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Review article

Second-life lithium-ion batteries for microgrids: A comprehensive review of integration, degradation, control, and reliability

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ABSTRACT

The rapid electrification of transportation has significantly increased the demand for efficient battery-based energy storage systems. Lithium-ion batteries (LiBs), widely adopted in electric vehicles (EVs), are typically retired when their State of Health (SoH) declines below 70%–80%, despite retaining substantial residual capacity, contributing to an estimated 14 million tonnes of retired EV battery waste by 2040. These retired batteries, termed Second-Life Batteries (SLBs), present a promising opportunity for stationary energy storage in microgrid applications, offering high energy efficiencies of 92%–99% and enabling cost-effective and sustainable solutions. Projections reported in the literature indicate that SLBs could provide approximately 96 GWh of storage capacity by 2030 and up to 3000 GWh by 2040, highlighting their large-scale potential. This paper presents a comprehensive meta-review of the prospects for SLB integration into microgrids, addressing critical operational and deployability gaps in existing literature that often treat technical, economic, and control aspects in isolation. A multi-scale framework is synthesized that links battery electrochemistry, degradation mechanisms, repurposing methodologies, mathematical modeling, and system-level energy management. The review further proposes an SLB grading framework, derived from existing battery standards, to support battery selection for microgrid deployment. Advanced control and energy management strategies, together with safety, reliability, environmental benefits and standardization requirements, are critically reviewed to identify barriers to large-scale deployment. Finally, key research challenges, gaps, and future research directions are presented to facilitate the reliable, safe, and economically viable integration of SLBs into modern microgrids. Overall, the study highlights that SLBs can serve as a sustainable, economical, and technically viable energy storage solution, supporting both the global transition toward clean energy systems and the continued growth of electric mobility in supporting circular economy.

Contents

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1. Introduction

The global energy sector is undergoing a rapid transformation driven by increasing deployment of renewable energy sources (RES), electrification of transport, and the urgent need to decarbonize power systems. Among these transitions, electric vehicles (EVs) have emerged as a key contributor to sustainable mobility. Governments worldwide have implemented supportive policies, such as research and development funding, purchase subsidies, and infrastructure investments to drive EV adoption, accelerate the energy transition, and to enhance environmental sustainability [1,2]. Global sales of electric cars reached approximately 17 million units in 2024, according to the International Energy Agency (IEA), accounting for over 20% of total new car sales worldwide [3]. Market outlooks further indicate that global EV sales are projected to rise significantly to nearly 40 million units annually by 2030, driven by continued cost reductions, policy support, and infrastructure expansion [4]. As shown in Fig. 1(a), the global EV stock has grown exponentially from about 3 million in 2017 to nearly 58 million in 2024, reflecting rapid cumulative adoption [3]. Similarly, Fig. 1(b) highlights that this growth is primarily driven by China, followed by Europe and the United States, with emerging markets contributing an increasing share of global sales [3]. Projections from the IEA suggest that global EV sales will continue their upward trajectory, surpassing 21 million annually in the near term under stated policy scenarios [3]. Together, these trends point to a structural and sustained shift in the global automotive landscape, with direct implications for the volume of end-of-life batteries entering the repurposing pipeline in the coming decade.

The EV market is mainly dominated by lithium-ion batteries (LiBs), particularly nickel–manganese–cobalt (NMC) and lithium iron phosphate (LFP) chemistries, due to their high energy density, superior performance, enhanced safety characteristics, and long operational lifespan [7]. Compared to other battery technologies, lithium-based batteries offer significant advantages, including higher energy and power density in a more compact form, the absence of memory effect, low self-discharge rates, and extended cycle life [8]. As a result, LiBs have been widely adopted in numerous commercial EVs and hybrid electric vehicles (HEVs), including models such as the Tesla Model 3, BMW i3, Honda e, Mercedes-Benz EQA, Jaguar I-PACE, Lexus UX 300e, and Nissan Leaf. Furthermore, the global LiB market has experienced substantial growth, exceeding USD 24 billion, with a projected compound annual growth rate (CAGR) of approximately 12% between 2017 and 2024 [7]. Although the EV transition significantly reduces tailpipe emissions, the increasing volume of end-of-life LiBs introduces critical sustainability challenges, particularly the disposal of these batteries.

The automotive use of EV batteries usually ends when the state-of-health (SoH) has dropped to around 70%–80%, which can be termed as the Retirement Capacity Boundary (RCB), even though they have substantial remaining energy-storage capacity [9]. Also, LiB degradation over time reduces the driving range of EVs, exacerbating range anxiety; automakers generally recommend it to be replaced at RCB [10]. Disposing of or directly recycling such batteries at this stage not only leads to environmental burdens but also overlooks their remaining economic and functional value. Furthermore, with this EV deployment acceleration, there is a corresponding increase in the number of retired battery volumes. According to policy and market assessments, when the end-of-life EV batteries are repurposed, they could offer almost 96 GWh of second-life storage capacity by 2030 and around 3000 GWh in 2040 [11]. Unless reuse or recycling plans are developed, these batteries will become a fast-growing waste stream, posing logistical, material-recovery, and environmental challenges. In this context, the concept of second-life lithium-ion batteries (SLBs) has gained substantial attention as a promising pathway toward circular economy implementation in the energy sector.

SLBs refer to retired EV batteries that are repurposed for less demanding stationary energy storage applications after their first-life automotive use. These applications include renewable energy integration, peak load management, backup power systems, and particularly microgrid energy storage [12]. Microgrids, which are localized energy systems capable of operating independently or in connection with the main grid, rely heavily on energy storage systems (ESS) to mitigate the intermittency of RES such as solar and wind. The growing penetration of distributed renewable generation has therefore intensified the demand for cost-effective, scalable, and sustainable storage technologies. According to recent energy market evaluations, battery storage facilities increased by a factor of about 43% in 2025 [13] and are targeted to reach 1500 GW by 2030 [14], as grids become more dependent on solar and wind generation and require increasingly flexible and dispatchable storage solutions. Although during the last decade the prices of LiB packs have been reduced considerably, the cost of storage projects at scale is still high, especially in developing economies, where grid instability, regular load shedding, and poor electrification remain persistent obstacles to socio-economic development [15,16]. SLBs present a compelling alternative to newly manufactured LiB systems due to their significantly lower capital cost and reduced environmental footprint. By extending the useful life of EV batteries, SLBs can reduce the demand for new raw materials, lower greenhouse gas emissions associated with battery manufacturing, and enhance overall system sustainability. Furthermore, their deployment in microgrids has the potential to improve energy access in remote and rural areas with low-cost storage, supporting decentralized electrification and energy resilience [17].

Recently, multiple reviews of SLBs in stationary grid services and distributed applications have been published in the literature [9], but few efforts have synthesized knowledge specifically on their incorporation into renewable-dominated microgrid systems. However, despite

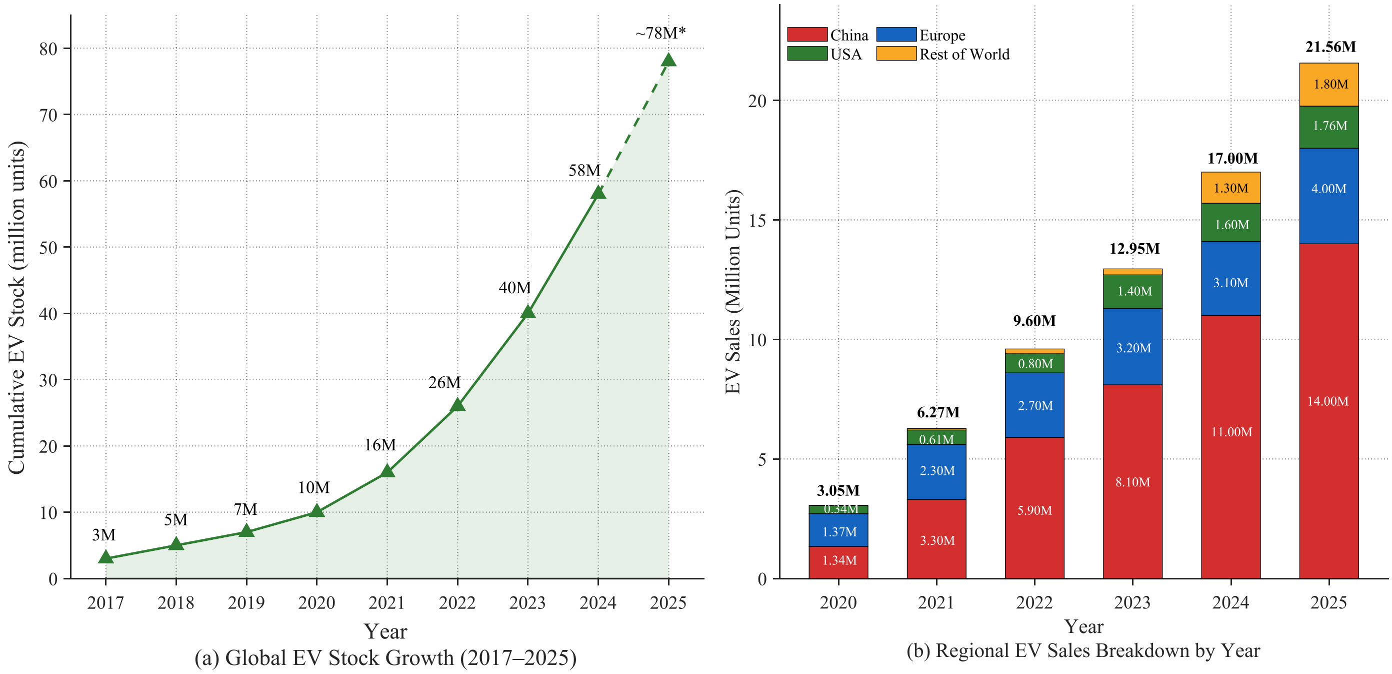

Fig. 1. Global EV growth and regional sales distribution [3,5,6].

its promising nature, SLB integration in microgrids faces significant technical challenges. Uncertain state-of-health estimation, aging-knee phenomena and heterogeneous degradation histories make reliable deployment difficult [9]. Safety threats such as thermal runaway and cell imbalance require careful screening, regrouping, and battery management [9]. Moreover, the dynamic operating environment of islanded microgrids creates additional stressors not generally found in automotive applications. These aspects highlight the necessity of a methodological evaluation of techno-economic feasibility, degradation behavior, energy-management approaches, SLB-grading mechanism, standards, and reliability considerations, particularly within microgrid systems. Several works in the past have elaborately reviewed the ways to utilize SLBs, keeping the challenges and solutions to them as their prime concern. Hu et al. [18] comprehensively reviewed the technical details and energy storage scenarios of retired LiBs in stationary energy storage applications, and concluded that the research on SLBs was in the early stages, and its rapid automatic sorting and regrouping were of great significance. Further, Neigum et al. [19] provided a brief comparative analysis using a two-fold approach — technological analysis, comparing them in terms of degradation, testing, refurbishing and modeling, as well as economic analysis, in terms of cost analysis, recycling, cost of refurbishing, and policies; however, microgrid context and stationary storage applications in a microgrid were not discussed. Gu et al. [20] reviewed the technological and economic aspects of SLBs, introducing first-life degradation models and identifying an opportunity to merge physics-based theories with data-driven methods for explainable, generalizable models. However, degradation models tailored to second-life conditions were absent, motivating further investigation into extending first-life models to SLBs. Iqbal et al. [21] further strengthened techno-economic surveying in the SLB domain for the first time, minutely analyzing recent studies on identification, selection, and control of application-based health indicators for accurate SoH estimation, offering future research directions. They also analyzed the economics, highlighting how accuracy in second-life SoH estimation and Remaining Useful Life (RUL) extension impacts projected revenue in stationary storage applications, and identified the lack of a standard business model based on future pricing trends and governing policies as an urgent research gap. Similarly, a systematic review conducted by Al-Alawi et al. [22] presented severe key limitations in the usage of SLBs in intensive renewable-integrated grid applications. Azizighalehsari et al. [23] provided a comprehensive review of the challenges associated with repurposing retired EV batteries for second-life applications. It examined various aspects, including technical, safety, uncertainty from first-life usage, Battery Management System (BMS), application suitability, and techno-economic considerations. The overarching objective was to thoroughly understand the principal challenges and delineate the research imperatives necessary for the successful implementation and prolonged lifespan of SLBs. To overcome the upfront adversities, Salek et al. [24] presented the use of equivalent-circuit models with 2RCs and 3RCs, which exhibited great accuracy for the estimation of the performance of LiBs during their second life. Song et al. [25] discussed safety issues and suggested critical solutions for thermal management based on structural optimization, parameter identification, advanced BMS, and artificial intelligence (AI)-based control strategies. Moreover, insights on cell inhomogeneity and compatibility issues have been discussed along with an additional review on solutions to data security and protection methods, including digital passports, smart meters, and Internet of Things (IoT). While SLB integration into real-world applications can prove to be one of the most remarkable steps toward sustainability, industry standards, business acumen, and social constraints also need to be matched. Eleftheriadis et al. [26] presented a lifecycle assessment of SLBs considering different business models that can be derived from reusing batteries before recycling, and analyzed their positive and negative impacts. Haram et al. [27] also included an extensive economic assessment addressing suitable selling price, repurposing cost, and comparison against new batteries, along with a comprehensive environmental impact analysis covering global warming potential (GWP), photochemical ozone formation potential (POFP), particulate matter formation potential (PMFP), freshwater eutrophication potential (FEP), and fossil depletion potential (FDP), together with the preparation of SLB assessment methods. Martinez-Laserna et al. [28] estimated a market price range of SLBs, evaluated the profitability, assessed market potential, and concluded that SLB integration could reduce EV battery costs by 6%–25%. Based on the literature, Kulkov et al. [29] and Tooraјipour et al. [30] proposed sustainable and circular frameworks for safe

Table 1
Comparison of key contributions: Existing reviews vs. Present work.

