximately 40 % less demand for reconditioned spare batteries, and a reduction by two years leads to an increase in demand of similar magnitude (Fig. 6, "Warranty period: 10 years [6 years]").

As a reminder, the base case assumes that OEMs do not use reconditioned spare batteries for warranty cases, even if the reconditioning costs are below the manufacturing costs for new batteries. Altering this assumption results in an increase in demand for reconditioned batteries by nearly 900 %, and an increase in supply by almost 300 % (Fig. 6, "Reconditioned batteries during warranty"). In absolute numbers, this translates to a requirement of 12.2 million reconditioned EVBs instead of 3.2 million units, and a supply of 8.35 million reconditioned EVBs instead of 0.85 million batteries. With regard to warranty cases, only two-thirds of those intended to be fulfilled by reconditioned batteries receive suitable supply. This discrepancy is attributed to a temporal mismatch of supply and demand of suitable batteries of the right cathodes. It becomes evident that the OEMs' decisions regarding the use of reconditioned spare parts during the warranty period are crucial for assessing the significance of reconditioning in the future.

Further parameters that were varied include the CO_2 savings of reconditioned batteries compared to new batteries (Fig. 6, "CO_2 savings reconditioning: 30 % [70 %]"), and the average lifetime loss compared to new batteries (Fig. 6, "Quality loss reconditioning: 2 years [6 years]"). A decrease in CO_2 emissions by 20 percentage points (from 50 % savings to 70 % savings; 40 % increase) results in an increase in demand of approximately 10 %, while an increase in emissions of the same magnitude reduces the demand by 10 %. A reduction in battery life expectancy of reconditioned batteries of six years instead of four years in the base case (+50 %) decreases the demand by approximately 20 %, whereas a reduction of two years instead of four years leads to an increase in demand by 45 %. Consequently, the quality of reconditioned EVBs significantly influences their demand and supply.

While most parameter variations change supply and demand for reconditioned batteries in the same magnitude, there are some parameters whose variation changes one of the KPIs more than the other. For instance, modifying the assumptions regarding the sales margin by 50 % does not affect the demand for reconditioned batteries but influences the attractiveness of supplying reconditioned batteries for the OEM (+8 % [−8 %]), in the event that the sales margin decreases [increases].

In the base case, a cathode scenario is assumed in which LFP will be dominant with about 60 % market share from 2030 onwards (cf. Fig. 4 b). As mentioned in Section 3.2.3, two other scenarios can be chosen, namely the *NCx* and the *Li-S & Li-Air* scenario (cf. Supplementary

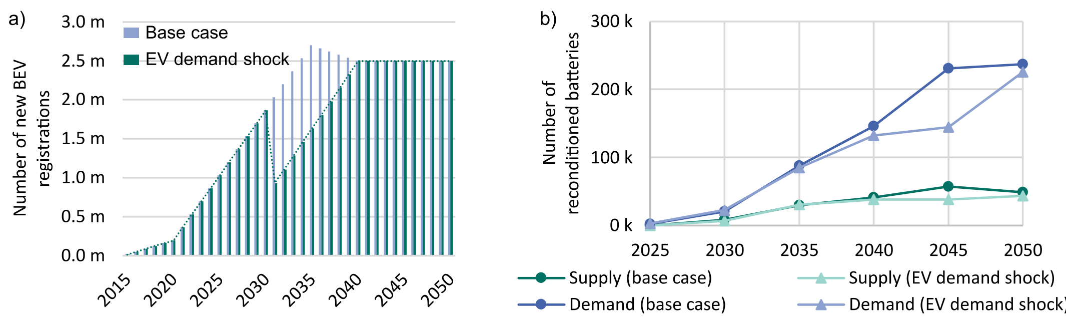


Fig. 7. a) BEV new registrations in case of a demand shock in 2031 and a 5-year recovery period. b) Resulting supply and demand for reconditioned EVBs.

