Resources, Conservation & Recycling 212 (2025) 107943

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Conceptual model for extending electric vehicle battery lifetime

America Rocio Quinteros-Condoretty [a,*], Minttu Laukkanen [a], Laura Kainiemi [b], Sara M. Pinto [d], Emanuel J. Lourenço [d], Luís Oliveira [d], Laura Albareda [a], Bernardo Barbiellini [c]

[a] LUT University, Business School, Yliopistonkatu 34, P.O. Box 20, FI-53851 Lappeenranta, Finland
[b] LUT University, School of Energy Systems, Mukkulankatu 19, FI-15210 Lahti, Finland
[c] LUT University, School of Engineering Science, Yliopistonkatu 34, P.O. Box 20, FI-53851 Lappeenranta, Finland
[d] INEGI, Campus da FEUP, Rua Dr. Roberto Frias, 400 4200-465 Porto, Portugal

ARTICLE INFO

Keywords:
Circular economy
Repurposing
Electric vehicles
Lithium-ion batteries
Second life
Third life

ABSTRACT

To maximise the resource efficiency of electric vehicle lithium-ion batteries (LIBs), their lifetimes can be extended through cascading second- and third-life applications. Using expert input, this study establishes a conceptual model for understanding these applications' state of health (SOH) thresholds and user requirements. Using a qualitative methodology, including focus group discussions with multistakeholder experts and policy analysis of the European battery regulatory landscape, we propose extending LIB use. Our model outlines potential second- and third-life applications aiming to maximise battery value retention. The findings highlight gaps in current European Union regulations that inadequately support battery-repurposing strategies. The conceptual model with an SOH threshold and key performance indicators serves as a foundation for researchers and industries to explore cascading battery applications, foster long-term resource efficiency and contribute to the circular economy by extending LIB lifespans through repurposing initiatives.

1. Introduction

With the global transition towards sustainable energy alternatives, electric vehicles (EVs) have become a central focus of both mobility and stationary energy storage system (ESS) applications (Quinteros-Condoretty et al., 2020; Virmani et al., 2023). The growing demand for lithium-ion batteries (LIBs) in EVs has increased interest in battery circularity, driving new regulations, such as the European Battery Regulation [Regulation (EU) 2023/1542; European Commission (EC), 2023a], which aims to promote sustainability by encouraging circularity in the battery industry. The literature has offered different circular economy strategies (CESs) for LIBs, including remanufacture, reuse, repurpose and recycling, along with different scenarios for developing the battery sector and life-cycle management (Baars et al., 2021; Bobba et al., 2019; Dunn et al., 2023; Glöser-Chahoud et al., 2021; Nurdiawati and Agrawal, 2022). The present article focuses on the repurposing of LIBs, a key strategy within the circular economy (CE) to extend the battery's lifespan by finding new applications beyond their original use (Stahel, 2016). LIBs can be effectively repurposed for various second- and third-life applications (Quinteros-Condoretty et al., 2021).

Defined as the complete or partial reuse of a battery for a different application (Börner et al., 2022), repurposing offers a sustainable alternative to immediate recycling (Dunn et al., 2023) with the aim of extending the battery's lifetime (Bobba et al., 2019). In the EV industry, batteries are seldom directly reused without refurbishment or remanufacturing (Glöser-Chahoud et al., 2021) because of the degradation of their technical characteristics over time (Hu et al., 2020). Repurposing is relevant for spent EV batteries, which can still serve in ESSs where diminished capacity is less critical (Baars et al., 2021).

Distinguishing between second- and third-life applications for EV batteries is important because they differ in their technical requirements. For example, an EV battery with 80% remaining capacity (Dunn et al., 2023; Shahjalal et al., 2022) may be deemed 'too good' for certain applications, for example, as a backup power source. Given that the circular EV LIB industry is a new and evolving domain (Albertsen et al., 2021), a systemic understanding of it and pertinent regulations and policies is critical (Morseletto, 2020; Nurdiawati and Agrawal, 2022); these regulatory frameworks are viewed not only as the most critical drivers of the adoption of CESs for LIBs (Wrålsen et al., 2021) but also as barriers to their widespread implementation (Chirumalla et al., 2023; Shahjalal et al., 2022). Furthermore, policy development should

---

* Corresponding author.
E-mail address: americaqc@gmail.com (A.R. Quinteros-Condoretty).

https://doi.org/10.1016/j.resconrec.2024.107943
Received 30 November 2023; Received in revised form 11 September 2024; Accepted 24 September 2024

incentivise the adoption of higher-level CESs, such as repurposing (Albertsen et al., 2021). A holistic approach is essential for maximising long-term resource efficiency by integrating a cascading use of EV batteries across their second and third lives (Quinteros-Condoretty et al., 2021).

Once EV LIBs degrade to 80% of their initial capacity, they have reached the end of their automotive lives (Haram et al., 2021). However, spent EV batteries retain a significant capacity and can operate for additional years when repurposed (Muhammad et al., 2019). Large batteries can be repurposed as stationary power sources (Colarullo and Thakur, 2022), allowing for better exploitation of the storage capacity of LIBs (Bobba et al., 2019) and increasing their utilisation and potentially decreasing their total lifetime costs (Börner et al., 2022); this will reduce their negative environmental impact more significantly than recycling (Dunn et al., 2023). However, repurposing has several challenges, such as delayed recycling and material recovery (Nurdiawati and Agrawal, 2022) and regulatory inconsistencies hindering its adoption (Chirumalla et al., 2023).

Most studies have focused on second-life applications in ESSs and their specific key performance indicators (KPIs) and state of health (SOH) thresholds (Börner et al., 2022). However, there is a gap in understanding the technical requirements for various repurposing applications, especially third-life applications. Second- and third-life applications, such as in residential households, uninterruptible power supplies (UPSs), and grid-scale power variance, can extend battery life by 7–10 years (Bobba et al., 2018; Haram et al., 2021; Muhammad et al., 2019). Although several studies have analysed second-life applications in stationary energy systems (Casals et al., 2019; Martinez-Laserna et al., 2018; Shahjalal et al., 2022), fewer have emphasised cascading approaches integrating third-life applications (Helander and Ljunggren, 2023; Ribeiro da Silva, 2023), highlighting the need to optimise multi-life battery systems across diverse applications (Börner et al., 2022) and investigate methods for extending the lifespan of LIB batteries, including repurposing thresholds and potential performance upgrades (Casals et al., 2019). Policy improvements are needed to support repurposing initiatives (Albertsen et al., 2021). Therefore, the current study was guided by the following two research questions (RQs):

- RQ1: How can the optimal pathway for spent EV batteries be determined through specific SOH thresholds and KPIs for various second- and third-life applications?
- RQ2: In what ways do current regulations support or hinder the extension of EV battery lifetimes through repurposing, and what policy changes could enhance these efforts?