Aspect reviewed	Hu et al. [18]	Gu et al. [20]	Iqbal et al. [21]	Al-Alawi et al. [22]	Azizighalehsari et al. [23]	Salek et al. [24]	Song et al. [25]	Hassan et al. [9]	Gharebaghi et al. [31]	Shahjalal et al. [32]	Present work
SLB lifecycle definition & EOL criteria	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Battery chemistry & degradation mechanisms	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓
SoH estimation methods (ML, ECM, hybrid)	✓	✓	✓	×	✓	✓	×	✓	×	×	✓
AC microgrid-specific SLB integration	×	×	×	×	×	×	×	✓	×	×	✓
DC microgrid-specific SLB integration	×	×	×	×	×	×	×	✓	×	×	✓
Hybrid AC/DC microgrid SLB integration	×	×	×	×	×	×	×	×	×	×	✓
Mathematical modeling of SLBs in microgrids	✓	✓	×	×	×	✓	×	✓	×	×	✓
Techno-economic analysis for microgrid deployment	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Energy management & control strategies for SLBs	×	✓	×	×	×	×	✓	✓	×	×	✓
BMS architecture for heterogeneous SLB packs	✓	✓	×	×	✓	✓	✓	×	×	×	✓
Thermal management & safety for SLBs	✓	×	×	×	✓	✓	✓	×	×	✓	✓
Safety standards & certification frameworks	×	×	×	×	✓	×	✓	×	×	×	✓
Environmental impact & LCA for SLBs	×	×	×	✓	×	×	×	×	×	✓	✓
Circular economy & second-life policy frameworks	×	×	✓	✓	×	×	×	×	×	✓	✓
Degradation modeling specific to SLBs	✓	✓	✓	×	×	✓	×	✓	×	×	✓
Heterogeneous pack modeling & cell inconsistency	✓	✓	×	×	×	✓	✓	×	×	×	✓
Renewable energy integration (PV/wind + SLB)	✓	×	×	✓	×	×	×	✓	✓	✓	✓
Standardized framework for microgrid SLB deployment	×	×	×	×	×	×	×	×	×	×	✓

and secure integration of SLBs and their synchronization with market forces. Furthermore, a detailed comparative analysis considering key parameters discussed by various authors in recently published research studies on SLBs has been presented in Table 1. Most previous review studies have primarily focused on general aspects of SLB deployment, and their discussions are generally limited to individual aspects of SLB applications rather than considering the complete integration pathway within microgrid environments.

1.1. Research gaps

The comparative evaluation (Table 1) of ten prominent review articles across eighteen criteria indicates that existing studies have largely overlooked the utilization of SLBs in microgrid applications. The comparison has been performed on various parameters such as SLB lifecycle definition and EOL criteria, battery chemistry and degradation mechanisms, SoH estimation methods, integration in microgrids, presence of formal mathematical models, techno-economic analysis, energy management and control strategies. Furthermore, it also checks if the reviews have assessed the BMS designs, thermal management, safety standards, environmental impact, and circular economy coverage for SLB policy frameworks. The aforementioned analysis presents significant gaps, as SLBs can be effectively deployed in off-grid microgrids, particularly in developing regions where grid electricity is unavailable. Their use offers a cost-effective solution for rural electrification by reducing overall microgrid deployment costs, while also supporting circular economy goals and minimizing environmental impact. This review provides a comprehensive synthesis of existing studies relevant to SLB integration within microgrid applications, presenting concise and structured insights for readers. Overall, the study aims to consolidate critical information from diverse research areas that supports and facilitates a clear understanding of current developments and to support future simulation and practical investigations for the effective and sustainable deployment of SLBs in microgrid applications. Even though some prior reviews address techno-economic feasibility, environmental impact, or control and EMS yet no single review collectively addresses these themes within the microgrid context. The novelty of this work also lies in a cross-domain integration of the previously siloed threads into a single coherent framework. The integration is materialized using three concrete artifacts — the seven-stage mathematical modeling hierarchy, unified pre-deployment SLB grading framework and control and EMS strategies linked to the modeling hierarchy. Specifically, the central research gap addressed by this review is the absence of a unified framework that jointly evaluates technical performance, economic feasibility, and environmental sustainability of SLBs within AC, DC, and hybrid microgrid contexts, a gap directly evidenced by Table 1, where "SLB integration" and "Standardized framework for microgrid SLB deployment" are marked ✓ only for the present work among all eleven reviews compared. The identified gaps in existing literature are as follows:

- *Lack of unified classification and repurposing framework:* There is currently no standard worldwide protocol to classify, test, and certify used batteries for second use. Research assumes perfect conditions in batteries used, while the reality is that used batteries have high variation in capacity, internal resistance, and state of degradation. Also, there is a lack of standard procedures to diagnose batteries for repurposing and sharing of data across battery manufacturing companies.
- *Limited integration between technical, economic, and operational models:* Most existing studies treat technical performance, economic feasibility, and operational control separately. A holistic framework that integrates degradation behavior, techno-economic analysis, and real-time microgrid operation is still lacking. In addition, uncertainty in market signals, pricing mechanisms, and demand variability is rarely incorporated into unified optimization frameworks, limiting real-world applicability.
- *Limited studies provide key information regarding the integration of SLBs in MG applications:* Few studies are available that have utilized simplified simulation models. There is a scarcity of any long-term experimentation or real-world demonstrations of SLBs within microgrids under actual conditions with RES. Furthermore, the effects of any severe conditions or any variations due to seasonal changes on SLBs have not been thoroughly examined.
- *Limited discussions on energy management and control integration:* The conventional energy management techniques may be unable to account for the SLB-specific aspects, including variations in SoH, aging, and reconfigurability. The intelligent control methodologies based on adaptive learning and distributed intelligence approaches are in nascent stages for SLBs.
- *Safety, reliability, and standardization challenges*: Moreover, no consensus exists on safety standards for the certification, transport, and reuse of EV batteries. Besides, there are limited methods to assess the reliability of SLBs in distributed microgrid systems. Thermal runaway, propagation of faults in modular batteries, and cyber threats in BMS add to the list of obstacles.
- *Gaps in environmental and circular economy quantification*: Although SLBs are widely promoted as sustainable solutions, there is limited consistent quantification of environmental benefits using life cycle assessment (LCA) and circular economy indicators across different deployment scenarios. Standardized metrics for evaluating carbon offset, resource efficiency, and end-of-life recycling integration are still lacking, hindering policy-level adoption and large-scale implementation.

The above factors significantly limit large-scale deployment and practical implementation of SLBs in renewable-dominated microgrid systems. Based on these gaps, the purpose of this review is to synthesize current studies on the utility and applicability of SLBs and propose a comprehensive framework for the sustainable and reliable implementation of SLBs in future microgrid systems.

1.2. Key contributions

This review introduces a comprehensive and structured perspective on SLBs in microgrid applications, serving as a valuable reference for the readers by:

- Providing a systematic end-to-end review framework, covering battery fundamentals, repurposing processes, microgrid integration, modeling, control, safety, and sustainability.
- Bridging the gap between technical performance, economic viability, and system-level operation, which are often treated independently in existing literature.
- Mathematical modeling approaches enabling researchers to simulate realistic SLB behavior in microgrid environments.
- Critically evaluating real-world challenges such as battery heterogeneity, degradation uncertainty, and lack of standardization, rather than focusing only on idealized cases.
- Highlighting emerging directions such as battery health prediction, standardisation framework, and circular economy-driven energy infrastructure development.

Moreover, this review aims to bridge the disconnect between theoretical modeling and practical deployment by integrating multi-domain perspectives, including system-level design, operational constraints, and real-world applicability. It also emphasizes the role of standardized methodologies and coordinated control architectures to handle heterogeneity, uncertainty, and lifecycle variability inherent in SLBs. By consolidating fragmented insights from existing literature, this work provides a structured pathway for scalable SLB integration, enabling improved decision-making for researchers, policymakers, and industry stakeholders in advancing next-generation resilient and cost-effective microgrid infrastructures.

This review paper is organized as follows: Section 2 covers LiB fundamentals, while Section 3 introduces SLBs and their repurposing from EVs to stationary storage. Section 4 discusses microgrids and the role of SLBs in improving reliability and cost-effectiveness. Section 4.2 reviews SLB performance and degradation characteristics, and Section 5 examines techno-economic and economic analyses. Section 6 presents mathematical modeling approaches for SLBs in microgrid applications. Section 7 focuses on control strategies and energy management systems, while Section 8 addresses safety, reliability, and standardization issues. Section 9 evaluates environmental and sustainability impacts, and Section 10 synthesizes the key quantitative findings of this meta-review into a consolidated set of results. Section 11 concludes with key challenges, limitations, and future research directions. Throughout, Sections 5, 6, and 9 are cross-referenced to highlight the economic-environmental trade-offs arising from degradation-driven dispatch decisions. Table 7 further consolidates the technical, safety, and economic screening criteria discussed across Sections 4.2, 5, and 8 into a single unified grading instrument for pre-deployment battery classification. Collectively, this structure allows the review to move beyond a thematic survey toward an integrated framework linking modeling, control, safety, and sustainability considerations for SLB deployment in microgrids.

2. Overview of lithium-ion batteries

As a context to study about SLBs, the knowledge of first-life LiBs, their chemistry, and their operating principles is a pre-requisite. Hence, this section deals with a brief overview of LiBs. The impact of Lithium as a metal to make batteries has been studied by [33–35] due to its high energy density, light weight, and good electrochemical characteristics. Since their commercialization in the early 1990s, continuous improvements in electrode materials, cell design, and BMSs have significantly enhanced their performance, safety, and reliability. The characteristics of LiBs are primarily determined by the chemistry of the cathode and anode materials, which influence important parameters such as energy density, power capability, thermal stability, lifetime, cost, and charging performance [36]. However, its high reactivity with air and water and the need to be placed in a tamper-resistant sealing act as shortcomings to these qualities. Likewise, Nickel too, with high energy density, enhances battery performance and is used in the NMC cathode. It acts as a key economic alternative to a lot of its competitors, yet studies have showcased its unstable nature at high temperatures, which may end up increasing the cooling systems and insulation costs

Table 2
Lithium-ion battery components, materials, and functions.

Battery component	Materials/Types	Structure	Operating voltage (vs. Li/Li^+)	Specific capacity	Primary function	Main advantages	Main limitations/ Issues	Typical values/Notes	Refs.
Cathode	LCO, LMO, NMC, NCA, LFP, Li-/ Mn-rich oxides	Layered (LCO/NMC/NCA), Spinel (LMO), Olivine (LFP)	3.2–4.3 V	120–220 mAh/g	Li^+ source during discharge	High energy density	Thermal instability (Co-rich), oxygen evolution	Determines cell energy density (150–300 Wh/kg)	[46–48]
Anode	Graphite, Si, Si-C, LTO	Layered graphite; Alloying (Si); Spinel (LTO)	0.05–1.5 V	372 mAh/g (Graphite); 3579 mAh/g (Si theoretical)	Li^+ storage during charge	High capacity; low potential	SEI formation; Li plating; 300% volume expansion (Si)	Cycle life 500–3000 cycles	[47, 48]
Electrolyte	$LiPF_6$ in EC/DMC/DEC; additives (FEC, VC)	Liquid organic carbonate system	Stable up to ~4.5–5 V	Ionic conductivity 10^{-3}–10^{-2} S/cm	Li^+ transport medium	High ionic conductivity	Flammable; HF formation; decomposition at high voltage	Most commercial cells use 1M $LiPF_6$	[49]
Separator	PE, PP, PP/PE multilayer, ceramic coated	Microporous polymer membrane	Electrically insulating	Porosity 30%–50%	Prevents short circuit	Lightweight; shutdown feature	Thermal shrinkage risk	Thickness 15–30 μm	[50]
Current collectors	Aluminum (cathode), Copper (anode)	Metallic foils	Conductive	Low resistivity metals	Electron transport	High conductivity	Adds inactive weight	Thickness 8–20 μm	[47]
Binder	PVDF; CMC/SBR (water-based)	Polymeric matrix	Insulating	1–5 weight % of electrode	Particle adhesion	Mechanical integrity	Adds dead mass	Water-based binders improve sustainability	[51]
BMS	Monitoring & balancing circuits	Embedded electronics	2.5–4.2 V per cell monitoring	SoC/SoH algorithms	Safety & control	Prevents overcharge/ overdischarge	Cost & complexity	Balancing accuracy ±10–20 mV	[47]
Recycling	Pyrometallurgical; Hydrometallurgical; Direct recycling	Metallurgical recovery processes	Material recovery	60%–95% metal recovery	Resource sustainability	Reduces mining dependency	Energy intensive (pyro)	Critical for EV-scale deployment	[52]

of the batteries [37–39]. Another alternative is Manganese, which provides high-rate capability, enhances safety and stability, and extends lifespan, by limiting the capacity fading but has low specific energy and strength [40–42]. Similarly, Cobalt also enhances thermal stability and is highly useful in elevating low-temperature performance, yet its high cost and environmental concerns related to mining become a primary challenge in its widespread usage [43]. Aluminum, on the other hand, increases structural stability and battery life and is both lightweight as well as cost-effective. It is used in small quantities, and its operation is limited to just specific applications [42, 44,45]. Thus, based on all the above-stated characteristics, LiBs have emerged as one of the most suitable technologies for energy storage applications.