Information Fig. S1). In the *NCx* cathode scenario, the demand for reconditioned batteries rises by approximately 17 %, while the supply decreases by 6 %. This can be explained, first, by the shorter lifetime that is assumed for NMC and NCA batteries compared to LFP batteries. It leads to more early battery failures compared to the vehicle life, so that the demand for spare batteries (new or reconditioned), rises. However, NMC batteries contain more valuable materials than LFP batteries, so that recycling might be more favorable than reconditioning, hence the slight decline in reconditioned battery supply. The *Li-S & Li-Air* scenario depicts the case where solid-state batteries enter the market in 2030 and gain a market share of about 60 % from 2040 onwards (Xu et al., 2020). As Fig. 6 shows, the demand for reconditioned batteries increases by 12 %, and the supply by 4 %. The higher demand can again be explained by the shorter assumed lifetime of NMC and NCA batteries, that per scenario assumption have a higher market share for longer than in the *LFP* scenario. This time, the supply partially follows the demand, since Li-S and Li-Air batteries, like LFP batteries, contain only a limited amount of valuable materials.

Workshops also have a significant influence on the adoption of reconditioned batteries. If instead of 50 % of the workshops, as assumed in the base case, 30 % [70 %] offer reconditioned spare batteries, supply and demand decrease [increase] proportionally by approximately 40 %.

While the factors discussed above are static throughout the simulation, time-dependent variables can also change, which is particularly useful for assessing the impact of disruptive events, such as a sudden shock in BEV registrations caused by tariffs or disruptions in the supply chain due to pandemics or political conflicts. To illustrate this, a scenario is examined where BEV demand experiences a sharp decline, halving from 2030 to 2031. After five years, the demand is assumed to return to its 2030 level, and five years after that, the base case and demand shock scenarios are assumed to realign. This is shown in Fig. 7a. Overall, the "EV shock scenario" results in a 13 % decrease in EV sales compared to the base case. Fig. 7b illustrates the corresponding effect on the supply and demand for reconditioned batteries. Given the long lifespan of both EVs and their batteries, and the distribution of their assumed lifetimes, the steep decline in demand is gradually smoothed out. The most significant impact occurs in 2045, when both demand and supply are approximately 35 % lower than in the base case. In total, the demand shock could lead to a 20 % reduction in the supply and demand for reconditioned batteries, a decline that is greater than the reduction in EV sales.

While the focus of this research is on the demand and supply of reconditioned batteries, it is pertinent to address an observation regarding the number of recycled EVBs that emerges when considering scenarios where the recycled content quotas of the EU Battery Regulation are doubled or disregarded entirely. In the absence of recycled content quotas within the system boundaries, no significant changes in the number of recycled batteries are observed (cf. Fig. 8). This indicates that with the minimum recycled contents mandated by the EU from 2031 to 2036 onwards, no batteries would be recycled prematurely instead of being reused, assuming the other parameters of the base case prove accurate. Conversely, if the minimum recycled content quotas were doubled (i.e., 32 %/12 %/12 % for Co/Li/Ni from August 2031 onwards and 52 %/24 %/30 % for Co/Li/Ni from August 2036 onwards), a notable shift in recycling quantities becomes apparent. In 2035, shortly after the introduction of minimum recycled material shares, 26 % more EVBs require recycling compared to the base case. This implies that to meet the demand for recycled content in new battery production, end-of-life batteries that would otherwise be economically viable for reuse in other applications must be recycled. The earlier recycling of some EVBs up to 2040 results in fewer battery systems being recycled later (2045–2050) than in the base case for two reasons:

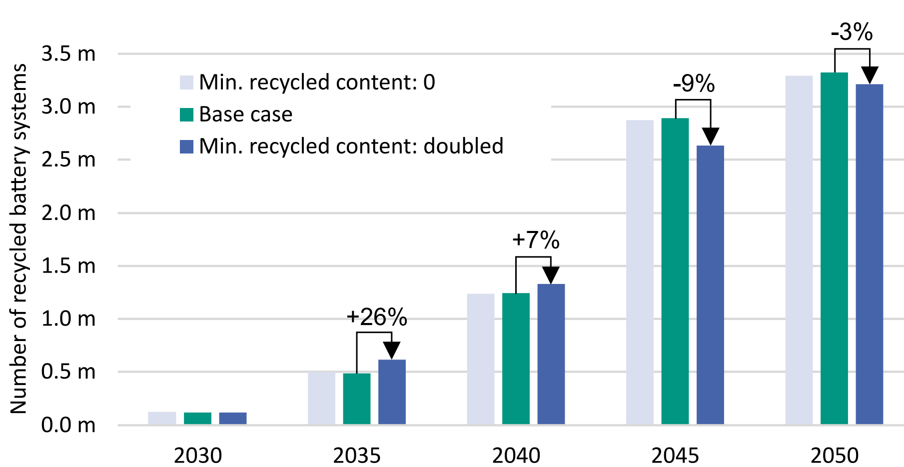


Fig. 8. Change in the number of recycled battery systems if there is no mandatory share of recycled materials in new batteries and if the target recycled content is twice as high as the EU Battery Regulation demands.

5. Discussion

First, in the more distant future, the numbers of returning and manufactured battery systems approach parity, and sufficient batteries return for final recycling from all previous applications to fulfil the demand for recycled materials. Consequently, early recycling at the expense of second-life applications would no longer be necessary. Second, batteries that would have been utilized for second-life purposes in the base case would have already been recycled earlier in the high recycled content scenario. Therefore, the recycling quantities would shift from a later point in time to the nearer future.

5.1. Evaluation and stakeholder recommendations

Regarding the low numbers of reconditioned batteries in the base case and most other cases of the case study, the question arises whether or not reconditioning is a relevant EoL option that should be further examined. The demand for reconditioned EVBs is projected to be approximately 20,000 in 2030 and 240,000 in 2050, with a supply of only 8600 reconditioned EVBs in 2030 (50,000 in 2050), assuming the base case scenario. These figures align with the estimates of Kastanaki and Giannis (2023), who project an annual supply of reconditioned EVBs in Germany ranging from 7000 to 29,000 from 2024 to 2034. It is important to note that these numbers pertain to the entire German market. In a scenario focusing on a single OEM with, for instance, a 10 % market share, these figures would decrease proportionally. Nevertheless, if OEMs intend to promote reconditioning, they could focus on developing long-lasting, high-quality reconditioning batteries, provide education to workshops about reconditioned parts, and, most importantly, utilize reconditioned spare batteries for warranty cases. While the longevity of batteries primarily addresses consumers' concerns regarding the quality of reconditioned spare batteries, educating workshops aims to reduce resistance against reconditioned and remanufactured parts (Huster et al., 2024a). Appropriate warranties could help in building up the workshops' trust in reconditioned products, thus increasing the share of workshops that offer reconditioned spare parts. It remains open whether in addition to perceived warranty issues and reduced profitability of reconditioned parts, other behavioral barriers, like status quo bias (Godefroid et al., 2023), have to be overcome. However, OEMs considering reconditioned spare batteries for warranty cases potentially has the most significant impact. Given that the simulation model only registers OEMs' demand for reconditioned batteries when the reconditioning costs are lower than the production costs for new batteries, it should be an intrinsic motivation for OEMs to utilize reconditioned batteries in such instances.