Drawing on insights from 20 focus group discussions (FGDs) organised under the EU Horizon REINFORCE project regarding standardised, automated, safe and cost-efficient processing of end-of-life batteries for second and third lives and for recycling, the current study provides a conceptual model for extending the lifetime of EVs. We contribute to prolonging the usefulness of EV batteries, maximising retained product value through second- and third-life applications (Reike et al., 2018). We identify SOH thresholds and KPIs for these applications, presenting a comprehensive conceptual model that encompasses multiple cascading battery life cycles. Together with its policy aspects, this model addresses the essential elements of battery repurposing, thus supporting battery circularity (Campbell-Johnston et al., 2020; Dunn et al., 2023; Morseletto, 2020).

The article is structured as follows: Section 2 discusses the conceptual background, Section 3 presents the research approach, Section 4 summarises the results, and Section 5 concludes the article by discussing the findings, presenting the study limitations and suggesting future research avenues.

2. Conceptual background

2.1. Definition and types of battery repurposing

Although no clear definition of repurposing exists, we define it as 'the usage of the battery in another application' (Börner et al., 2022, p.3), providing a second and third life to the spent EV battery. There are two kinds of repurposing (Bobba et al., 2018). The first, known as 'direct reuse', does not dismantle the battery pack but tests it, and if the SOH threshold is met, it is directly used in the second application. The second strategy—'battery repurposing'—dismantles the battery at the module level, creating a new battery pack with extra costs, but is more flexible and suitable for specific applications (Casals et al., 2017).

Second- and third-life concept approaches innovate battery use to prolong battery usefulness and maximise the retained product value (Reike et al., 2018) and critical raw material (CRM) value before recycling. Second-life batteries are no longer useful in EVs but still have sufficient capacity, typically approximately 80%, for use in other applications, such as industrial stationary ESSs (Ali et al., 2021). Third-life batteries are repurposed for a third use after their initial automotive and second-life applications, such as for power grids, microgrids or backup power systems. Various scenarios concerning end-of-life (EOL) batteries have been discussed (Aguilar Lopez et al., 2023; Baars et al., 2021; Bobba et al., 2019; Börner et al., 2022; Glöser-Chahoud et al., 2021; Nurdiawati and Agrawal, 2022; Ribeiro da Silva et al., 2023; Wrålsen et al., 2021). However, studies on multiple life cycles beyond the second life cycle are still nascent (Helander and Ljunggren, 2023), even though cascaded use is recognised as important for extending resource use and retaining the added value of materials (Campbell-Johnston et al., 2020).

2.2. Applications and benefits of second- and third-life batteries

Empirical studies on the second and third life of batteries provide concrete examples of how repurposing can be implemented. For instance, Martinez-Laserna et al. (2018) investigated EV battery repurposing for use in stationary ESSs, demonstrating significant potential for extending battery life and enhancing grid stability. Similarly, Kamath et al. (2020) examined the reuse of spent batteries in renewable energy applications and found that even with diminished capacity, these batteries can effectively support solar and wind power systems. Helander and Ljunggren (2023) explored the potential for third-life applications of EV batteries within a product-service system offered by an underground hard-rock mining equipment manufacturer, focusing on multiple reuse and recycling loops. These studies underscore the feasibility and benefits of repurposing batteries and provide valuable insights into the technical, economic and environmental aspects of second- and third-life applications.

The concept of repurposing within a CE has gained significant attention as a strategy to enhance resource efficiency and minimise waste. Literature reviews by Bobba et al. (2018) and Melin et al. (2021) highlighted the benefits of extending product life cycles, conserving resources and reducing environmental impacts. Casals et al. (2017) and Ahmadi et al. (2017) discussed the economic advantages, including cost savings and new market opportunities. The cascading use of batteries optimises resource utilisation, reduces costs and offers environmental benefits by extending battery lifespans (Albertsen et al., 2021; Börner et al., 2022; Shahjalal et al., 2022). However, challenges remain, such as ensuring efficient dismantling, assessment and repackaging processes; managing capacity decreases and internal resistance issues; and addressing regulatory uncertainties and economic feasibility (Albertsen et al., 2021; Börner et al., 2022; Ribeiro et al., 2023; Shahjalal et al., 2022). Additionally, labour costs, valuation complexity and potential competition over spent batteries because of higher resource prices complicate commercial deployment (Albertsen et al., 2021; Ribeiro et al., 2023), and no standards and policies are a hurdle (Haram et al., 2021).

2.3. State of health and key performance indicators

The SOH is critical for determining spent EV battery suitability for repurposing in second- and third-life applications (Börner et al., 2022). Important KPIs like capacity and internal resistance play a vital role in evaluating the health and performance of these batteries (Börner et al., 2022; Shahjalal et al., 2022). For instance, starting a battery's second life at 80% SOH and setting the EOL at 60% SOH can extend its useful life by 3 to 3.5 years (Casals et al., 2019). Accurate SOH assessment methods, including impedance measurements and capacity estimation, are essential to ensure the optimal performance and longevity of repurposed batteries (Shahjalal et al., 2022). Additionally, monitoring SOH variations, maintaining optimal depth of discharge levels and balancing other KPIs, such as cycle times and internal resistance, are crucial to avoid premature degradation and maximise repurposed batteries' efficiency (Casals et al., 2019; Shahjalal et al., 2022). These factors collectively ensure that repurposed batteries can meet the performance demands of secondary applications, thereby contributing to enhanced resource utilisation and sustainability.

3. Material and methods

Given the exploratory nature of cascading repurposing strategies for spent EV batteries, we adopted a qualitative research design (Eriksson and Kovalainen, 2008). This approach allowed us to develop a comprehensive and nuanced understanding of the topic, informed by expert insights and policy analysis. The methodology consisted of FGDs with experts, complemented by a review of relevant literature and policy documents.

3.1. Data collection

The primary data collection method was FGDs, chosen for their effectiveness in capturing diverse perspectives and generating insights through group interaction (Barbour, 2018; Morgan, 1997). A total of 20 FGDs were conducted between June and November 2023, involving 25 experts from 14 organisations representing seven industries and seven research and development organisations. Details of the FGDs and participants are summarised in Table 1.

Each FGD started with broad, open-ended questions – such as 'What are the most important factors to consider in extending the useful lifetime of EV batteries?' – to foster discussion. These were followed by specific probes, such as 'When is a battery considered a spent EV battery?', as well as defining the SOH thresholds and identifying KPIs for different repurposing applications. The iterative nature of the FGDs allowed for continuous refinement of themes across sessions. Moderators from both research and industry backgrounds ensure balanced input and guided discussions. For further details on the FGD design and specific questions posed, refer to Supplementary Material SM1.

The FGDs covered a range of topics critical to the research, including second- and third-life applications of spent batteries, technical requirements, and the regulatory implications of current and future EU policies. Data from the FGDs were documented using meeting minutes, recordings, and Excel templates.