2.1. Battery chemistry

The key elements of a battery are: (i) Cathode which serves as a Li^+ source during discharge, (ii) Anode, which stores the Li^+ during charge, (iii) Electrolyte for high ionic conductivity, (iv) Separator for separating the anodic and the cathodic region, (v) Current collectors for high conductivity, (vi) Binders, that provide mechanical integrity, and (vii) BMS, to prevent overcharge, over-discharge, and deep discharge. Table 2 references several common cathode and anode chemistries by their standard abbreviations: Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Nickel–Cobalt–Aluminum oxide (NCA), and Lithium Titanate (LTO), in addition to NMC and LFP introduced earlier. A detailed description of these elements is provided in Table 2 providing a comprehensive overview of all key components of LiBs including cathode, anode, electrolyte, separator, current collectors, binders, BMS, and recycling processes. It covers their materials, structure, operating voltage, specific capacity, primary function, advantages, limitations, and typical values, serving as a foundational reference for understanding LiB architecture.

2.2. Operating principles

Table 3 presents the operating principle and electrochemical reaction involved in the working of LiBs. It describes the fundamental working principles of LiBs, covering the rocking chair mechanism, electrochemical reactions, charge capacity equations, Coulombic efficiency, ion transport, and the Coupled Ion-Electron Transfer (CIET) theory. It bridges basic chemistry with mathematical formulations, providing a structured understanding of how LiBs store and deliver energy. Along with each aspect, it lists the relevant equations and important parameters, and summarizes the main takeaway or finding associated with that mechanism. It also touches the instantaneous and hysteresis performance of the cell, capturing how the battery responds under sudden changes and prolonged or extreme operating conditions. Overall, it lays out both the descriptive and quantitative side of LiB operation in one place for quick reference. The battery works through a rocking chair mechanism [53] wherein the Li-ions rock back and forth between the anode and the cathode through the electrolyte. Along with the mathematical equations and modeling, Coulombic efficiency, component functions, and ion transport mechanisms are also described. Further, CIET theory, the intercalation process, and hysteresis performance are also described. The working principle is analogous to the cellular diffusion and vascular circulation in biological systems, wherein the ion transport can be imagined to be similar to the blood flow and the electron circuit can be visualized as the nervous system and its impulses [54].

2.3. Charging–discharging characteristics

Charging–discharging characteristics play a centric role in the studies relating to LiBs. Zhang et al. [57] provided an experimental characterization of high-capacity NMC cell for BMS modeling and parameter identification while Liu et al. [58] investigated the impact of discharge rate (0.5C–4C) on thermal, electrical, and capacity characteristics. Previously, Li et al. [59] studied the cycle life degradation under rapid

Table 3
Operating principles and electrochemical characteristics of LiBs.

Aspect	Description	Key equation/Formula	Parameters/Components	Key findings	Refs.
Basic operating principle	LiBs operate via reversible lithium-ion intercalation and deintercalation between positive and negative electrodes during charge/discharge cycles.	During charging: Electrical energy → Chemical energy During discharging: Chemical energy → Electrical energy	Li^+ ions shuttle between electrodes through electrolyte; electrons travel via external circuit.	The process is analogous to cellular diffusion and vascular circulation in biological systems.	[55]
Electrochemical reaction	During discharge: Li-ions deintercalate from anode, intercalate into cathode. During charge: Reverse process occurs.	General equation: $Li_xM^{n+} + ne^- \rightleftharpoons Li_yM$ (where M = metal such as Co, Ni, Mn)	• x, y = stoichiometric coefficients • n = number of electrons • M = transition metal	Cathode materials undergo minimal crystalline structure changes during ion insertion/deinsertion.	[55]
Rocking-chair mechanism	Li-ions "rock" back and forth between anode and cathode through the electrolyte during cycling.	–	• Anode: Oxidation (loss of electrons) • Cathode: Reduction (gain of electrons)	Lithium's small size (third only to H and He) enables high voltage and charge storage per unit mass/volume.	[53]
Charge capacity equation	The total charge stored or delivered during discharge is the time integral of current.	$Q = \int_0^t I\,dt$ where: Q = charge (Coulombs) I = discharge current (Amperes) t = time (seconds)	1 Ah = 3600 C	–	[53]
Coulombic efficiency	Ratio of charge discharged to charge required to charge the cell.	$\eta_{coulombic} = \frac{Q_{discharge}}{Q_{charge}} \times 100\%$	Ideally 100%; lower values indicate side reactions or degradation.	–	[53]
Component functions	• Anode (Negative electrode): Oxidation, releases electrons • Cathode (Positive electrode): Reduction, accepts electrons • Separator: Prevents physical contact between electrodes • Electrolyte: Ionic conductor, transports Li^+ ions	–	Cathode is typically the most expensive component.	–	[55]
Ion transport mechanism	Li-ions move through electrolyte and micro-permeable separator; electrons travel through external circuit, powering connected devices.	–	Li^+ ions are small enough to pass through separator pores.	–	[53]
CIET theory	Lithium-ion intercalation requires simultaneous electron transfer from electrolyte to electrode, lowering the energy barrier.	CIET Framework: More accurate than traditional Butler–Volmer models for predicting intercalation rates.	Measured for >50 combinations of electrolytes and electrodes (NMC, LCO).	Traditional Butler-Volmer models do not accurately predict intercalation rates; CIET provides superior mathematical description.	[56]
Intercalation process	Li-ions insert themselves into solid electrode during discharge; de-intercalate and return to electrolyte during charging.	–	• Intercalation: Li^+ enters electrode • Deintercalation: Li^+ leaves electrode	Electrons must transfer at the same time as ions to overcome the energy barrier.	[56]
Instantaneous performance	Immediate changes in voltage, current, and internal resistance when battery is subjected to extreme conditions (temperature, mechanical impact, electrical abuse).	–	• Voltage drop/rise • Current surge/limit • Resistance change	Can indicate imminent failure if thresholds are exceeded.	[54]
Hysteresis performance	Potential for continuous evolution or irreversible degradation if operation continues after experiencing extreme conditions.	–	Irreversible capacity loss, impedance growth.	Operating beyond limits leads to permanent damage.	[54]

1C charge–discharge cycling using impedance analysis, and Zhang [60] compared different charging protocols and their impact on cycle life. These studies concluded that a higher C-rate, which is a measure of how fast the battery gets charged or discharged relative to its nominal capacity, caused sharp capacity loss [58], increased the internal resistance [58,59] as well as temperature to I^2R heating and losses. On the other hand, higher C-rate charging accelerated the Li plating [60] and Solid Electrolyte Interphase (SEI) growth, hence enhancing the resistance during charge-transfer [59,60]. Thus, it has been observed that the cycle life strongly depended upon impedance growth [59], was sensitive to charging protocol [60], and thermal stress extensively contributed to degradation [57,58].

2.4. *Aging and degradation mechanisms (Calendar and cycle aging)*

Aging and degradation are the primary challenges of LiBs. Kirkaldy et al. [61] provided an open-source dataset for cycle aging under different State of Charge (SoC) windows and temperatures, quantifying the degradation modes and concluded that low SoC cycling accelerates the degradation of SoC. High SoC cycling promotes lithium plating & cathode degradation and temperature accelerates it further. Affirming to this, Khan et al. [62] found that calendar aging is strongly dependent upon the SoC & temperature. Electrochemical Impedance Spectroscopy (EIS) at multiple SoC revealed the evolution of internal resistance and degradation pathways. Zhang et al. [63] too observed that calendar capacity fade was mainly a consequence of SEI growth and aging mechanism shifted to an exceedingly faster pace at high temperature. Also, the impedance features strongly correlated with degradation.

Various studies altogether reported that calendar aging was dominated by SEI growth due to loss of Lithium Inventory (LLI) [63,64], accelerated to exceedingly high rates at high SoC and temperatures [62,63], caused impedance rise and capacity fade, and led to structural degradation. Cycle aging caused LLI and loss of active material (LAM) simultaneously [61,65]. Low SoC cycling caused silicon (Si) degradation [61], mechanical stress was a key reason of particle cracking and active material loss and the impedance grew strongly with aging [61–65].

2.5. SoH estimation

Modern energy storage applications require efficient batteries which can serve as ESS. With the increasing renewable penetration, this need has increased manifold. So, in order to quantify this degradation and further utilization in a microgrid, a figure of merit termed as SoH is used to evaluate how well the battery is functioning. Rout et al. [66] proposed a machine learning (ML)-based SoH estimation framework (7 ML models including Long Short-Term Memory (LSTM) networks) for EV applications. Chen et al. [67], on the other hand, developed a Particle Swarm Optimization (PSO)-Extreme Learning Machine (ELM) model using IC curve features for SoH estimation. Zhu et al. [68] developed a parallel deep learning model (Temporal Convolutional Network (TCN) + LSTM) for SoH & RUL estimation; clearly defines End-of-Life (EOL). SoH, in all the papers is defined relative to different quantities, such as, Capacity-based SoH [66–68], Resistance-based SoH [68,69], Feature-based SoH [67,70] and a combined definition [70]. The EOL criteria is also assumed distinctly such as capacity less RCB or internal resistance $\geq 2\times$ initial value [68]. The pack-level EOL may occur earlier due to cell inconsistency [69] and EOL has been explicitly linked to safety risk and performance limitation [66,70]. Similarly, the model-based approaches also differ being model-based - like ECM, electrochemical models, Kalman filters [70], data-driven - ELM, Convolutional Neural Network (CNN), LSTM, TCN [66–68], and the hybrid approaches have seemingly been increasing in the recent literature [70]. Future aspirations based on AI-based models showcase a higher capability for nonlinear modeling. Accurate SoH estimation is therefore a prerequisite for second-life repurposing, as it determines whether a retired EV battery retains sufficient capacity and power capability to meet the performance thresholds of stationary microgrid applications. The estimated SoH directly governs the grading, grouping, and dispatch strategy of SLBs, making reliable health quantification the foundational step before any second-life integration can be attempted.

3. Concept of second-life lithium-ion batteries

LiBs have been widely adopted in EVs due to their lower cost, long life, high energy and power density, and higher Wh/kg capacity [71]. However, their rigorous utilization in EVs can cause the degradation of the battery, henceforth reducing its lifespan. This can be a resultant of varying causes like — loss of cyclable lithium, solid–electrolyte interphase growth, mechanical stress on the electrode, particle cracking, side reactions, active material structure changes, and increased resistance. The life of LiBs can also be affected by numerous other factors such as temperature, depth of discharge, and charging and discharging rates [71]. These retired batteries can be crucial and still suitable for less demanding and stationary applications. They are known as second-life batteries. Generally, the threshold for this EOL is at 80% of the total capacity; however, its subjectivity is still under the question of conservativeness [72]. The section further describes how SLBs have been defined in literature, their relevance to microgrids, their selection criteria, and henceforth enlists their advantages and disadvantages for microgrid applications.

Based on the battery capacity, the operation of the battery can be divided into three phases – (i) First Life - with battery capacity 100%–80% - suitable for EV application, (ii) Second Life, with battery capacity <80% (RCB) to ∼30%, suitable for ESS application and (iii) Recycling – below 30% [25], as also depicted in Fig. 2. To further clarify the distinction between the two operating regimes, Table 4 summarizes the key differences between first-life LiBs and SLBs across state of health, capacity retention, internal resistance, degradation behavior, safety, operational constraints, cost, and typical applications. This comparison underscores that SLBs are not simply degraded first-life batteries but a distinct operating regime with its own performance envelope, safety margins, and deployment logic, which is the basis for the microgrid-specific challenges discussed throughout this review.

Furthermore, Table 5 describes how various authors in their reviews and descriptions define SLBs, specifying their EOL and SoH retirement thresholds and the key concept each emphasizes. It reveals a general consensus around the 70%–80% capacity retirement threshold while highlighting differences in application-dependent interpretations and the varying conservativeness of EOL criteria across literature. Taken together, these varying definitions underscore that "second-life" is not a fixed technical state but a context-dependent classification shaped by application requirements, economic viability, and risk tolerance. This lack of a standardized EOL/SoH threshold across the literature further motivates the need for a unified, parameter-rich screening framework such as the one proposed in this work.

SLBs have several practical utilities. They can be utilized in various distinct applications such as grid-connected ESS, renewable integration, peak shaving and energy arbitrage, frequency regulation and ancillary services [9,28,31]. Moreover, they reduce the EV upfront cost, thus, extending the battery value chain and supporting the circular economy transition, therefore, reducing the environmental burden on premature recycling [22,32,73]. However, there are still some key challenges that surround the notion of using SLBs for critical applications such as lack of standardized EOL and SoH criteria, degradation variability and inconsistency of the cell, safety hazards – especially thermal runaway risks, regulatory and market uncertainty, trustworthiness and the cost of test, sorting and repurposing [9,25,72]. Thus, providing suitable techniques for the integration of SLB into ESS applications, defining appropriate standards and introducing correctly framed regimes and policies can prove to be an important step in devising methods for integration of SLBs into microgrids.

3.1. Analysis of batteries: EV → repurposing → microgrid/grid → recycling

As stated in the previous section, due to cycle aging and reducing SoH EV batteries no more stay useful with time for the desired application, and they are retired at RCB due to reduced range and performance. This threshold is inherited from the automotive requirements [25,28,32]. To make these batteries useful after the end of the first use, they are repurposed. This process is called Second-Life processing. The steps involved in this process are: (i) Testing and SoH screening, (ii) Sorting and grading, (iii) Re-manufacturing and module reconfiguration, and (iv) Safety and BMS adaptation. The decision pathways of the utilization of these repurposed batteries, called SLBs, depend on the remaining capacity, degradation history, and the economics surrounding it [72,73]. After repurposing, SLBs can be deployed in several important applications such as photovoltaic (PV)-integrated microgrids, wind along with storage hybrid systems, frequency regulation, peak shaving, and energy arbitrage. Most of the papers identify stationary ESS for renewable integration as the dominant and primary second-life application [9,22,25]. Once this second-life application is performed and the battery capacity starts degrading, and when capacity drops below 30% or when the safety risks start to heighten, the batteries need to get recycled [25]. Recycling generally aims to recover the precious metals like Lithium, Nickel, Cobalt, and Copper. The majority of papers in existing literature position recycling as the last step in the circular economy model [28,32].