Even if OEMs do not facilitate reconditioning with the aforementioned measures, the economically viable quantities of reconditioned batteries remain significant. If approximately 850,000 EVBs are reconditioned up to 2050 (accumulated number in the base case), this equates to approximately 65 GWh in battery capacity. In the event that new spare batteries were utilized instead, approximately 5.2 million tons of CO_2 equivalents more would be expended for battery production, assuming an average global warming potential of approximately 80 kg CO_2 equivalents/kWh capacity for cell production, including benefits from hydrometallurgical recycling (Mohr et al., 2020). Even with the assumed CO_2 intensity of reconditioning at 30 %, 50 %, or 70 % of the new production emissions, the savings are substantial from an ecological perspective. These figures provide only a rough estimate, and future research could offer a more detailed quantification of the ecological contribution of reconditioning. While numerous LCAs of EV batteries include recycling (e.g. Feng et al., 2022; Mohr et al., 2020), repurposing is less frequently considered (e.g., Liu et al., 2023; Wrålsen and O'Born, 2023; Zhou et al., 2025), and to the authors' knowledge, no LCA includes reconditioning in detail (Husmann et al., 2024). Future research could built upon the work of Philippot et al. (2022), who explore the reuse of EV batteries in vehicles following an inspection step but without reconditioning, and extend their approach by differentiating between various current and future battery chemistries, including solid-state batteries, as Popien et al. (2023) have done for the production phase.

Furthermore, reconditioning provides consumers with cost-efficient spare parts, potentially enhancing the perceived service level. If only a limited number of batteries are reconditioned, the costs for researching and developing reconditioning processes are allocated to a small number of batteries, thereby increasing the reconditioning cost. This primarily affects destruction-free disassembly and testing technologies. However, these technologies are also beneficial for repurposing activities, and they are essential in cases where single modules or even cells should be replaced under warranty, rather than replacing the entire battery system. Therefore, further research into technologies that enable reconditioning supports other EoL strategies, and vice versa. This research can be promoted by policymakers through the provision of research grants, by companies through investments in this area of development, and by universities and other research institutions.

Policymakers have recognized the importance of EoL battery management through circular economy legislation, with one prominent example being the EU Battery Regulation. As outlined in Section 3.1, this regulation assigns responsibility for proper EV battery EoL treatment to the economic operator who places the battery on the market, typically the OEM, through an EPR scheme. However, it does not grant this operator ownership of the EoL batteries. For remanufactured or repurposed batteries, the EPR is transferred to the operator who places the second-life battery on the market (European Parliament and European Council, 2023a). Additionally, the proposed new End-of-Life Vehicle Directive mandates that EV batteries must be removable from the vehicle, making them replaceable, potentially with reconditioned batteries (European Parliament and European Council, 2023b). On one hand, these regulations could promote reconditioning and repurposing by leveling the playing field for various stakeholders, setting uniform rules, and providing valuable information about battery chemistry and disassembly procedures via the Battery Passport. On the other hand, these regulations might also pose challenges, as the requirements could be too stringent for some stakeholders. Furthermore, there are still grey areas within the legislation that may be addressed once delegated acts, which have yet to be implemented, are executed. Given the conflicting interests of different stakeholders, finding a solution that ensures safety for end customers, fairness for economic players, and environmental benefits is a significant challenge for policymakers. Despite the constraints imposed by current and proposed legislation, policymakers still have opportunities to promote specific EoL pathways. If reconditioning is a priority, various stakeholders can be targeted with tailored measures: subsidies for reconditioned spare batteries could lower their cost, thus stimulating demand, while public information campaigns could help shift consumer attitudes toward reconditioned products. OEMs and other business entities could be incentivized to invest in reconditioning technologies through subsidies or other forms of funding. Additionally, both end customers and workshops may be more inclined to adopt reconditioned batteries if warranties for reconditioned parts are clearly defined and easy to enforce.

Another recommendation for policymakers addresses planning security. Most parameters in the model reflect decisions to be made by OEMs, consumers, recyclers, reconditioners, and policymakers. It was notable that altering the quotas for minimum recycled content shifted the recycling quantities to earlier points in time. This is relevant for OEMs and recyclers with regard to building recycling capacity and manufacturing new (spare) batteries. Additionally, decisions made in the present will often only come into effect much later, due to the long lifetime of batteries and vehicles. Therefore, policymakers should acknowledge the long lifetime of batteries and provide planning security well in advance.