3.2. Data analysis

The data analysis followed an abductive approach, integrating theory-driven and data-driven processes to iteratively refine our understanding of the repurposing of spent EV batteries (Timmermans and Tavory, 2012). Initial coding categories were developed based on both the literature and insights generated from the FGDs. Coding was performed manually, and findings were cross-validated using secondary sources to ensure reliability. This approach aligns with the abductive method, where theories guide the initial analysis while remaining open to new patterns and interpretations that emerge from the data. The coding process was structured hierarchically into three levels: first-level *descriptive codes* captured specific observations from the FGDs; *sub-themes* grouped related descriptive codes into more refined categories; and *broader themes* represented the highest level of abstraction, identifying overarching patterns consistent with theories of repurposing and the CE.

To structure the analysis, we initially applied three primary broader themes: "applications of spent EV batteries," "requirements for those applications," and "regulations for repurposing." These themes facilitated the organisation of the FGD data into categories of practical applications, technical requirements, and regulatory considerations. Based on the results, we refined our themes and sub-themes. For instance, the broader theme of "requirements" was redefined as "battery assessment," with sub-themes "SOH assessment" and "KPIs" used to evaluate battery performance. Ultimately, we refined the broader themes into four main categories: "high-performance applications" (second life), "low-performance applications" (third life), "battery assessment," and "repurposing policy," as detailed in Table 2 on the data structure.

For policy analysis, we conducted an in-depth assessment of the EU regulatory framework on batteries, focusing on how policies support

Table 1
Overview of the focus group discussions (F) and details of the participating organisations (R: research, I: industry, T: total).

Session	Topic	Participating organisations			Number of participants			Date	Duration
F1	Understanding the main topics on extending EV battery lifetime	R:4	I:5	T:9	R:6	I:7	T:13	7.6.2023	1 h
F2	Clustering the main topics for repurposing	R:4	I:2	T:6	R:6	I:3	T:9	3.7.2023	1 h
F3	Identifying the main processes and opportunities for second and third battery lives	R:3	I:3	T:6	R:4	I:3	T:7	17.7.2023	1 h
F4	Exploring future market opportunities for second and third battery lives	R:7	I:4	T:11	R:13	I:6	T:19	20.7.2023	1.5 h
F5	Conceptual model development: Preliminary criteria for CES adoption	R:3	I:1	T:4	R:6	I:1	T:7	25.7.2023	1 h
F6	Conceptual model development: Criteria for CES adoption	R:2	I:0	T:2	R:5	I:0	T:5	4.8.2023	0.5 h
F7	Key concept definitions: Validation	R:3	I:2	T:5	R:7	I:2	T:9	28.8.2023	1 h
F8	New battery regulation	R:3	I:2	T:5	R:5	I:2	T:7	31.8.2023	0.5 h
F9	Conceptual model development	R:2	I:0	T:2	R:5	I:0	T:5	7.9.2023	1 h
F10	Criteria for CES adoption: Validation 1/3	R:3	I:3	T:6	R:5	I:4	T:9	11.9.2023	1 h
F11	Criteria for CES adoption: Validation 2/2	R:2	I:0	T:2	R:5	I:0	T:5	20.9.2023	1 h
F12	Criteria for CES adoption: Validation 3/3	R:3	I:2	T:5	R:6	I:3	T:9	25.9.2023	1 h
F13	Battery transportation and safety issues	R:2	I:1	T:3	R:4	I:1	T:4	29.9.2023	0.5 h
F14	Conceptual model development: Modelling perspective	R:2	I:1	T:3	R:4	I:3	T:7	9.10.2023	1 h
F15	Battery pack disassembly strategies	R:5	I:3	T:8	R:6	I:7	T:13	23.10.2023	1 h
F16	User requirements for second- and third-life batteries	R:4	I:4	T:8	R:6	I:5	T:11	26.10.2023	1 h
F17	Second- and third-life applications: Identification	R:2	I:4	T:6	R:3	I:5	T:8	6.11.2023	1 h
F18	Second- and third-life applications: Technical aspects 1/2	R:4	I:2	T:6	R:5	I:3	T:8	10.11.2023	1 h
F19	Second- and third-life applications: Technical aspects 2/2	R:4	I:2	T:6	R:6	I:3	T:9	20.11.2023	1 h
F20	Conceptual model validation	R:4	I:1	T:5	R:6	I:2	T:8	27.11.2023	1 h

Table 2
Data structure.

Broader theme (3rd level)	Sub-themes (2nd level)	Descriptive codes (1st level)
High-performance applications (2nd life)	Stationary energy storage	• Renewable farming • Area and frequency regulation • Load levelling • Generation-side asset management • Peak shovelling • Reactive power support • Microgrid • Smart grid • Load following • Power quality & reliability • Spinning reserve • Renewable energy integration
	Telecoms	• Powering cell towers • Powering base stations
	Mobile applications	• EV charging station • Electric boats • Electric aircraft and drones • Renewable energy integration
Low-performance applications (3rd life)	Backup power & UPS	• For homes • For businesses • For computers and other critical equipment
	Urban electromobility and micro batteries	• E-bikes and scooters • Home appliances • Portable power for laptops and mobile devices
Battery assessment	SOH assessment	• Battery chemistry • Battery format • Battery unit • Battery Management System
	KPIs	• Internal resistance • Cycle lifetime • Energy density • C-rate (discharge/charge rates)
Repurposing policy	Current policy support	• European Green Deal • Circular Economy Action Plan • The Raw Materials Action Plan • Sustainable and Smart Mobility Strategy • New EU Battery regulation • Battery Passport • Critical Raw Materials Act • Inland transport of dangerous goods
	Policy recommendations to support repurposing	• Regulatory framework • Financial support • Operational support • Market engagement

different CESs, including repurposing and recycling, while noting any conflicts, synergies or complementarities (Morseletto, 2020). FGD data on policy recommendations to support repurposing were manually coded and categorised into four dimensions: policy and regulatory framework, financial and economic support, operational and structural support, and market engagement (see Section 4.3, Table 4 for more details).

4. Results

The findings present a model for repurposing to extend the product lifetime of LIBs by cascading their use to second- and third-life applications. This model is accompanied by a list of potential user segments and repurposing application categories, related SOH thresholds and KPIs. Additionally, the model highlights the interaction between practical applications and regulatory frameworks in extending the lifetime of EV batteries.

Our findings have three primary elements: (1) an optimal pathway for spent EV batteries through repurposing, showing cascading applications for lifetime extension involving second- and third-life applications and their corresponding SOH thresholds and KPIs; (2) an assessment of the remaining battery capacity based on the battery's technical characterisation; and (3) policies on extended battery lifetimes, based on regulations that either boost or hinder the repurposing of batteries for second- and third-life applications in a cascading setting (Fig. 1).

4.1. *Optimal pathway for repurposing spent EV batteries*

Our model shows multiple life cycles and applications for spent EV batteries. To find adequate technical measures for extending the lifetime and maximising the utilisation of batteries, our conceptual model proposes four distinct consecutive stages, where the first stage, *first life,* is the primary life of an *EV battery* within the EV itself, typically spanning 10–15 years. Here, the battery retains approximately 80% of its initial capacity.