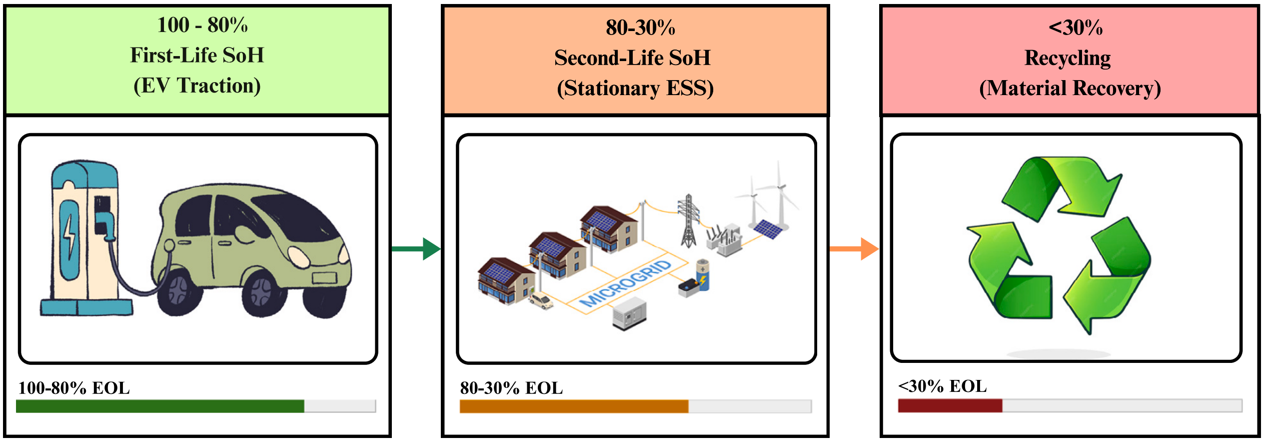

Fig. 2. Battery Lifecycle Phases and SoH Thresholds.

Table 4
Comparison between first-life LiBs and second-life batteries [9], [25], [28], [72].

Parameter	First-life LiBs	Second-life Li-ion batteries
State of Health (SoH)	100%–80%	<80% (RCB) down to ∼30%
Capacity retention	High and relatively uniform across cells and modules	Reduced and heterogeneous, varying with prior EV duty cycle and chemistry
Internal resistance	Low and stable, close to nameplate values	Elevated and unevenly distributed across cells, altering current sharing
Degradation behavior	Gradual, well-characterized, and largely predictable from standardized testing	Non-linear, history-dependent, and harder to predict due to unknown first-life stress factors
Safety considerations	Governed by first-life certification standards under known, uniform conditions	Requires additional screening and monitoring, as safety margins shift with aging and heterogeneity
Operational constraints	Designed for high power/energy density and dynamic EV duty cycles	Better suited to lower-rate, stationary duty cycles with relaxed power requirements
Cost	Higher upfront cost reflecting new-cell manufacturing	Lower acquisition cost, but with added testing, sorting, and repurposing costs
Typical applications	Electric vehicles requiring high energy and power density	Stationary ESS, microgrids, peak shaving, frequency regulation, and renewable integration

3.2. Battery selection criteria

Another important part regarding the usage of SLBs is the battery selection criteria. The methodologies can be interlinked from the selection criteria used for First-life LiBs. Table 6 describes how various methodologies have been described with their selection criteria and the lifecycle context considered, summarizing battery selection criteria used across different lifecycle stages, from grid-scale battery energy storage system (BESS) and EV operation to PV-integrated and renewable microgrid systems. It shows that most studies prioritize either EV performance-safety tradeoffs or techno-economic efficiency, with no centralized framework integrating criteria across the full EV-to-microgrid lifecycle.

Based on the current literature, it can be concluded that most studies prioritize EV performance and safety tradeoff [77,80]. On the other hand, microgrid and grid-related studies prioritize the techno-economic efficiency of SLBs [78,79] while environmental lifecycle integration remains limited [76]. Multi-Criteria Decision Making (MCDM) dominates the selection methodology [79,80] but there exists no centralized framework that integrates EV → repurposing → microgrid → recycling selection criteria. To bridge this gap, Table 7 proposes a unified pre-deployment grading framework that consolidates all nine evaluation indices alongside their constituent raw parameters into a single screening instrument. Batteries are classified into Grade A (AC microgrid), Grade B (DC microgrid), or Grade C (hybrid microgrid backup) using a worst-case rule, whereby a battery is assigned the lowest grade triggered by any single parameter. Any parameter falling in the disqualified range removes the battery from the second-life pool entirely, irrespective of all other scores. The reason Grade A, B, and C batteries are assigned to AC, DC, and hybrid microgrids is that each type of microgrid places different demands on the battery. AC microgrids need batteries to handle bidirectional power flow through inverters, along with frequency regulation and peak shaving, all of which cause fast, back-and-forth current swings. These conditions are hardest on a battery, so only the healthiest packs – Grade A, with SoH ≥ 0.80, Health Index ≥ 0.80, Degradation Index ≤ 0.20, and the lowest thermal risk and imbalance – can meet the tighter efficiency (≥96%) and reliability needs of AC-coupled duty. DC microgrids, used for things like PV buffering and EV charging, involve steadier, mostly one-directional charge/discharge cycles with fewer sudden transients, since there is no AC/DC inversion loss. This means the thermal, resistance, and cycling limits can be relaxed a bit, while still needing decent capacity and cell balance. Grade B batteries (SoH 0.70–0.79, thermal risk of 35–42°C, round-trip efficiency 93%–95%) fit well here, since the lack of inversion losses makes up for their slightly higher resistance and lower reliability compared to Grade A. Hybrid microgrids, which combine AC and DC buses and are mainly used for backup power, can accept the lowest usable grade (Grade C) because backup duty is shallow, occasional, and not time-critical. This allows batteries with SoH as low as 0.60–0.69, thermal risk up to 45°C, and efficiency of 90%–92% to be used safely, as long as they stay above the disqualification limits. So overall, the stress on the battery decreases from AC to DC to hybrid duty, which lets lower-health batteries go to less demanding jobs instead of being

Table 5
Overview of literature on SLBs definition and EOL criteria.

Authors/year/Refs.	Work done	How second-life is defined	EOL/SoH criteria for second-life	Key concept emphasized
Gharebaghi et al. 2025 [31]	Comprehensive survey of SLBs in stationary ESS applications	Retired EV batteries reused when automotive SoH drops to ∼80%, but still retain 70%–80% capacity	EV batteries retired at ∼80% SoH; reused for BESS	Second-life extends value chain; economic & environmental benefits
Patel et al. 2024 [72]	Review of second-life pathways and policy implications	Batteries no longer suitable for EV (at RCB) but viable for less-demanding applications	EOL defined at RCB; second-life depends on application tolerance	Highlights overly conservative 80% EOL rule; application-dependent retirement
Campoverde-Pillco et al. 2024 [74]	Systematic literature review of EV battery reuse in power systems	Reuse of EV batteries in grid systems to support renewable integration	EOL implied when no longer fit for EV use	Focus on circular economy and renewable energy support
Chirumalla et al. 2023 [73]	Case study evaluating remanufacturing, repurposing, reuse	"Battery second life" = remanufacturing, repurposing, or reuse after primary use	Capacity reduced ∼20% (≈80% remaining) triggers retirement	Circular business models; remanufacturing most viable
Al-Alawi et al. 2022 [22]	Techno-economic review of retired EV battery repurposing	Repurpose/reuse = employing retired EV batteries in secondary applications	Retired at RCB	Technical & economic feasibility of second-life ESS
Hassan et al. 2023 [9]	Review on SLBs for power grid applications & degradation	Retired EV batteries (70%–80% capacity remaining) reused for grid ESS	Retired after 20%–30% capacity loss	Links degradation, SoH, and grid services
Illa Font et al. 2023 [75]	Short review & perspectives on EV battery second life	SLB = battery retired from EV at 70%–80% capacity and reused	Retirement when 20%–30% capacity utilized	Second-life as lifecycle extension before recycling
Song et al. 2024 [25]	Overview of second-life utilization & challenges	Second-life battery = EV battery entering Phase 2 after <80% capacity	Phase 1: 100%–80%; Phase 2: <80% (second-life); Phase 3: <30% (recycling)	Defines clear 3-phase lifecycle model
Shahjalal et al. 2022 [32]	Comprehensive review of second-life prospects & challenges	Second-life = application of LiB after falling below 80% nominal capacity	EOL at 80% capacity	Emphasizes economic and transport-grid synergy
Martinez-Laserna et al. 2018 [28]	Foundational critical review on battery second-life concept	Second-life = reuse of EV batteries not meeting automotive requirements but usable for grid storage	Implicit 80% threshold	Economic, technical & environmental viability review

Table 6
Battery selection criteria across lifecycle stages.

Authors/year/Refs.	Lifecycle context considered	Battery selection criteria identified
Jaradat & Khatib, 2025 [76]	Focus on grid-scale BESS lifecycle (manufacturing → operation → EoL via LCA)	Environmental impact (GWP, toxicity), LFP environmental superiority, sizing optimization (MILP, SOCP, GA, PSO), DoD impact, C-rate, SoC management, techno-economic-environmental integration
Zhou et al. 2022 [77]	EV battery lifecycle until failure threshold (∼80% capacity)	Direct Health Index (HI): capacity, internal resistance; Indirect HI: voltage, IC curve, temperature rise, charging time; SoH-based retirement criteria
Tsianikas et al. 2019 [78]	PV + Battery system during grid outage (operational stage)	Battery cost ($/kWh), efficiency, Depth of Discharge (DoD), capacity size, resilience (LOLP), Value of Lost Load (VOLL)
Pang et al. 2021 [79]	Renewable penetration stage (grid integration phase)	Storage efficiency, storage capacity, discharge ability, maintenance, environmental impact, economic & social criteria, multi-attribute evaluation using Choquet integral
Loganathan et al. 2021 [80]	EV operational stage (vehicle application)	Energy density, specific power, safety, reliability, cost, lifespan, electrode material (LCO, LFP, NMC, LTO), performance-cost tradeoff

scrapped early. No existing study combines all nine of these parameters into one SLB screening framework — the individual thresholds for SoH, thermal limits, and cell balance limits used here are based on established standards, including IEC 62619 [81,82], and prior techno-economic literature, brought together into one unified framework. The worst-case rule is a conservative and safety-first design principle instead of a rule derived from empirical failure-rate data on SLBs. It prioritizes the elimination of high-risk cells and batteries and the screening stage over maximizing their utilization rate and reflects the high uncertainty and heterogeneity inherent to them.

3.3. Advantages and disadvantages of SLBs

Fig. 3 maps the deployment of SLBs against the United Nations Sustainable Development Goals (SDGs), illustrating how second-life reuse simultaneously advances objectives related to affordable clean energy (SDG 7), responsible consumption (SDG 12), and climate action (SDG 13). The alignment underscores that SLB integration is not merely a technical proposition but a cross-cutting sustainability strategy that addresses resource efficiency, carbon reduction, and equitable energy access within a single unified framework. SLBs can be highly advantageous not only to the environment, but also to the economy, energy production, microgrid stability, and sustainability. The key advantages of SLBs are:

- *Lifecycle Extension & Circular Economy:* SLBs extend battery service life beyond EV retirement (70%–80% SoH), improving material utilization efficiency [28,32].
- *Economic Value Recovery:* Reduced capital cost for stationary ESS and potential levelized cost of energy reduction in microgrids [22,83].
- *Environmental Benefits:* Lower per-kWh environmental impact compared to immediate recycling; delayed raw material extraction [32,72].

Some critical disadvantages include:

Table 7
Unified pre-deployment grading framework for SLBs in microgrid applications.