5.2. Limitations

The presented simulation model captures the complexity associated with estimating the future demand and supply of reconditioned EVBs by allowing parametrization with 49 parameters. While the spectrum of scenarios assessable with the model is extensive, there are limitations to the approach. For selected parameters, the effect of varying those on the demand and supply of reconditioned EVBs was examined. However, this does not substitute for a detailed feature importance ranking, as is common for other types of models (e.g., machine learning methods, König et al., 2021). Without ascertaining the importance of a parameter, it cannot be guaranteed that it has a significant influence on the model and does not merely add complexity without contributing value. Since each simulation run requires approximately 10 min with AnyLogic 8.9.0 on workstation equipped with an Intel Core i9-14900K processor (24 cores, 32 threads, 3.2 GHz) and 192 GB RAM, it would be advantageous to reduce the complexity if a large-scale simulation study is intended. That holds especially because due to stochasticity in the model, replications of each run are recommended, which increase the time to evaluate one configuration. The long runtime and the high number of parameters also make it difficult to conduct detailed sensitivity studies, such as Monte Carlo simulations, as they would require excessive computational time. For smaller studies that evaluate selected scenarios only, reducing the complexity by decreasing the number of input factors is of minor relevance. Looking ahead, one possible approach to address these challenges is to approximate the simulation model using machine learning methods, which could facilitate more efficient sensitivity analysis and scenario evaluation.

Another limitation of the simulation model is the lack of consideration for demand for repurposed batteries. In the base case, approximately 27 GWh of repurposed EVBs are supplied in 2030. Engel et al. (2019) estimate that the supply of reconditioned batteries for stationary applications will be approximately 35 GWh per year in 2030 in the EU, while the annual demand is expected to be two-thirds higher. Considering that Germany produces about 14.4 % of the electricity in Europe (IEA, 2023b), the supply estimated in this study might exceed the demand. Other studies estimate the installed capacity of large-scale energy storage systems in Germany to be 50–100 GWh in 2030 and increase to 275–375 GWh in 2050 (Frontier Economics, 2023). Therefore, the supply estimated by the simulation model may be within the boundaries for energy storage demand, but it may also exceed it. Further studies are necessary to determine demand for second-life EVBs more precisely. If the mechanisms are fully understood, they can be integrated into the simulation model.

Additionally, the simulation model could be further refined to integrate the technical feasibility of reconditioning or repurposing in greater detail. Currently, the economic balance is considered for repurposing, while both economic factors and the preferences of consumers and workshops are taken into account for reconditioning. Furthermore, to address technical limitations and defects, a proportion of batteries is deemed unsuitable for any reuse strategy and is directed straight to recycling. Another portion is considered suitable for repurposing in less demanding applications than the original, but not for reconditioning. For a more comprehensive simulation, the supply chain model could be expanded to include a chemical simulation that accounts for the aging of battery cells in each EV battery system. This would allow for more informed decisions regarding the feasibility of repurposing or reconditioning at the cell or module level. Currently, it is often assumed that EV batteries are retired when they reach 70 %–80 % of their original State-of-Health (SoH), with repurposing being the only reuse option thereafter (e.g. Al-Alawi et al., 2022; Wrålsen and O'Born, 2023). However, the validity of the 70 %–80 % threshold for retirement has been widely questioned (Etxandi-Santolaya et al., 2023). Consequently, integrating cell aging and stakeholder-specific criteria for EV battery retirement could enhance the decision-making process between repurposing and reconditioning.