The second stage*, second life* applications, emerges once the battery's capacity for EV use diminishes, at which point it transitions to secondary applications geared towards high-performance *uses*, including stationary energy storage both on- and off-grid, serving purposes such as renewable energy integration, load levelling and peak shaving. Here, the battery can operate for an additional 5–8 years. These applications typically require batteries with 60–80% SOH that can endure 550 cycles or more while maintaining energy densities ranging from 100 to 300 Wh/kg and operating within varying temperature ranges. Additionally, batteries repurposed for telecom and mobile applications must meet specific cycle life and energy density criteria tailored to support powering cell towers, base stations and various mobile EVs under different environmental conditions (see Table 3).

The third stage, *third life,* occurs when the battery's remaining capacity targets *lower performance demands*, focusing on backup power systems for residential and commercial use, urban electromobility (e.g. e-bikes and scooters) and portable power solutions for everyday electronics. This stage can extend the battery's life by another 5–10 years. As Table 3 shows, these applications utilise batteries with reduced capacity with 40–60% SOH, longer cycle life exceeding 5000 cycles and energy densities ranging from 70 to 120 Wh/kg operating under milder temperature conditions. This categorisation underscores the diverse utility potentials of repurposed EV batteries across different life-cycle stages, emphasising optimisation for specific performance metrics and operational environments.

Finally, the fourth stage, *recycling,* ends by *closing the loop* with the recovery of valuable materials, such as lithium, cobalt and nickel, and their reintroduction into the battery production cycle as secondary resources, minimising the need for primary resource extraction.

4.2. *Assessment of SOH and KPIs*

Once the potential extended-life battery applications are defined, the question arises regarding how to determine the optimal pathway for a spent EV battery, including second- and third-life use. In our cascade model, when repurposing a battery, its remaining capacity must be carefully assessed and monitored to ensure safety and optimal decision-making regarding its potential second- or third-life applications. The

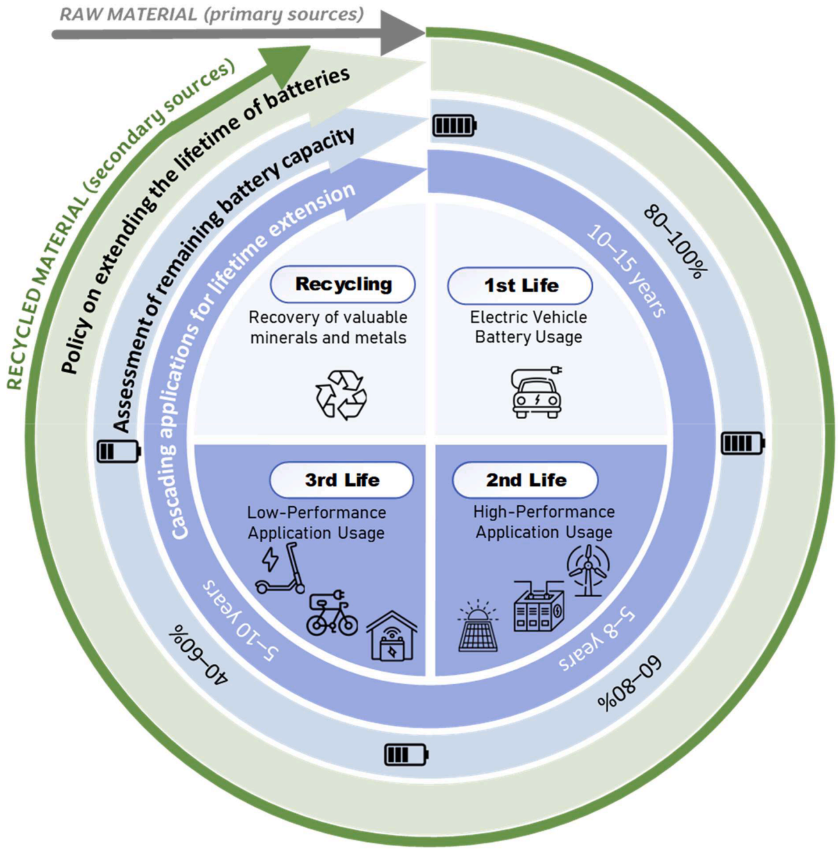

Fig. 1. Conceptual model of the extension of EV battery lifetime.

battery's SOH serves as a KPI of the battery, describing the degree of its degradation relative to its original state. This degradation in the ESS of a battery unit leads to a decline in its performance over its lifespan. The battery's SOH can manifest as the capacity SOH, reflecting that the battery's capacity fades over time, or as the power SOH, which correlates with the increase in the internal resistance of the battery unit over time. Hence, battery performance depends on various factors, such as power, internal resistance, voltage and self-discharge. To acquire the essential data for battery assessment, safety inspections are imperative to ensure the battery's integrity and safe dismantling, followed by retrieval of battery management system (BMS) data to diagnose the battery's condition. A comprehensive battery assessment entails a well-defined characterisation process gathering any missing data on the battery's current state, thereby facilitating SOH evaluation.

When assessing a battery to determine its capacity and when deliberating on repurposing strategies for spent EV batteries, several factors merit consideration: battery chemistry, battery unit level and battery shape. For example, from a demand-orientated perspective, the choice of battery chemistry, such as nickel manganese cobalt (NMC) or lithium iron phosphate (LFP), plays a pivotal role, with each possessing unique attributes. Depending on an application's specific requirements, it might utilise both chemistries or one of them. Some second- and third-life applications may be better suited for NMC or LFP batteries, depending on variables such as the energy density, life cycle and safety considerations. Furthermore, an inclusive evaluation at the battery unit level—spanning pack, module or cell—provides a holistic understanding of specific parameter ranges. Considering the diverse cell formats—prismatic, cylindrical and pouch—enriches the conceptual model by enabling comprehensive assessment of repurposing possibilities. For instance, pouch cells cannot be dismantled.

In selecting the appropriate cathode chemistry for repurposing spent EV LIBs, it is crucial to consider the unique characteristics of NMC and LFP chemistries, particularly as the market transitions towards increased use of LFP batteries for both EVs and energy storage systems. NMC batteries, with higher energy density and greater material recyclability due to their nickel and cobalt content, are better suited for applications requiring long-range capabilities, such as passenger EVs and high-performance stationary energy storage systems. However, the economic incentive to extend the life of NMC batteries before material recycling is a key factor, as their valuable CRMs make them attractive for recovery. In contrast, LFP batteries, which contain more abundant and less expensive materials like iron, are not economically viable for recycling but offer significant advantages in repurposing due to their superior safety and longer cycle life. LFP batteries are thus ideal candidates for second- and third-life applications, particularly in lower-value and high-safety applications such as backup power systems, urban electromobility and off-grid energy storage. Choosing an inappropriate chemistry for a given application can lead to safety concerns, including potential thermal runaway, underscoring the need for careful selection based on performance requirements and life-cycle considerations.