Parameter category	Metric/Index	Grade A (AC microgrid)	Grade B (DC microgrid)	Grade C (Hybrid microgrid)	Disqualified (Recycle)
Health & degradation	SoH	≥0.80	0.70–0.79	0.60–0.69	<0.60
	Health Index (HI)	≥0.80	0.65–0.79	0.50–0.64	<0.50
	Degradation Index (DI)	≤0.20	0.21–0.40	0.41–0.55	>0.55
Thermal safety	Thermal Risk Index (TRI)	≤0.20	0.21–0.40	0.41–0.55	>0.55
	Peak temperature T_{max}	≤35 °C	35–42 °C	42–45 °C	>45 °C
	Rate-of-rise $(\dot{T})_{max}$	≤0.2 °C s^{-1}	0.2–0.5 °C s^{-1}	0.5–1.0 °C s^{-1}	>1.0 °C s^{-1}
Reliability & RUL	Reliability Index (RI)	≥0.80	0.65–0.79	0.50–0.64	<0.50
	RUL (normalized, RUL/L_{max})	≥0.70	0.50–0.69	0.30–0.49	<0.30
	Daily cycling frequency f_{cyc}	≤1.0 cycle day^{-1}	1.0–2.0 cycles day^{-1}	2.0–3.0 cycles day^{-1}	>3.0 cycles day^{-1}
Operational stress	Operational Stress Index (OSI)	≤0.25	0.26–0.45	0.46–0.60	>0.60
	Depth of Discharge (DoD)	≤0.60	0.61–0.75	0.76–0.85	>0.85
	C-rate (normalized, C_{rate}/C_{max})	≤0.30	0.31–0.55	0.56–0.70	>0.70
Pack imbalance	Battery Imbalance Index (BI)	≤0.20	0.21–0.40	0.41–0.55	>0.55
	Cell voltage imbalance ΔV_{imb}	≤10 mV	10–30 mV	30–80 mV	>80 mV
Variability & fleet spread	Variability Index (VI)	≤0.20	0.21–0.40	0.41–0.55	>0.55
	Capacity deviation CV_C	≤0.05	0.05–0.10	0.10–0.15	>0.15
	Resistance deviation CV_R	≤0.05	0.05–0.12	0.12–0.20	>0.20
Safety	Safety Index (SI)	≤0.20	0.21–0.40	0.41–0.55	>0.55
	Overcurrent events	None	≤2 month^{-1}	3–5 month^{-1}	>5 month^{-1}
Economic	Economic Index (EI)	≥0.70	0.50–0.69	0.30–0.49	<0.30
	Procurement cost factor C_f	≤0.30	0.30–0.38	0.38–0.45	>0.45
Microgrid suitability	Round-trip efficiency η	≥96%	93%–95%	90%–92%	<90%
	Remaining capacity	≥80%	70%–79%	60%–69%	<60%
	Recommended application	AC MG: frequency regulation, peak shaving	DC MG: PV buffering, EV charging	Hybrid MG: low-demand backup storage	Recycling/disposal

Notes: All composite indices (HI, DI, TRI, RI, EI, VI, SI, OSI, BI) are min–max normalized to $[0,1]$. **Worst-case rule:** a battery is assigned the lowest grade triggered by *any single* parameter; disqualification on any parameter mandates removal from the second-life pool regardless of all other scores. T_{safe} = 45 °C and T_{crit} = 60 °C follow IEC 62619; BMS rebalancing threshold 30 mV and unsafe limit 80 mV per IEC 62619. Cost-factor thresholds follow the ≤40% new-battery-cost viability criterion established in the techno-economic analysis (Section 5).

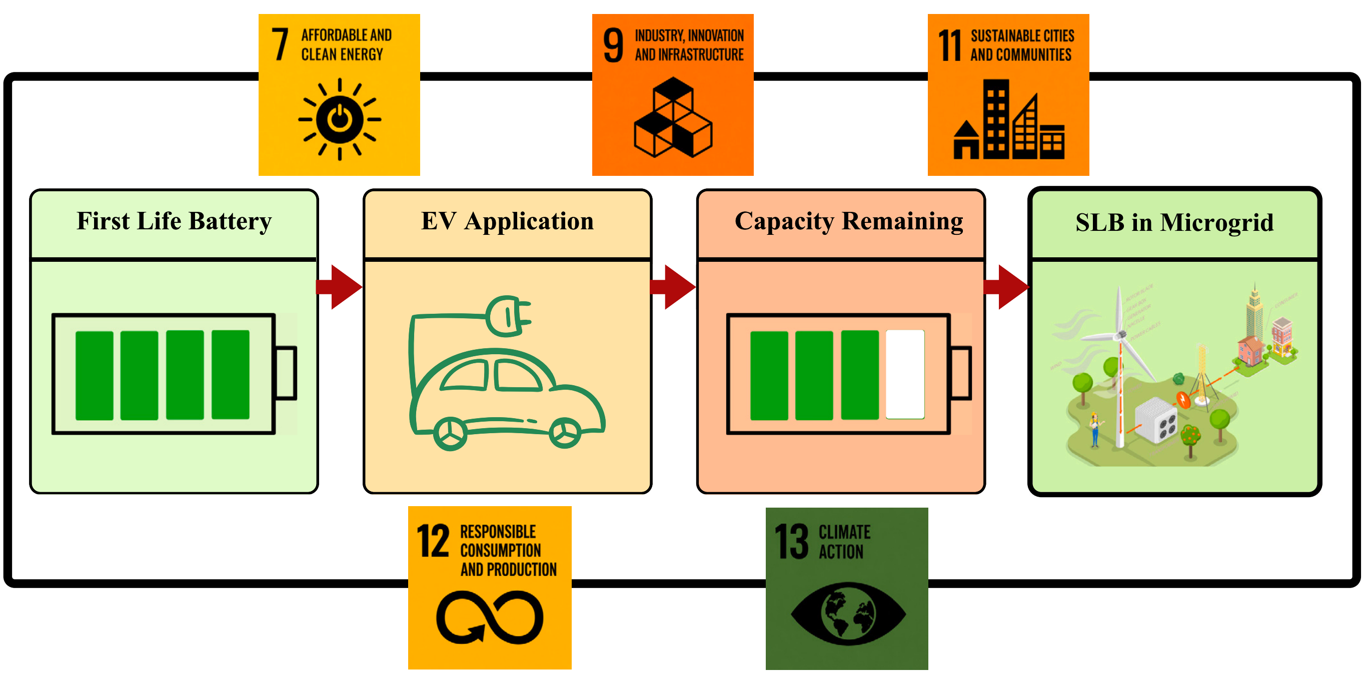

Fig. 3. Alignment of SLBs with UN SDGs.

- *Technical Uncertainty:* Unknown degradation history and cell heterogeneity significantly affect reliability [28,32].
- *Safety Risks:* Thermal runaway and certification challenges remain major concerns [9,25].
- *Economic Barriers:* High testing, sorting, and remanufacturing cost reduce profitability [22,28].
- *Regulatory & Standardization Gaps:* Lack of unified SoH/EOL criteria and absence of global policy frameworks [25,72].
- *Market Immaturity:* Limited warranty models and investor uncertainty hinder large-scale deployment [72].

Overall, SLBs are technically viable and an environmentally promising solution; standardization gaps, safety validation, economic uncertainty, and lack of integrated decision frameworks still act as major constraints. Most of the studies treat the advantages and disadvantages separately, and very few integrate technical, economic, environmental, and policy dimensions into a unified SLB evaluation model.

4. Significance of SLBs in microgrid applications

This section provides a brief overview of the relevance of ESS in microgrids and discusses different types of microgrids, their performance expectations from SLBs, and their operational requirements. Microgrids are localized and small-scale power systems that integrate distributed generation sources, loads, and ESS and are capable of operating both independently as well as in a grid-connected manner [84–86]. They work by coordinating the power generation, storage, and consumption using energy management systems (EMS) along with inverter-based control, making sure grid codes are not violated, by ensuring stable voltage, frequency, and supply reliability [86,87]. Based on the mode in which they are operating, microgrids can be divided into distinct types, namely, Grid-connected, that operates in a synchronized way with the main grid, thus, allowing bidirectional power flow and enhanced efficiency [85,88], Islanded, which operates independently in case of outages and ensure an uninterrupted local supply [85,86] and Hybrid, combining renewable sources, storage and backup generators for flexible and resilient operation [88,89]. A key role in the optimal functioning of microgrids is played by ESS, and batteries have proven to be the most common and most reliable storage device. They are used for multidimensional operations like load balancing & power mismatch compensation [86], renewable energy smoothing & intermittency mitigation [87,89], voltage & frequency stabilization [86,88], backup supply during grid outages or disasters [85] and improving the reliability and operational flexibility [84]. Along with ESS, they also have some key operational requirements such as storage and control systems used to maintain the supply–demand balance [84,86], ESS compensation for renewable smoothing due to its intermittent nature [87], EMS optimization for minimal low-cost power consumption [87], backup power supply for islanded operation with uninterrupted supply during faults or disasters [85,88] and at last, system stability and power quality maintenance [86,88]. Table 8 summarizes microgrid definitions, classifications, storage roles, and operational requirements from six recent studies. It establishes the performance baseline that SLBs must meet in microgrid contexts, covering grid-connected, islanded, and hybrid modes along with the critical roles of ESS in load balancing, renewable smoothing, frequency regulation, and backup power.

4.1. Performance expectations from SLBs in microgrids

SLBs generally retain SoH close to RCB making them unfit for EV application, but they can still be highly suitable for stationary storage applications such as microgrids and renewable energy support [90–92]. Even at this reduced capacity, they can demonstrate reliable operations in real microgrid systems and without any major operational failures [17]. Thus, they are capable of being used in microgrid applications which have lower power and performance requirements, which allow the usage of degraded EV batteries to remain technically functional and economically useful [92,93]. The efficiencies of SLBs depends upon their size, chemistry, and degradation [91]. Sarker et al. [94] demonstrated the feasibility of integrating SLBs into a photovoltaic-based EV charging station, reporting an 85% battery round-trip efficiency and a 94.2% bidirectional inverter efficiency, while achieving an energy self-sufficiency ratio of 78% under tropical operating conditions. This efficiency makes it highly relevant for critical functions such as renewable energy buffering, load balancing and frequency regulation, confirming that they can provide performance comparable to the new ones. Also, they can be extremely beneficial for energy management-based operations such as load balancing and peak demand reduction which are the primary requirements of microgrid operation. Experimental deployment results have demonstrated 60% peak demand and 39% peak-time energy reduction [17]. Similarly, the retired $LiFePO_4$ batteries have achieved stable voltage, temperature and capacity for long-term operation [94] acting as a testimony to the suitability for this application.

A major performance expectation is enabling renewable energy integration by supporting renewable-based microgrids: absorbing excess PV energy, supplying power during decreased solar and wind output, and improving renewable penetration for clean and sustainable energy [17,94]. This aligns with scenario-based evidence from semi-arid regions showing that hybrid solar-wind configurations consistently outperform single-source deployments in renewable share, fuel savings, and emission reduction [95]. They also enable critical grid services such as frequency regulation, energy arbitrage and renewable smoothing [91,93]. Although usable, the unpredictable and fast degradation of SLBs is still one of the central issues. Their increased internal resistance and capacity fading overtime hampers the reliability for the consumer. Their performance is strongly dependent on initial SoH, degradation rate, operating temperature and charging–discharging cycles and C-rate [92,93]. Improper management can be a key cause of further reduction in lifetime and accelerated degradation. SLBs require an advanced system architecture and control to ensure optimal performance, including SoC balancing between heterogeneous battery packs [93], BMS for monitoring and safety [17], and pack-level control using converters for heterogeneous battery management [93]. Yet, they offer significant economic advantages, the foremost being their lower cost than new batteries [17,91] and a more viable long-term solution [90]. However, the economic performance depends on the degradation rate, condition of the initial battery, and management cost [96]. Based on all the papers, SLBs must meet at least the following conditions for reliable use in microgrids: (i) ≥70% remaining capacity, (ii) ≥90% energy efficiency, (iii) Stable voltage and temperature and reliable charge–discharge performance. Despite their hopeful characteristics, BMS, degradation monitoring and system level optimization play an important role for installation in the microgrids.

4.2. Technical specifications and performance characteristics

To use the SLBs in microgrid applications, the study of their technical specifications and performance characteristics is essential. The key characteristics that must be considered are capacity retention and energy availability, energy efficiency and electrical performance, internal resistance and power capability, thermal performance and safety characteristics, and the remaining useful life corresponding to the degradation. SLBs generally end up retaining around 70%–80% of their actual functionality and capacity, which is enough for stationary applications in microgrids and ESS [97]. Gao et al. [92] demonstrated the stable operation of retired $LiFePO_4$ batteries with around 80% remaining capacity, assuring reliability for the microgrid applications. Similarly, Lacap et al. [17] demonstrated commercial-scale SLB in a microgrid system showcasing a reliable operation with an average SoH of 71% proving that capacity loss plays no role in their usage as ESS. However, critical performance evaluations have shown that the usability varies significantly depending upon degradation conditions and operational history of the batteries [17] with various review studies affirming their range of operation within a 60%–80% usable capacity range, depending on the chemistry and aging conditions [98]. The most critical requirement for utilizing SLBs is high energy efficiency and high-grade electrical performance. They have proven to achieve energy efficiencies between 92% (NCA) and 99% (NMC), demonstrating performance suitable for grid-service and microgrid applications [97]. Deployment in real-world applications has also confirmed their stable voltage regulation and efficient power delivery for long-term operation [17]. Sustainability analysis has also shown that efficiency degradation is not instantaneous but a gradual process and can be managed if worked under proper operating conditions [90] and it

Table 8
Microgrid types, storage roles, and operational requirements.

Authors/year/Refs.	Definition & How microgrids work	Types of microgrids	Role of energy storage	Operational requirements
Hossain et al. 2025 [86]	Microgrid is a local energy grid integrating PV, storage, and inverters, capable of operating independently or with the main grid; EMS coordinates PV, storage, and loads for optimal power flow.	Grid-connected and islanded modes supported via grid-following and grid-forming inverters.	BESS provides voltage support, frequency control, inertia support, and immediate compensation during load increase.	Load balancing during demand increase; renewable variability compensation; fault ride-through; stability during solar fluctuations.
Tajjour & Chandel, 2023 [87]	Microgrids are decentralized renewable energy systems supplying local loads, especially in remote areas, controlled by EMS.	Grid-connected and isolated microgrids widely used in rural and urban systems.	ESS maintains frequency stability, energy storage, and reliable supply during renewable intermittency.	Peak shaving, load forecasting, renewable smoothing, reliability improvement, optimal power flow.
Kumar et al. 2024 [88]	Microgrid integrates distributed generators, storage, EVs, and loads, operating as an independent or grid-connected entity.	Grid-connected mode (GCM), islanded mode (IM), AC microgrid, DC microgrid, hybrid AC/DC microgrid.	Storage technologies (batteries, flywheels, compressed air) support reliability and power continuity.	Voltage and frequency control; bidirectional power flow; fault protection; reliable supply.
Dosa et al. 2025 [89]	Microgrids are self-contained power systems combining renewable generation, storage, and loads, operating autonomously or connected to the grid.	Hybrid renewable microgrids integrating solar, wind, storage, and backup generators.	Batteries store excess renewable energy and provide power during low generation periods.	Renewable smoothing, backup supply, cost optimization, load demand management, emission reduction.
He & Lin, 2025 [85]	Microgrid is a small-scale power system integrating distributed energy resources for local generation and supply, improving resilience.	Grid-connected and islanded operation.	Storage enhances continuous power supply during disasters or grid outages.	Backup supply, resilience during outages, recovery after disturbances.
Samal et al. 2026 [84]	Microgrid is a small-scale controlled power system integrating loads and distributed energy resources, improving efficiency and reliability.	Multiple operational modes and configurations (grid-connected, islanded, hybrid).	Storage devices allow energy to be stored and used when needed, improving reliability.	Load-generation balancing; voltage/frequency regulation; energy management; renewable integration.

remains sufficient for stationary applications irrespective of aging and its effects [91].