The proposed case study focuses on Germany and considers it as a closed ecosystem. This limitation can partially be addressed by extending the system boundaries in other case studies by selecting the values for the 49 parameters accordingly. However, in every non-global scenario, the outflow of batteries or battery materials from the system is possible and probable in reality. For instance, in 2017, approximately 34 % of the de-registered vehicles in the EU were unaccounted for (Williams et al., 2020). The 2017 figures predominantly encompass vehicles with internal combustion engines rather than electric vehicles; nevertheless, they provide insight into the potential magnitude of vehicles and batteries that could be affected by system outflow. For the simulation model, this outflow is not modeled, as it is unlikely to significantly impact the supply and demand of reconditioned EV batteries. In the model, both batteries and vehicles must meet specific criteria regarding their condition, measured, for example, in terms of remaining useful life to be eligible for reconditioning or receiving a spare battery. It is assumed that the issue of unaccounted vehicles primarily affects batteries and vehicles in poor condition.

It has been laid out that the 49 parameters allow for modeling a broad range of real-world scenarios. This is done by feeding an MS Excel file with one column per parameter and one row per scenario to the simulation model. However, there might be changes in reality that cannot be captured by the parameters. In this case, the simulation model has to be adjusted. Some changes can easily be made, for instance with regard to the cathode scenario, for which the annual market share of different cathodes from 2015 to 2050 is drawn from a table ("database" object in AnyLogic). Similarly, the composition of the different cathodes per kWh is stored as a table and can easily be exchanged. Other changes would require more effort and more information about the system. That holds especially with regard to stakeholders other than the ones already implemented. For example, retailers may influence the availability of reconditioned parts for workshops, local governments may affect end customers attitude towards reconditioned spare batteries through subsidy schemes, or environmental activists could shift the perception of reconditioning by awareness campaigns. However, empirical analyses on how these stakeholders interact with those already implemented would be necessary and remain a field for future studies.

6. Conclusion

This paper presents a simulation model for estimating the demand and supply of reconditioned EVBs based on scenarios constructed from 49 parameters. These parameters encompass aspects such as BEV sales development, battery cathode evolution, expected lifetimes of batteries and vehicles, consumer preferences, and the development of costs for EoL options. The model accounts for the economic trade-offs faced by stakeholders, including OEMs' decisions to recycle, repurpose, or recondition a battery, and private consumers' decisions regarding the replacement of faulty EVBs with reconditioned or new spare batteries. Furthermore, the model incorporates the effects of the EU Battery Regulation concerning minimum recycled content requirements.

A case study focused on Germany revealed that reconditioning represents a niche EoL option for EVBs when these batteries are utilized solely as spare batteries by consumers for battery swaps after the warranty period. Consumer demand can be primarily influenced by the longevity of reconditioned batteries and the attitudes of workshops towards these batteries. The most significant factor affecting both supply and demand for reconditioned EVBs is the OEMs' decision to utilize these batteries for warranty cases. Should OEMs choose to do so, demand and supply will increase substantially. However, due to potential temporal mismatches between returning batteries of a specific type and the demand for that type, not all warranty cases can be fulfilled with reconditioned batteries, necessitating the continued use of new spare batteries.

OEMs and policy makers have the most significant influence on the EoL option selected for EVBs. OEMs can focus on enhancing the quality of EVBs and communicate this to consumers and workshops through appropriate warranty provisions, while strategically pricing to avoid cannibalizing new spare battery sales. Additionally, they can potentially reduce warranty expenses by utilizing reconditioned batteries. Policy makers primarily influence the EoL option by establishing the regulatory framework, which should remain stable for a considerable period due to the long lifetime and consequent long-term planning requirements of EVBs.

CRediT authorship contribution statement

Sandra Huster: Writing – original draft, Methodology, Conceptualization. **Raphael Heck:** Writing – review & editing, Methodology. **Andreas Rudi:** Writing – review & editing, Supervision. **Sonja Rosenberg:** Writing – review & editing, Conceptualization. **Frank Schultmann:** Writing – review & editing, Supervision.

Use of generative artificial intelligence

During the preparation of this work the authors used the tool “Paperpal” in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125783.

Data availability

Additional data beyond that provided in the supplementary information is available from the corresponding author upon reasonable request.

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