4.3. Policy on the extended lifetime of lithium-ion batteries

To estimate the extent of policy support and potential bottlenecks to the realisation of the conceptual model, we mapped relevant policies for repurposing EV batteries (Table 4).

The European Parliament (2023) defined the CE as a conceptual model that emphasises sharing, leasing, reusing, repairing, refurbishing and recycling to extend product life cycles. The EC (2018) stated that it is crucial for the EU to transition to a CE to ensure a competitive and sustainable EU economy with low carbon emissions and efficient use of resources; this aim is reflected in the CEAP, which introduced the concept of circularity into EU policy and represents the EU's

Table 3
Second- and third-life applications of spent EV batteries.

	Category	Application	Potential user segment	KPIs				
				Capacity [% SOH]	Internal resistance [%]	Cycle life	Energy density	Operating temperature
2nd Life	High-performance applications	Stationary energy storage (on-grid)	• Renewable farming • Area and frequency regulation • Load levelling • Generation-side asset management • Peak shovelling • Reactive power support	60–80	60–80	550 cycles (80% SOH)	100–300 Wh/kg	Discharge −20–55°C, Charge 0–40°C
		Stationary energy storage (off-grid)	• Microgrid • Smart grid • Load following • Power quality & reliability • Spinning reserve • Renewable energy integration					
		Telecoms	• Powering cell towers • Powering base stations			800 cycles (NMC), 2000 cycles (LFP),	80–180 Wh/kg	Discharge −20–50°C (NMC), −30–60°C (LFP), Charge: 0–40°C
		Mobile applications	• EV charging station • Electric boats • Electric aircraft and drones • Renewable energy integration			500–1500 cycles	100–300 Wh/kg	−20–60°C
3rd Life	Low-performance applications	Backup power & UPS	• For homes • For businesses • For computers and other critical equipment	40–60	40–60	> 5000 cycles	70–120 Wh/kg	5–35°C
		Urban electromobility and micro batteries	• E-bikes and scooters • Home appliances • Portable power for laptops and mobile devices			500 cycles (70% SOH)	N/A	Charge 0–45°C, Discharge −20–60°C

Table 4
EU policies relevant to EV LIBs.

Policy	Aim	Objectives relevant to EV LIBs and CES adoption
European Green Deal (EC, 2019)	Transform the EU into a resource-efficient, fair, competitive and carbon-neutral economy by 2050	• Adopt the use of a life-cycle approach • Create a predictable and simplified regulatory environment
Circular Economy Action Plan (CEAP) (EC, 2020a)	Transition the European economy to a circular model	• Improve battery durability, reusability, upgradability, reparability, and resource and energy efficiency • Reduce hazardous chemicals and environmental and carbon footprints • Support recycling, remanufacturing and product-as-a-service business models • Standardise European battery recycling
The Raw Materials Action Plan (2020) (EC, 2020b)	Ensure sufficient and sustainable supply of CRMs	• Promote sustainable product design, innovation, extended product lifetimes and use of secondary raw materials • Develop resilient EU value chains and sourcing; source 80% of lithium from Europe by 2025 • Diversify sources and promote responsible sourcing from third countries
Sustainable and Smart Mobility Strategy (2020) (EC, 2020c)	Build a resilient and sustainable mobility network for Europe	• Achieve 90% reduction in CO2 emissions from mobility by 2050 • Achieve at least 30 million zero-emission vehicles by 2030 • Achieve almost 100% zero-emission vehicles by 2050
New battery regulation (2023/1542) (EC, 2023a)	Facilitate the reuse, repurposing and recycling of batteries	• Achieve performance and durability requirements • Recover 90% of cobalt, nickel and copper and 35% of lithium from batteries by 2025 • Recover 95% of cobalt, nickel and copper and 70% of lithium from batteries by 2030 • Achieve the following recycled battery content requirements by 2030: 12% cobalt, 85% lead, 4% lithium and 4% nickel; and the following by 2035: 20% cobalt, 10% lithium and 12% nickel
2023/0079 Critical Raw Materials (CRM) Act (EC, 2023b)	Develop circular and sustainable European raw materials supply chains by increasing self-sufficiency and diversifying supply	• Strengthen the European CRMs value chain • Diversify CRM imports • Improve Europe's capacity to monitor and mitigate supply disruption risks • Ensure functioning markets for CRMs, maintain a high level of environmental protection and improve circularity and sustainability • Increase recycling and use of secondary CRMs • Promote ecodesign to reduce resource use and increase durability, reparability and reusability and to ensure recycling, remanufacturing or recovery
Directive 2008/68/EC inland transport of dangerous goods (EC, 2008; United Nations, 2023)	Ensure safe transport of dangerous goods between Member States and third countries according to the ADR, RID or ADN[1]	• Ensure that LIBs are packed and labelled correctly, and transported in a vehicle equipped with appropriate safety features • Ensure that LIBs with a capacity of more than 100 Wh are transported as dangerous goods • Ensure that all damaged or defective LIBs are transported as dangerous goods

[1] ADR: European Agreement concerning the International Carriage of Dangerous Goods by Road, RID: Regulation concerning the International Carriage of Dangerous goods by Rail, ADN: European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways.

commitment to integrating circularity into its future policy instruments (Talens Peiro et al., 2020). The CEAP aims to increase recycled content, reduce battery waste and facilitate recycling, reuse and repurposing in the EU. The Strategy for Sustainable and Smart Mobility notes the increasing demand for batteries in the mobility sector (EC, 2020c), and the Raw Materials Action Plan (EC, 2020b) considers the increased circularity necessary to improve access to raw materials. Although these policies stress the importance of multiple CESs, the Green Deal (EC, 2019), for instance, rarely mentions reuse or repurposing, indicating that not all CESs have been fully integrated. European Battery Regulation 2023/1542 (EC, 2023a) contains measures such as battery health checks, collection targets for recycling and requirements for minimum recycled content in new batteries (EC, 2023a). LIB raw materials, damaged LIBs and LIBs with a capacity exceeding 100 Wh are considered dangerous goods according to Directive 2008/68/EC, which presents rules for LIB labelling and transportation (EC, 2008; United Nations, 2023). Raw Materials Act 2023/0079 focuses on EOL vehicles and ecodesign. The retrievability of components and materials from used cars, including EVs, should be ensured, and products should be designed to prolong their lifetimes (EC, 2023b).

Although policy strategies highlight the importance of supporting second-life solutions, the policy measures are focused on recycling, and there are significant differences between measures implemented to support repurposing and those utilised to support recycling. The most significant measures to stimulate EV LIB repurposing are presented in European Battery Regulation 2023/1542 (EC, 2023a), including a BMS and battery 'health check' which enables the recategorisation of repurposable batteries from waste to product. Although regulation 2023/1542 sets clear targets for recycling rates and requirements for recycled content, it has no targets or objectives for repurposing (EC, 2023a). Measures such as battery health checks and battery passports enable repurposing but do not create incentives as strong as those used to support recycling. Furthermore, there is no mention of a third life in any of the policy documents. The exclusion of a third life as a possible strategy for battery lifetime expansion signals that it was not considered a potential option or that recycling was seen as preferable to a third life.