SLBs also exhibit an increased internal resistance in comparison to new batteries, which reduces their peak power delivery capacity [98], which is a natural consequence of aging and is deeply linked to capacity degradation [90]. Despite this plight, SLBs manage to maintain sufficient power capability and stable voltage behavior in microgrids, demonstrated by Gao et al. [92], which indicates their acceptable voltage behavior despite their aged characteristics. Suitable power management strategies can be used to mitigate these losses caused by increased resistance [91]. SLBs have also demonstrated stable thermal behavior during charge and discharge cycles [92], showcasing that they maintained safe temperature ranges during long-duration deployment [17]. It has been concluded by the existing literature that the thermal performance strongly relies on the operating conditions and battery degradation state [90]. Advanced energy management and thermal-monitoring systems can be employed to improve operational safety [91], and it is a critical requirement for ensuring the safe and reliable second-life operation [98]. SLBs continue to degrade further during the operation. These rates are significantly slower than EV operation [90]. This length of deployment can be extended or be made operationally stable and optimal using proper system design [17], and it heavily influences the RUL [91]. Contemporary performance reviews have also emphasized continuous SoH monitoring in order to ensure reliable operation [98] so that they can continue to provide their valuable services in microgrids. They can achieve a significant reduction in the peak demand, complementing the load management in a microgrid system [17]. Retired $LiFePO_4$ batteries have been useful in PV and renewable integration for microgrid operation [92]. They have also demonstrated solid and robust performance with extendable RUL [91], providing a trustworthy condition for stationary applications despite degradation [98]. Thus, SLBs retain electrical, thermal, and operational characteristics enough for stationary energy storage applications, especially in microgrids, despite the reduced capacity and high internal resistance. Their success is highly dependent on remaining battery capacity, degradation condition, thermal management, system-level design, and the managing environment.

5. Techno-economic assessment methodologies and findings for SLBs

In order to deploy the SLBs into real-world, its cost and economic parameters play an essential role. Studies like [94] have shown that SLB systems extensively reduce the capital expenditure in comparison to the new ones in PV hybrid charging stations. Gautam et al. [96] identified that acquisition cost played a deterministic role in determining whether SLBs are feasible or not. To supplement the horizon of economic incentives, Cao et al. [99] discovered and demonstrated that cost benefits and upfront cost reduction play an important role in influencing the net present value (NPV), even more than the technical degradation parameters. To enhance the modeling, Farakhor et al. [91] explicitly incorporated the degradation cost, energy loss cost and decommissioning cost into the operational optimization. Zhuang et al. [100] modeled the SLB cost as a function of the revenue streams generated from its second-life applications. Lieskoski et al. [101] quantified the cost of repurposing between 27.2–38.3 EUR/kWh for module-level processing. This section further breaks down the entire cost into its components and discusses how contemporary literature has modeled it.

Fig. 4 consolidates the principal techno-economic metrics reported across the reviewed literature, encompassing acquisition cost, levelised cost of storage (LCOS), NPV, internal rate of return (IRR), and repurposing expenditure. The most important concern revolving around the SLBs is the cost of repurposing and testing them. In the previous sections, it was found that there exists no standard model to determine the battery parameters for SLB refurbishment. Lieskoski et al. [101], in the techno-economic analysis for SLB potential for SLB business in Finland, concluded that cell-level disassembly is economically unfavorable and the operation is highly infeasible due to high labor intensity requirements. Patel et al. [72] also added to it stating that collection, sorting, and SoH evaluation significantly add to the logistical complexity and

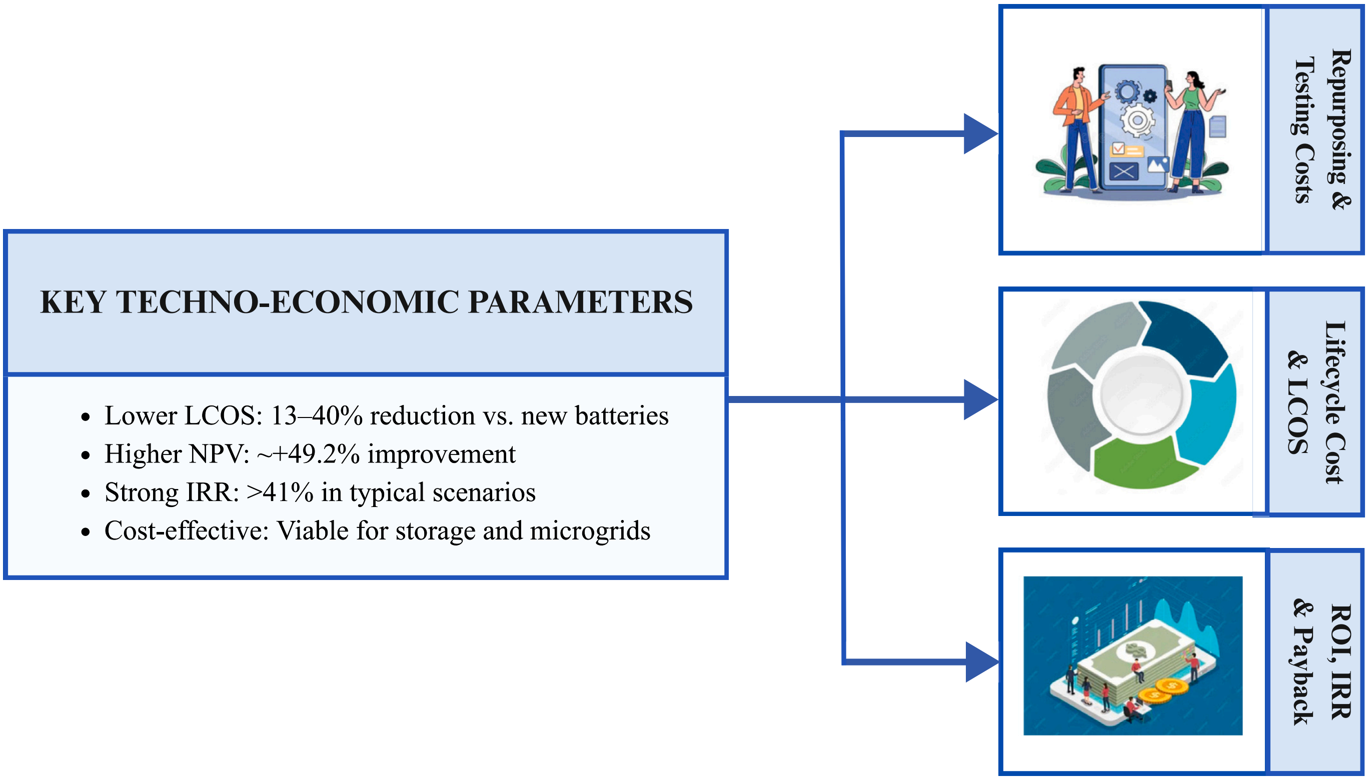

Fig. 4. Key techno-economic metrics of SLB systems.

cost; its repurposing and the SLB would become viable only when its cost is ≤40% of the new battery [96]. Wangsupphaphol et al. [102] also demonstrated that the reduced acquisition cost somewhat compensates for the degradation uncertainty and surrounding trustworthiness issues. Sarker et al. [94] reported that a 40% reduction in LCOS when SLB is used in place of new batteries. Cao et al. [99] also showed that SLBs achieve a 49.2% higher NPV with respect to the new battery systems and a 13.8% lower operation LCOS. As a testimony to the claims, Wangsupphaphol et al. [102] showed that SLBs outperform the newer batteries economically when exposed to high Depth of Discharge (DoD) operations. Similarly, Cao et al. [99] reported that SLBs achieved a 41.9% IRR in comparison to new batteries with significant commercial building deployment. Wangsupphaphol et al. [102] also demonstrated a 10-year economic feasibility analysis for PV-SLB systems for sustainable EV home charging. The economic analysis by Zhuang et al. [100] came out with an interesting fact that frequency regulation is the most profitable second-life application at $273/kWh value (market-dependent), thus showcasing its economic benefits.

From the previous subsections, it is clear that SLBs can be a beneficial option for microgrid deployment. The study [94] clearly showcased 78% renewable self-sufficiency in SLB-PV charging systems, and [91] also showed that optimal power management significantly improves the economic utilization of SLB in grid storage. Zhuang et al. [100], on the other hand, showcased that profitability varies widely depending upon the grid service market. Thus, it can be concluded that acquisition cost is the center of attention of techno-economic feasibility. Degradation modeling, though necessary, but it is not the primary driver of the economy. Irrespective of their shortcomings, SLBs tend to be a viable alternative to the new LiBs as they outperform the operation in most realistic dispatch scenarios with less than 40% cost of the new battery price. These SLBs can be widely used in frequency regulation due to their highest returns with LCOS reductions between 13%–40%, thus being a significant reason for policy incentives and attaining sustainability. This proves that microgrid and EV-charging integration improves the proposition of SLB value. Table 9 provides a brief overview of the techno-economic analysis provided in the existing literature and compares cost structures, repurposing costs, lifecycle cost comparisons, LCOS metrics, and Return on Investment (ROI)/payback insights from eight key studies on SLB economic viability. It confirms that acquisition cost is the primary driver of feasibility, with SLBs becoming economically attractive when priced below 40% of new battery cost, achieving LCOS reductions between 13%–40%.

Table 10 summarizes key technical and economic parameters of SLBs across multiple studies consolidating the technical parameters such as SoH range, SoC limits, cycle life, and service duration alongside economic parameters including cost per kWh, NPV, IRR, and LCOS reductions from eight prominent studies. It provides a quick reference showing that while technical characteristics are fairly consistent, economic feasibility varies significantly with acquisition cost and target application. Technically, SLBs typically operate at 70%–80% SoH and can provide an additional 1–16 years of service, with performance influenced by SoC range and degradation conditions. Economically, SLBs are viable when priced at 20%–60% of new batteries, with reported costs of $23–273/kWh and LCOS reductions up to 40%. Overall, while technical characteristics are fairly consistent, economic feasibility mainly depends on acquisition cost and application, making SLBs attractive for stationary storage and EV-related systems. While the techno-economic analysis establishes the financial viability of SLBs, translating these benefits into reliable real-world operation necessitates accurate mathematical models that can capture the electrochemical, thermal, and degradation behavior of SLBs within microgrid environments — the development of which is addressed in the following section.

Table 9
Comparative overview of techno-economic studies on SLBs in the literature.

Authors/year/Refs.	Cost structure of SLBs	Repurposing & testing cost	Lifecycle cost comparison (New vs. SLB)	LCOS/Economic metric	ROI/Payback/ Feasibility	Microgrid/Deployment insight
Sarker et al. 2026 [94]	CAPEX includes SLB acquisition + PV + inverter + installation; lower battery cost vs. new	Includes module validation and integration	40% lower LCOS compared to new batteries	LCOS reduced by ∼40% vs. new battery	Renewable self-sufficiency 78%; viable under tropical solar profile	Demonstrates PV-SLB charging station feasibility in tropical regions
Gautam et al. 2025 [96]	Integrates degradation cost, dispatch cost, replacement schedule	Repurposing viable when SLB cost ≤40% of new battery	SLBs become financially attractive below 40% cost threshold	Economic viability threshold defined	Financial attractiveness driven by acquisition cost	Grid-connected EV charging station with optimized dispatch
Cao et al. 2025 [99]	Includes acquisition cost, incentives, degradation modeling, dispatch	Real-world data used; testing cost implicit in acquisition	49.2% higher NPV vs. new batteries	13.8% lower $LCOS_{op}$ vs. new battery	41.9% higher IRR vs. new battery	Commercial building demand-charge reduction case
Farakhor et al. 2025 [91]	Includes degradation cost (Ah-throughput model), energy loss, decommissioning	No cell-level sorting; heterogeneous packs optimized	Shows economic benefit through optimal power management	Cost-minimized dispatch	Economic gain through degradation-aware control	Utility-scale SL-BESS grid support
Zhuang et al. 2025 [100]	Integrates degradation + revenue models	Decision support model compares reuse vs. recycling	SLB value varies $23–273/kWh depending on application	Application-dependent valuation	Frequency regulation most profitable	Supports reuse vs. recycling decision framework
Patel et al. 2024 [72]	Discusses economic tradeoffs of reuse vs. recycling	Sorting, collection and logistics cost barriers	Repurposing extends value before recycling	Not LCOS-focused	Highlights economic-policy dependency	Policy-sensitive second-life pathway
Lieskoski et al. 2024 [101]	Material-flow and business-level cost breakdown	Repurposing cost 27.2–38.3 EUR/kWh	Cell-level disassembly not feasible	LCOS considered at business level	Pack/module-level feasible; cell-level not viable	Regional repurposing business case
Wangsupphaphol et al. 2023 [102]	Includes degradation cost + DOD modeling	Used battery lower upfront cost	SLB advantageous at 85% DoD	LCOE used for hybrid PV-battery	10-year projected viability	Residential PV + EV charging

Table 10
Technical and economic parameters of SLBs from literature.