Based on insights gathered from the FGDs, a nuanced approach is recommended to foster effective battery-repurposing initiatives across four defined categories (Table 5). Although current policies, such as the new battery regulation (2023/1542), play a crucial role, there is a notable gap in incentivising repurposing efforts. Rather than solely enabling policies, there needs to be robust financial incentives aimed at both businesses and consumers. Specific measures could include proposing subsidies, tax incentives and tailored incentive schemes designed to mitigate repurposing costs and promote wider adoption of repurposed batteries. Moreover, it is essential to advocate for increased funding for research and development initiatives and facilitate stronger collaborations between the public and private sectors. These actions are vital for stimulating market demand and driving continuous innovation.

5. Discussion and conclusion

The present research addresses critical gaps by investigating the optimal pathways for battery repurposing and necessary regulatory

Table 5
Recommendations to support battery-repurposing initiatives.

Category	Themes	Specific recommendation
Policy and regulatory framework	Regulatory compliance and standards	• Develop certification programmes for safety and compliance standards on digital product passports (DPPs) • Set guidelines for necessary information to enable repurposing and consumer right to repair • Standardise battery health monitoring • Develop and enforce harmonised standards for repurposing processes • Standardise testing methods for safety and performance
	Legal frameworks and mandates	• Implement extended producer responsibility (ERP) mandates • Establish clear regulations for ownership and liability of repurposed batteries • Specify hazardous material classification in DPPs • Establish battery design regulations
Financial incentives and economic support	For businesses	• Offer subsidies and tax breaks to businesses in battery repurposing • Architect incentive schemes to offset the costs of repurposing (e.g. transportation, testing, dismantling, reassembly) • Subsidise technological innovation (e.g. AI-enabled disassembly)
	For consumers	• Provide tax benefits for buyers of repurposed batteries • Lower VAT for refurbished, repurposed and remanufactured batteries • Subsidise storage optimisation that uses repurposed batteries
	Economic impact assessment	• Cost comparison between new and repurposed batteries • Link subsidies to job creation in battery-repurposing initiatives
Operational and structural support	Research and development	• Fund R&D initiatives to advance repurposing technologies • Support pilot projects for battery repurposing • Subsidise innovations for efficient and environmentally friendly repurposing processes
	Infrastructure support	• Invest in robust battery collection and recycling systems • Establish centralised locations and logistical frameworks for battery return and transport • Support local value chain improvement and development of new, sustainable recycling technologies
	Data and transparency	• Create tracking systems to manage the life cycles of batteries • Ensure transparency through labelling to build consumer confidence • Facilitate data exchange among stakeholders (manufacturers, recyclers and repurposing entities)
Market engagement and impact	Consumer and market engagement	• Educate consumers and businesses on the advantages of repurposed batteries • Promote the use of repurposed batteries in government projects and public infrastructure • Forster collaborations between the public and private sectors to drive market demand and innovation
	Environmental and economic considerations	• Calculate environmental impact benefits to align incentives with cost savings from positive environmental practices • Monitor the retention of battery materials within Europe to reduce dependency on imports

enhancements. Our model delineates a range of potential applications for extending EV batteries into second and third lives. These applications span from stationary ESSs to smaller-scale uses for residential and micro-urban electromobility. Additionally, we explore specific SOH thresholds and KPIs to support decision-making on maximising EV battery lifetimes through repurposing and analyse how current regulations support or hinder these efforts, proposing policy changes to enhance repurposing initiatives. The contributions are twofold: first, we define specific SOH thresholds and user requirements tailored to different second- and third-life applications based on expert insights and, second, we critically evaluate current policies and identify specific recommendations to encourage greater emphasis on battery repurposing over recycling.

5.1. Theoretical contribution

Our study makes significant theoretical contributions by establishing repurposing as a crucial strategy for extending the lifespan of EV batteries within the CE framework. By defining specific SOH thresholds and user requirements for different second- and third-life applications, our model addresses gaps in the literature. For instance, although Albertsen et al. (2021) and Casals et al. (2019) discussed the general benefits of second-life applications, our research offers a more detailed and actionable pathway tailored to distinct user needs. Additionally, unlike Martinez-Laserna et al. (2018), who focused on regulatory aspects, our findings integrate business strategies with technical analyses, providing a more holistic approach to battery capacity assessment and policy challenges. This comprehensive model goes beyond the scope of Ribeiro da Silva (2023) and Shahjalal et al. (2022) by proposing a multistage cascade of battery use, optimising resource utilisation and reduces total lifetime costs, as supported by Börner et al. (2022). Moreover, our research identifies specific regulatory shortcomings and offers targeted policy recommendations, thus filling the critical gap noted by Dunn et al. (2023) and Hoarau and Lorang (2022) regarding the need for enhanced incentives for repurposing. Through these contributions, our study enriches the theoretical discourse on CESs in battery life-cycle management.

5.2. Managerial implications

Our study reveals contrasting perspectives in the literature regarding battery-repurposing strategies within a CE. Unlike previous studies emphasising regulatory support (Martinez-Laserna et al., 2018; Kamath et al., 2020), our findings highlight a predominant focus on recycling within existing frameworks. This presents a strategic opportunity for managers to proactively explore the underutilised potential of second- and third-life battery applications. By implementing our model, organisations can optimise resource utilisation and operational efficiency, thereby aligning with environmental sustainability goals while reducing the costs associated with traditional disposal methods. The insights derived from contrasting our findings with the literature (Bobba et al., 2019) emphasise the importance of managerial decisions that prioritise flexibility and innovation in battery life-cycle management. This approach not only addresses regulatory uncertainties but also enhances organisational resilience by leveraging diverse end-use scenarios and adapting to evolving market dynamics.

5.3. Policy implications

Despite the EU's emphasis on battery circularity (Barkhausen et al., 2023), the results show that the implemented policies provide stronger incentives for recycling than other CESs. This finding aligns with that of Albertsen et al. (2021), who noted that although the EU Battery

Directive introduces recycled content requirements and aims to enhance information availability, it indirectly supports repurposing without strong incentives. Although Regulation 2023/1542 includes measures such as the use of a BMS and battery health checks, it lacks mandatory requirements or substantial incentives for repurposing. Dunn et al. (2023) emphasised that prioritising second- and third-life applications over recycling reduces the lifetime environmental impact of LIBs. Hoarau and Lorang (2022) suggested adjusting recycled content requirements to support second-life applications. We recommend a systemic approach that harmonises recycling with second- and third-life strategies through robust regulations that encompass all CES options. This aligns with Börner et al. (2022) and Riveiro et al. (2023), who stressed the importance of data sharing and transparency across the battery value chain. Additionally, policies should be technology-neutral to adapt to emerging technologies (Melin et al., 2021). The differences in circularity-related policies across countries, such as China's temporary ban on large-scale repurposing (Geng et al., 2022), highlight the need for universal standards to benefit CESs (Chirumalla et al., 2023). Comprehensive policies that integrate repurposing strategies into national energy frameworks (Kamath et al., 2020) can significantly enhance the utility and environmental benefits of batteries.

5.4. Limitations and recommendations for further research

The present study contributes to extending the lifespan of spent EV batteries within a conceptual model while acknowledging certain limitations. The proposed model—derived from FGDs and secondary data—serves as a theoretical framework rather than an empirically tested framework guiding the achievement of CE targets. Empirical investigations are needed to validate and refine the presented concepts. No economic analysis for potential applications was conducted, highlighting the need for studies to assess the economic viability of each repurposing application, particularly in relation to different battery chemistries. For example, further exploration is needed to determine when NMC or LFP batteries are most appropriate for specific applications, considering trade-offs between recyclability value, safety and long-term performance benefits. The dynamic nature of the CE and sustainable battery management, influenced by ongoing technological advancements and regulatory changes, may impact the efficacy of the outlined strategies. Although the present study offers insights into potential pathways for extending the EV battery lifespan and aligning with CE goals, further research, particularly through real-world applications, is essential for validating and refining the model. Future research should explore the practical implementation of the model in diverse contexts, evaluate its effectiveness and consider safety concerns to mitigate risks associated with repurposing while refining strategies to maximise the value and lifespan of EV batteries within the CE model.

CRediT authorship contribution statement

America Rocio Quinteros-Condoretty: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Minttu Laukkanen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Laura Kainiemi:** Writing – review & editing, Writing – original draft, Investigation. **Sara M. Pinto:** Writing – original draft, Data curation. **Emanuel J. Lourenço:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Conceptualization. **Luís Oliveira:** Validation, Conceptualization. **Laura Albareda:** Writing – review & editing, Supervision. **Bernardo Barbiellini:** Writing – review & editing, Supervision.

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.

Data availability

The data that has been used is confidential.

Acknowledgments

This study was supported by the REINFORCE project funded by the EU's Horizon 2020 Research and Innovation Programme (Grant Agreement No. 101104204).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107943.

References

Aguilar Lopez, F., Billy, R.G., Müller, D.B., 2023. Evaluating strategies for managing resource use in lithium-ion batteries for electric vehicles using the global MATILDA model. Resour. Conserv. Recycl. 193, 106951. https://doi.org/10.1016/J.RESCONREC.2023.106951.

Ali, H., Khan, H.A., Pecht, M.G., 2021. Circular economy of Li batteries: technologies and trends. J. Energy Storage 40, 102690. https://doi.org/10.1016/J.EST.2021.102690.

Ahmadi, L., Young, S.B., Fowler, M., Fraser, R.A., Achachlouei, M.A., 2017. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int. J. Life Cycle Assess. 22, 111–124. https://doi.org/10.1007/s11367-015-0959-7.

Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C., Plepys, A., 2021. Circular business models for electric vehicle lithium-ion batteries: an analysis of current practices of vehicle manufacturers and policies in the EU. Resour. Conserv. Recycl. 172, 105658. https://doi.org/10.1016/j.resconrec.2021.105658.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4, 71–79. https://doi.org/10.1038/s41893-020-00607-0.

Barbour, R., 2018. Doing Focus Groups, 2nd ed. Sage Publications, UK. https://doi.org/10.4135/9781849208956. Sage, Open University.

Barkhausen, R., Fick, K., Durand, A., Rohde, C., 2023. Analysing policy change towards the circular economy at the example of EU battery legislation. Renew. Sustain. Energy Rev. 186, 113665. https://doi.org/10.1016/j.rser.2023.113665.

Bobba, S., Podias, A., Di Persio, F., Messagie, M., Tecchio, P., Cusenza, M.A., Eynard, U., Mathieux, F., Pfrang, A., 2018. Sustainability assessment of second life application of automotive batteries (SASLAB). JRC Exploratory Research (2016-2017): Final technical Report. EUR 29321 EN, Publications Office of the European Union, Luxembourg, JRC112543. https://doi.org/10.2760/53624, 2018, ISBN 978-92-79-92835-2.

Bobba, S., Mathieux, F., Blengini, G.A., 2019. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. Resour. Conserv. Recycl. 145, 279–291. https://doi.org/10.1016/j.resconrec.2019.02.022.

Börner, M.F., Frieges, M.H., Späth, B., Spütz, K., Heimes, H.H., Sauer, D.U., Li, W., 2022. Challenges of second-life concepts for retired electric vehicle batteries. Cell Rep. Phys. Sci. 3, 101095. https://doi.org/10.1016/j.xcrp.2022.101095.

Campbell-Johnston, K., Vermeulen, W.J., Reike, D., Brullot, S., 2020. The circular economy and cascading: towards a framework. Resour. Conserv. Recycl. X, 100038. https://doi.org/10.1016/j.rcrx.2020.100038.

Casals, L.C., García, B.A., Aguesse, F., Iturrondobeitia, A., 2017. Second life of electric vehicle batteries: relation between materials degradation and environmental impact. Int. J. Life Cycle Assess. 22, 82–93. https://doi.org/10.1007/s11367-015-0918-3.

Casals, L.C., Amante García, B., Canal, C., 2019. Second life batteries lifespan: rest of useful life and environmental analysis. J. Environ. Manage. 232, 354–363. https://doi.org/10.1016/j.jenvman.2018.11.046.

Chirumalla, K., Kulkov, I., Vu, F., Rahic, M., 2023. Second life use of Li-ion batteries in the heavy-duty vehicle industry: feasibilities of remanufacturing, repurposing, and reusing approaches. Sustain. Prod. Consum. 42, 351–366. https://doi.org/10.1016/j.spc.2023.10.007.

Colarullo, L., Thakur, J., 2022. Second-life EV batteries for stationary storage applications in Local Energy Communities. Renew. Sustain. Energy Rev. 169, 112913. https://doi.org/10.1016/J.RSER.2022.112913.

Dunn, J., Ritter, K., Velázquez, J.M., Kendall, A., 2023. Should high-cobalt EV batteries be repurposed? Using LCA to assess the impact of technological innovation on the waste hierarchy. J. Ind. Ecol. 27, 1277–1290. https://doi.org/10.1111/jiec.13414.

Eriksson, P., Kovalainen, A., 2008. Qualitative Methods in Business Research. SAGE Publications Ltd. https://doi.org/10.4135/9780857028044.

European Commission, 2008. Directive 2008/68/EC of the European Parliament and of the European Council of 24 September 2008 on the inland transport of dangerous goods. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0068-20230621 (accessed 10 October 2023).

European Commission, 2018. Report on critical raw materials and the circular economy. https://op.europa.eu/en/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-80004733 (accessed 10 October 2023).