Authors/year/Refs.	Technical parameters	Economic parameters	Application
Gu et al. (2023) [20]	SoH: 70%–80%; reduced power capability; requires regrouping	SLB cost: 20%–80% of new battery cost	General ESS applications
Mathews et al. (2020) [103]	SoH: 80%; SoC range: 15%–65%; Lifetime: >16 years	Profitability condition: <60% of new battery cost; BOS: ∼150 $/kWh	PV + Grid storage
Zhuang et al. (2025) [100]	Lifetime: 1–6 years; SoC limitation improves lifetime	Value range: 23–273 $/kWh; Reference new battery: ∼132 $/kWh	Frequency regulation, ESS
Dong et al. (2023) [104]	SoH: at RCB; Lifetime: 5–15 years; Cycle life: 1000–10 000 cycles	SLB cost: 44–180 $/kWh; New battery: 150–250 $/kWh; Cost ratio: 20%–80%	Residential, grid storage
Farakhor et al. (2024) [91]	SoH: 70%–80%; Temperature + C-rate dependent degradation model	Includes: degradation cost, energy loss cost, decommissioning cost	Grid-scale BESS
Gautam et al. (2024) [96]	SoH: 70%–80%; PV-integrated SLB system	SLB viable if ≤40% of new battery cost	EV charging station + PV
Cao et al. (2025) [99]	SoH: 70%–80%; Lifetime: 5–10 years; lower efficiency than new batteries	Higher NPV: +49.2%; IRR: +41.9%; LCOS reduction: 13.8%	Commercial buildings
Sarker et al. (2026) [94]	System: 50 kWh battery; PV: 15 kW; degradation: 3%–4% per 100 cycles	LCOS reduction: ∼40% vs. new battery	EV charging + PV

6. Mathematical modelling of second-life lithium-ion batteries

To model the behavior of SLBs and simulate and track their characteristics for software-based implementations, their mathematical modeling is essential. Existing literature lacks a detailed and comprehensive methodology to model SLBs specifically for microgrid applications. Table 11 lists the mathematical formulation and its application in microgrid for SoC estimation, equivalent circuit models, electrochemical models, power and energy equations, efficiency modeling, degradation models, thermal models, heterogeneous pack models, EIS-based SoH, and microgrid integration equations. The framework progresses from electrochemical foundations through circuit modeling, state estimation, degradation and thermal modeling, intelligent SoH estimation, and ultimately to system-level dispatch optimization. All of these play a key role in formulating the actual behavior of the SLBs when integrated into microgrids.

Several papers have modeled SoC for SLBs. The estimation of SoC when the first life of a battery ends has been the most important step in battery repurposing. S. S. et al. [105] modeled the Li-ion diffusion using Fick's second law and integrated LSTM-based prediction for the forecast of SoC. Similarly, Zheng et al. [106] identified Coulomb counting combined with ECM as the most important real-time SoC tracking method in BMS applications. In addition to this, MathWorks created a SLB app that applied support vector regression to estimate the SoH from the voltage and current features [107]. For comprehensive

Table 11
Mathematical modeling of SLBs.

Category	Model type	Mathematical formulation	Application in microgrid	Refs.
SoC estimation	Coulomb counting	$SOC(t) = SOC_0 - \frac{1}{C_n}\int_0^t I(\tau)\,d\tau$	Real-time BMS integration	[106]
	Diffusion-based PDE SoC	$\frac{\partial c}{\partial t} = D\nabla^2 c$	Physics-based SoC prediction	[106]
	LSTM SoC model	$SOC_t = f_\theta(V, I, T, SOC_{t-1})$	Data-driven forecasting	[66]
	SVR-based SoH/SoC	$y = \sum \alpha_i K(x_i, x) + b$	Feature regression (V, I)	[107]
Equivalent circuit models	2nd order Thevenin ECM	$V = OCV(SOC) - IR_0 - V_1 - V_2$; $\dot{V}_i = -\frac{1}{R_iC_i}V_i + \frac{I}{C_i}$	Microgrid dynamic simulation	[108]
	RC performance model	RC-network identification	Mobile SL charging	[109]
Electrochemical models	ESPM	$\frac{\partial c_s}{\partial t} = \frac{D_s}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c_s}{\partial r}\right)$	Capacity fade prediction	[110]
	P2D model	Coupled electrolyte & solid PDEs	High-fidelity aging modeling	[106]
Power & energy equations	Instantaneous power	$P = VI$	Microgrid dispatch	[108]
	Energy	$E = \int_0^T VI\,dt$	Energy balancing	[108]
	SoC-power coupling	$P_{max} = f(SOC, T, SOH)$	Dispatch constraints	[111]
Efficiency modeling	Round-trip efficiency	$\eta = \frac{E_{out}}{E_{in}}$	LCOS calculations	[109]
Degradation models	SEI growth	$\frac{dQ_{SEI}}{dt} \propto e^{-E_a/RT}$	Calendar aging	[110]
	Lithium plating	Butler–Volmer kinetics extension	High SoC stress	[110]
	Capacity fade model	$Q = Q_0 - Q_{LLI} - Q_{LAM}$	SoH tracking	[110]
	Semi-empirical aging	$Q_{loss} = k_1 t^{0.5} + k_2 Ah_{throughput}$	Microgrid long-term simulation	[111]
	Linearized SL aging	Piecewise trend identification	No first-life data needed	[112]
Thermal models	Lumped thermal	$C_{th}\frac{dT}{dt} = Q_{gen} - hA(T - T_{amb})$	Electro-thermal microgrid simulation	[111]
	Heat generation	$Q_{gen} = I^2R + I\eta$	Aging acceleration modeling	[110]
Heterogeneous pack models	Module-SoH ECM	Different (R, C, C_n) per module	SL imbalance modeling	[108]
EIS-based SoH	NN + impedance features	$SOH = f(Z(f_i))$	Fast non-invasive SL assessment	[115]
Microgrid integration	Power balance equation	$P_{PV} + P_{grid} + P_{bat} = P_{load}$	Energy management	[108]
	SoC constraint	$SOC_{min} \le SOC \le SOC_{max}$	Safe operation	[111]
	SoH update equation	$SOH_{t+1} = SOH_t - \Delta Q_{loss}/Q_0$	Long-term lifecycle simulation	[112]
	Dispatch optimization	$\min \sum C_{energy} + C_{degradation}$	Economic microgrid control	[114]

equivalent circuit modeling (ECM), Salek et al. [108] developed a second-order ECM for heterogeneous SLB packs integrated with PV systems. Hassini et al. [109] also validated an RC-based ECM for the performance tracking in mobile second-life charging stations. Zheng et al. [106] also highlighted ECM suitability for a fast control due to its low computational complexity.

Physics-based and aging models have been formulated to capture the degradation characteristics of the SLBs. Pozzato et al. [110] extended the Extended Single Particle Model (ESPM) to include other components like SEI growth, lithium plating and loss of active material for the prediction of second-life. Ganesh et al. [111] compared the semi-empirical and physics-based aging models under frequency regulation and fast charging profiles, making this model critical to be used in microgrid applications. Pérez et al. [112] proposed a degradation model that linearizes capacity fade trends without the requirement of any prior first-life idea. Teixeira et al. [113] also developed degradation models that specifically focused on stationary second-life applications. Bhattacharjee et al. [114] too, formulated aging modeling frameworks for second-life business and economic optimization studies. To map the thermal and electrothermal coupling, Ganesh and D'Arpino [111] integrated a lumped thermal modeling with aging mechanisms under second-life duty cycles. Pozzato et al. [110], further enhanced the model by including Joule heating and overpotential heat generation in electrochemical degradation modeling. Salek et al. [108] demonstrated that the modules with lower SoH exhibited higher resistance and altered the current distribution in heterogeneous second-life packs.

With the advancements in the fields of AI, Neural network and data-related technologies, data-driven and hybrid models have come into picture. Camboim et al. [115] demonstrated that EIS, in a combination with neural network achieved <1.2% SoH estimation error in the SLBs. Zheng et al. [106] came out with a key conclusion of using physics-data modeling as a major research direction for future generation battery modeling. Takahashi et al. [116] extracted statistical features from voltage and current during charging–discharging to accurately enable the estimation of SoH across NMC, LCO and LFP chemistries. Adding to this, Jameel et al. [117] and Alqahtani et al. [118] observed that time intervals for equal voltage differences proved to be an effective health indicator for capacity loss tracking in SLBs. Ensemble Gaussian Process Regression (GPR) with bagging, employed by Takahashi et al. [116], achieved a Root Mean Square Error (RMSE) below 1.48% with a significantly lowered computational burden. PSO-optimized LSTM outperformed CNN and Support Vector Regression (SVR), thus achieving a Mean Absolute Error (MAE) of 0.67% and R^2 close to 0.93 in SoH estimation [119] while PSO-ELM achieved a Mean Absolute Percentage Error (MAPE) less than 0.25% outperforming Back-Propagation (BP) and Support Vector Machine (SVM) [67]. Adam optimizer, on the other hand, achieved an RMSE between 5e−4 to 5.7e−4 overcoming the shortcomings of AdaGrad and RMSProp [118]. Making data-driven models relevant on first-life data to estimate the second-life SoH, Jameel et al. [117] trained SVR using only terminal voltage data with an RMSE of the order of 0.0012–0.0158.

Apart from data-driven models, hybrid and physics-informed approaches have also been used to map the degradation dynamics. Wang et al. [120] combining solution and degradation dynamic functions achieved an MAPE of 0.87% across 387 batteries for SoH estimation of based on relaxation voltage and also found that a Physics-Informed Neural Network (PINN) trained on 1–2 batteries matched Multi-Layer Perceptron (MLP)/CNN performance with 3–4 batteries, hence proving its efficiency. Another critical finding included that freezing the degradation network while fine-tuning the solution network enabled an effective cross chemistry transfer from first-life to SLB. Luque et al. [121] applied Random Forest to estimate the battery SoH in residential PV systems using four features and achieved $R^2 = 0.975$ for daily degradation prediction observing that calendar aging accounted for almost two-thirds of degradation. A further inference on computational complexity was that ML models ran 10^6 times faster than simulations (7 ms vs. 54.9 min) with just 0.1% five-year error.

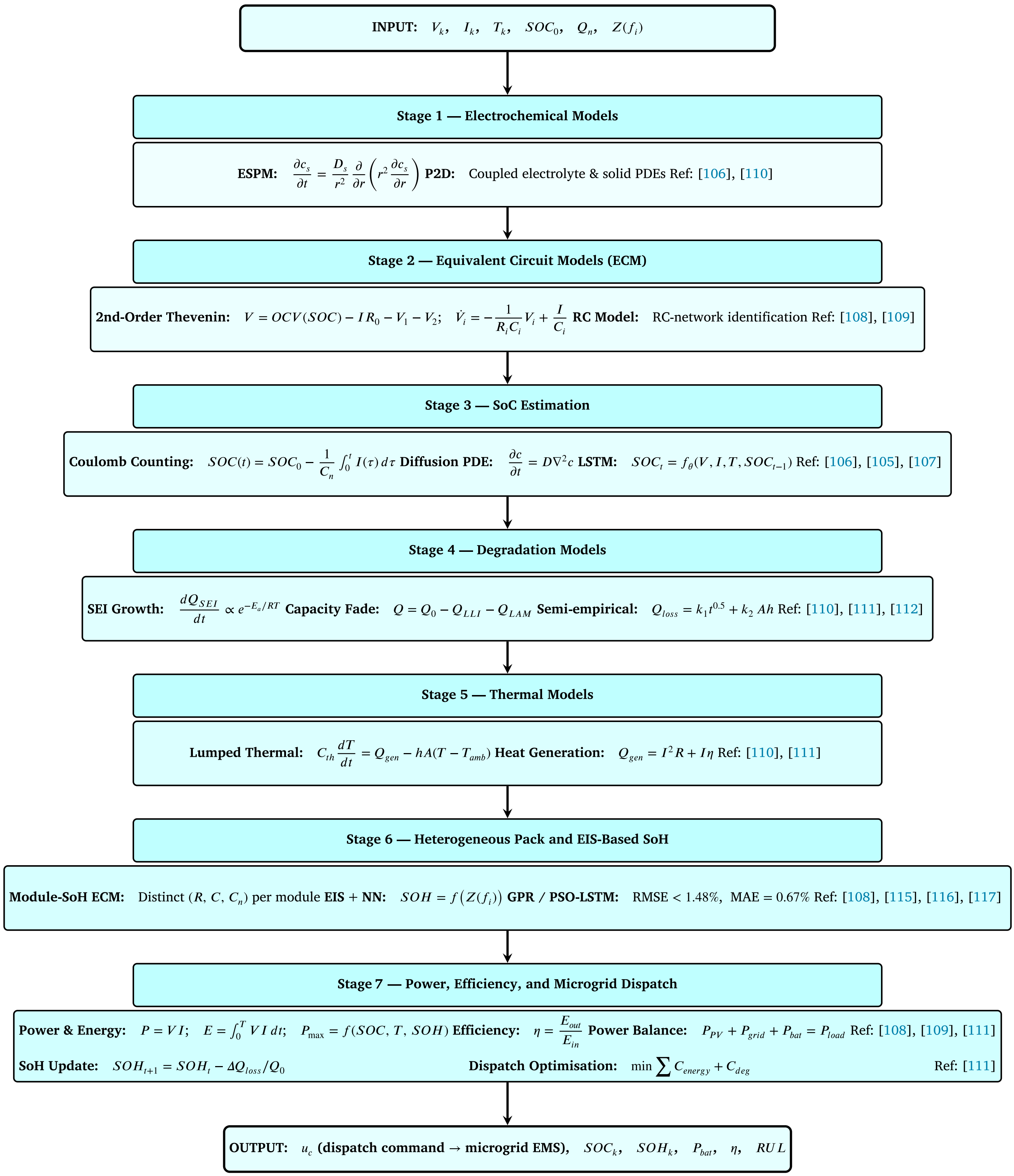

Fig. 5. Seven-Stage Mathematical Modelling Hierarchy for SLBs.