European Commission, 2019. The European Green Deal. COM(2019) 640. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX%3A52019DC0640 (accessed 10 October 2023).

European Commission, 2020a. A new Circular Economy Action Plan for a cleaner and more competitive Europe. COM(2020) 98. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF (accessed 21 October 2023).

European Commission, 2020b. Critical raw materials resilience: charting a path towards greater security and sustainability. COM(2020) 474. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474 (accessed 21 October 2023).

European Commission, 2020c. Sustainable and Smart Mobility Strategy – Putting European transport on track for the future. COM(2020) 789. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0789 (accessed 20 October 2023).

European Commission, 2023a. Regulation 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries. http://data.europa.eu/eli/reg/2023/1542/oj (accessed 21 October 2023).

European Commission, 2023b. Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials. 2023/0079 (COD). COM(2023) 160. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160 (accessed 20 October 2023).

European Parliament, 2023. Circular economy: definition, importance and benefits. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits?&at_campaign=20234-Economy&at_medium=Google_Ads&at_platform=Search&at_creation=RSA&at_goal=TR_G&at_audience=circular%20economy%2 (accessed 24 October 2023).

Geng, J., Gao, S., Sun, X., Liu, Z., Zhao, F., Hao, H., 2022. Potential of electric vehicle batteries second use in energy storage systems: the case of China. Energy 253, 124159. https://doi.org/10.1016/j.energy.2022.124159.

Glöser-Chahoud, S., Huster, S., Rosenberg, S., Baazouzi, S., Kiemel, S., Singh, S., Schneider, C., Weeber, M., Miehe, R., Schultmann, F., 2021. Industrial disassembling as a key enabler of circular economy solutions for obsolete electric vehicle battery systems. Resour. Conserv. Recycl. 174, 105735. https://doi.org/10.1016/j.resconrec.2021.105735.

Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P., Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges. Alexandria Eng. J. 60 (5), 4517–4536. https://doi.org/10.1016/J.AEJ.2021.03.021.

Helander, H., Ljunggren, M., 2023. Battery as a service: analysing multiple reuse and recycling loops. Resour. Conserv. Recycl. 197, 107091. https://doi.org/10.1016/j.resconrec.2023.107091.

Hoarau, Q., Lorang, E., 2022. An assessment of the European regulation on battery recycling for electric vehicles. Energy Policy 162, 112770. https://doi.org/10.1016/j.enpol.2021.112770.

Hu, X., Xu, L., Lin, X., Pecht, M., 2020. Battery lifetime prognostics. Joule 4, 310–346. https://doi.org/10.1016/j.joule.2019.11.018.

Kamath, D., Shukla, S., Arsenault, R., Kim, H.C., Anctil, A., 2020. Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications. Waste Manage. 113, 497–507. https://doi.org/10.1016/J.WASMAN.2020.05.034.

Martinez-Laserna, E., Gandiaga, I., Sarasketa-Zabala, E., Badeda, J., Stroe, D.I., Swierczynski, M., Goikoetxea, A., 2018. Battery second life: hype, hope or reality? A critical review of the state of the art. Renew. Sustain. Energy Rev. 93, 701–718. https://doi.org/10.1016/j.rser.2018.04.035.

Melin, H., Rajaefar, M., Ku, A., Kendall, A., Harper, G., Heidrich, O., 2021. Global implications of the EU battery regulation – a much needed law may have unintended global consequences. Science 373, 6553. https://doi.org/10.1126/science.abh1416.

Morgan, D.L., 1997. Focus Groups as Qualitative Research, 2nd ed. SAGE Publications, Thousand Oaks. https://doi.org/10.4135/9781412984287.

Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553.

Muhammad, M., Attidekou, P.S., Ahmeid, M., Milejevic, Z., Lambert, S., 2019. Sorting of spent electric vehicle batteries for second life application. In: Proceedings of 2019 the 7th International Conference on Smart Energy Grid Engineering (SEGE 2019), pp. 325–329.

Nurdiawati, A., Agrawal, T.K., 2022. Creating a circular EV battery value chain: end-of-life strategies and future perspective. Resour. Conserv. Recycl. 185, 106484. https://doi.org/10.1016/j.resconrec.2022.106484.

Quinteros-Condoretty, A.R., Albareda, L., Barbiellini, B., Soyer, A., 2020. A socio-technical transition of sustainable lithium industry in Latin America. Proc. Manuf. 51, 1737–1747. https://doi.org/10.1016/j.promfg.2020.10.242.

Quinteros-Condoretty, A.R., Golroudbary, S.R., Albareda, L., Barbiellini, B., Soyer, A., 2021. Impact of circular design of lithium-ion batteries on supply of lithium for electric cars towards a sustainable mobility and energy transition. Proc. CIRP 100, 73–78. https://doi.org/10.1016/j.procir.2021.05.012.

Reike, D., Vermeulen, W.J., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.

Ribeiro da Silva, E., Lohmer, J., Rohla, M., Angelis, J., 2023. Unleashing the circular economy in the electric vehicle battery supply chain: a case study on data sharing and blockchain potential. Resour. Conserv. Recycl. 193, 106969. https://doi.org/10.1016/j.resconrec.2023.106969.

Shahjalal, M., Roy, P.K., Shams, T., Fly, A., Chowdhury, J.I., Ahmed, M.R., Liu, K., 2022. A review on second-life of Li-ion batteries: prospects, challenges, and issues. Energy 241, 122881. https://doi.org/10.1016/J.ENERGY.2021.122881.

Stahel, W., 2016. The circular economy. Nature 531, 435–438. https://doi.org/10.1038/531435a.

Talens Peiro, L., Polverini, D., Ardente, F., Mathieux, F., 2020. Advances towards circular economy policies in the EU: the new Ecodesign regulation of enterprise servers. Resour. Conserv. Recycl. 154, 104426. https://doi.org/10.1016/j.resconrec.2019.104426.

Timmermans, S., Tavory, I., 2012. Theory construction in qualitative research: from grounded theory to abductive analysis. Sociol. Theory 30 (3), 167–186. https://doi.org/10.1177/0735275112457914.

United Nations, 2023. ADR 2023 – agreement concerning the international carriage of dangerous goods by road. https://unece.org/transport/standards/transport/dangerous-goods/adr-2023-agreement-concerning-international-carriage (accessed 24 October 2023).

Virmani, N., Agarwal, V., Karuppiah, K., Agarwal, S., Raut, R.D., Paul, S.K., 2023. Mitigating barriers to adopting electric vehicles in an emerging economy context. J. Clean. Prod. 414, 137557. https://doi.org/10.1016/j.jclepro.2023.137557.

Wrålsen, B., Prieto-Sandoval, V., Mejia-Villa, A., O'born, R., Hellström, M., Faessler, B., 2021. Circular business models for lithium-ion batteries – stakeholders, barriers, and drivers. J. Clean. Prod. 317, 128393. https://doi.org/10.1016/j.jclepro.2021.128393.