Thus, for enhanced SLB modeling in microgrids, expanded modeling frameworks must include microgrid power balance equations, dispatch constraints, SoH update dynamics, thermal-electrochemical coupling, degradation cost integration, heterogeneous module modeling, data-driven SoH estimation, and multi-scale hybrid modeling to match the exact behavior and test the efficiency in real-time applications. Fig. 5 presents a consolidated seven-stage mathematical modeling hierarchy that maps this progression systematically – from fundamental electrochemical cell physics and equivalent circuit representations, through degradation and thermal models, to intelligent data-driven

SoH estimation and system-level microgrid dispatch optimization. Each stage builds upon the previous, forming an integrated and scalable framework that captures the complete mathematical toolkit required for the reliable, safe, and economically optimal deployment of SLBs in microgrid systems.

The modeling hierarchy begins at the electrochemical level, where the ESPM and Pseudo-2-Dimensional (P2D) formulations govern lithium-ion diffusion and intercalation dynamics. These physics-based foundations feed into second-order Thevenin equivalent circuit models that translate electrochemical states into terminal voltage and current predictions tractable for real-time BMS implementation. State estimation via Coulomb counting, diffusion-based Partial Differential Equations (PDEs), and LSTM networks then converts these circuit-level signals into continuous SoC and SoH trajectories, which in turn serve as inputs to the degradation layer — where SEI growth kinetics, capacity fade, and semi-empirical Ah-throughput models quantify the cumulative health loss unique to second-life duty cycles. Thermal coupling closes the electrochemical-degradation loop by feeding Joule heating and overpotential losses back into the aging rate, while the heterogeneous pack layer accounts for cell-to-cell resistance and capacity scatter inherent in retired EV modules. Finally, the EIS-based and data-driven SoH estimators distil all lower-stage outputs into a single health signal that drives the microgrid dispatch optimization, where the power balance constraint, SoC bounds, and degradation cost term together ensure that energy delivery, battery longevity, and economic return are simultaneously managed.

Comparing these modeling families directly, the electrochemical-level ESPM and P2D formulations offer the highest physical fidelity and are best suited for offline degradation and safety analysis, but their coupled PDE structure imposes a heavy computational burden and demands extensive parameterization data, making them impractical for direct real-time microgrid dispatch [110,111]. Equivalent-circuit models (ECMs) sit at the opposite end of the complexity spectrum: their low computational cost and straightforward parameter identification make second-order Thevenin and RC-based ECMs the preferred choice for real-time BMS and dispatch-loop integration, though this efficiency comes at the expense of reduced accuracy in capturing degradation-driven parameter drift and cell-to-cell heterogeneity [106,108,109]. Data-driven models, by contrast, can achieve very high SoH and capacity-fade accuracy, with reported errors below 1.5% RMSE and MAE, and generalize well across chemistries once trained [67,115–119], but they require large, representative training datasets that are rarely available for heterogeneous SLBs and offer limited interpretability of the underlying degradation physics. Hybrid and physics-informed approaches attempt to reconcile these trade-offs, embedding physical constraints within learning architectures to reduce data requirements while retaining strong predictive accuracy, and recent evidence shows they can match purely data-driven performance using an order of magnitude fewer batteries and run several orders of magnitude faster than full electrochemical simulations [120,121]. For real-time microgrid energy management specifically, this places ECMs and lightweight hybrid/data-driven estimators as the most operationally viable options, with high-fidelity electrochemical models better reserved for offline calibration, degradation-model validation, and safety-margin verification rather than online dispatch.

7. Control and energy management strategies

Even though the idea of incorporating SLB to operate as an ESS in a microgrid seems fascinating and a low-cost sustainable alternative, yet its utility and technological integration is under development phase. The control and energy management strategies reviewed in this section operationalize the mathematical framework established in Section 6 — specifically, the dispatch optimization formulation, the SoH update dynamics, and the microgrid power balance constraint — translating these modeling constructs into real-time control decisions that govern charging schedules, converter topologies, and SoH-aware dispatch across heterogeneous SLB packs in AC, DC, and hybrid microgrid configurations. Marasciuolo et al. [122] proposed the SLB usage with a comprehensive techno-economic analysis in a two photovoltaic generators-based microgrid in two villages in Ethiopia, simulating and investigating its applicability in energy access microgrids in developing nations and thus concluded that SLBs could act revolutionary by extensive cost benefits in comparison to new ESS. In order to boost the integration mechanism in a more practical manner, Hassanpour et al. [123] proposed a Partial Power Converter (PPC) to integrate the SLBs into 350 V DC microgrids by laboratory prototyping of a 4-kW PPC with droop-based decentralized control. The PPC achieved 99.45% peak efficiency and smoothly transitioned between the buck, boost and flyback modes, thus enabling plug-and-play integration. Similarly, Zhang et al. [124] patented a method for super multi-objective management in community microgrids using SLBs wherein the Non-dominated Sorting Genetic Algorithm III (NSGA-III) was used combining residual life decay modeling, consumer behavior analysis and renewable forecasting, providing optimal charging and discharging schedules for everyday operation taking battery degradation and household consumption patterns into account. For distributed control and SoH balancing strategies, Nunes et al. [125] proposed a distributed control method that balances SoH among multiple SLBs in a DC microgrid — directly implementing the SoH update dynamics at the pack level — overcoming the conventional methods of SoC balancing which might end up shortening the battery lifespan. A distributed current sharing control with a tunable SoC band constraint was formulated to limit the imbalance and the control methodology achieved optimal SoH balancing across aggregated SLBs, reducing maintenance frequency and enhancing reliability by increasing the SLB lifespan. Wang et al. [126] also developed a virtual DC machine (VDCM)-based control strategy that addressed the poor consistency among the retired battery packs and DC bus voltage fluctuations. The strategy involved a reconfigurable topology with SoC balancing strategies for equalization current. VDCM leveraged the capacity characteristics to increase the inertia of the system, maintaining SoC balancing during charge/discharging, thus, reducing the overshoot and settling time of DC voltage by 64.2% and 55.6% respectively. Following this, Fagundes et al. [127] provided a comprehensive review of EMS strategies for balancing SoC among BESS units in microgrids including second-life applications, analyzing the centralized and decentralized control, multiagent systems, optimal algorithms, and power converter topologies.

Farakhor et al. [91] provided the first-of-its-kind study on economic power management of the SLBs — grounding its cost minimization objective directly in the degradation-cost dispatch formulation of Section 6 — minimizing the overall cost and maximizing the returns under heterogeneity constraints, highlighting the importance of prudent power management for economically optimal SLB utilization. A model-free adaptive voltage control embedded in dung beetle-inspired heuristic optimization for optimal SLBs capacity and dispatch was proposed by Yuan et al. [128]. Similarly, Bai et al. [129] proposed an iterative design framework that incorporated battery degradation — modeled through the semi-empirical aging formulation and the SoH update equation of Section 6 — into microgrid planning to ensure reliability and economic viability of SLBs. To improve the BMS architecture and monitoring capability, [130] developed an open, adaptable and modular BMS design for stationary SLB storage with cloud-based architecture targeting 30% lower refurbishment expenditure, 25% faster assessments, +20% SoX reliability, +10% lifetime extension, ≥25% lifecycle CO_2 reduction and a faster thermal runaway detection. In addition to this, Fraunhofer [131] developed an open and interoperable BMS framework for SLBs across diverse chemistries and configurations, enabling diverse operations across different types of batteries, embedding advanced decision-making algorithms into edge-level devices, ensuring complete agreement and compliance with European safety standards. A universal BMS architecture was proposed by Šuňal et al. [132], which addressed the complex problems of cell inhomogeneity that the conventional products could not handle. It helped in the combination of different types of modules when it was more advantageous for operation. Making a further advancement, the Battery2Life project [130] designed a groundbreaking SLB incorporating state-of-the-art BEMS with deep integration of BMS and EMS. The data from EMS created digital twins, advanced machine learning algorithms extracted insights, and a cloud-based optimization was employed for charging strategy — operationalising the EIS-based SoH estimation and heterogeneous pack modeling of Section 6 within a live operational framework.

In order to complement the control architectures, Hassanpour et al. [123] proposed a novel PPC for integrating SLBs into DC microgrids with topologies compatible with all, buck, boost and flyback modes along with a regenerative snubber, solid-state circuit breaker and droop-based decentralized control. To simplify the complex logic of battery balancing, Lee et al. [133] developed a low-cost, high-efficiency, logic-driven battery balancing technique for SLB BMS to improve the capabilities of power transfer between SLB modules. Sutton [134] developed a simulation model to study the effects on cost of energy of SLBs comparing four operating strategies, namely, timed peak shaving, setpoint peak shaving, load leveling and load shifting — each evaluated against the power balance constraint and round-trip efficiency model of Section 6 — and validated the strategy on a 40 kW hardware prototype. Adding further to the Artificial Intelligence (AI)-based control strategies, authors in [25] identified AI and machine learning as critical for futuristic control of SLBs, highlighting the need for digital passports, smart meters, and IoT for data security as well as its applicability in cell inhomogeneity solutions. Even though several enhancements have been made, no framework unifies real-time SoH integration with adaptive microgrid control and ignores the cell-to-cell variations in the retired EV packs. Lack of multi-timescale optimization with just standard load profiles does not allow realistic mapping of its characteristics.

8. Safety, reliability and standardization for SLBs utilization

Safety and reliability are two key concerns when it comes to utilization of SLBs in microgrids as well as in other real-world applications. Table 12 catalogs over twenty global safety standards from organizations including Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), Institute of Electrical and Electronics Engineers (IEEE), National Fire Protection Association (NFPA), European Union (EU) and national bodies from China and Japan, which apply to LiBs. It covers standards for thermal runaway testing, energy storage safety, transport, grid interconnection, and battery certification, highlighting the regulatory landscape and scope of how can they be applicable for SLBs.

Though there are several global standards reported for the utilization of LiBs [81,82,135–155], there is no single global standard for the utilization of SLBs. This is due to their heterogeneous behavior and variability in the degradation characteristics during their second life. To overcome the lack of standardized models, various studies have extensively studied about the failure mechanisms and safety and monitoring methods of batteries which also need to be followed by the SLBs. Table 13 reviews eleven studies on LiB failure mechanisms, safety monitoring methods, and their specific implications for SLBs. It consistently identifies thermal runaway (TR) as the dominant safety risk and underscores that degradation alters safety boundaries over time, necessitating adaptive monitoring, advanced BMS diagnostics, and standardized certification before SLB repurposing.

Chen et al. in [156] explained the strong influence of electrochemical reactions, operating voltage, and temperature conditions in LiB's safety, which are a main cause of heat generation and release of gas in case of failures. Adding on to it, Dai and Panahi [157] found thermal runaway to be the primary failure mechanism, which was a consequence of overcharge, short circuits or mechanical damage. Zhou et al. [161] validated this claim experimentally, depicting that overcharging significantly increased the temperature and expansion forces inside the cells, leading to severe thermal runaway incidents. Tschirschwitz et al. [162] demonstrated that thermal runaway led to the release of a large amount of heat and toxic gases, which can propagate from one single cell to a complete battery module. Wang et al. [158] found that these gases are highly inflammable and can cause disastrous explosions in confined SLBs and are mainly caused by uncontrolled thermal runaway reactions during abnormal operating conditions [159].

For advanced monitoring and diagnostics, Gu et al. [160] proposed a state of safety monitoring framework that evaluated the health of the battery using temperature, voltage, strain, and pressure signals to detect thermal runaway in advance. Son and Du [165] presented a model-based fault detection algorithm that analyzed the temperature of the battery and its behavior to identify atypical operating conditions, and this could play a key role in the improvement of BMS. Börner et al. [163] stressed the fact that SLBs exhibited heterogeneous degradation and varying SoH, making safety assessment and a single standard model for testing the reliability extremely difficult. Patel et al. [72] also highlighted that the inconsistency in battery chemistries and battery pack designs complicated the deployment of SLBs on a large scale, and it required a standardized testing procedure. To overcome this issue of battery behaviors and enhance reliability, Manaia et al. [164] proposed a certification methodology that was based on regulatory frameworks and testing procedures to ensure safe repurposing of EV batteries for their future role and utilization in stationary applications. The study in [156] emphasized that international testing standards and certification protocols play an essential role in ensuring the safety of batteries and increasing trustworthiness during their operational phase, while Manaia et al. [164] identified UL 1974 and EU Battery Regulation 2023/1542 as one of the most important frameworks in governing this certification of SLBs. Patel et al. [72] further argued that global harmonization of safety standards is crucial to enable large-scale SLB adoption.

It is important to clarify why the existing LiB standards cannot be applied to SLBs without modification. Standards such as UL 1974, IEC 62619 [137] and ISO 12405 [144] were originally formulated for new, first-life cells and packs, and therefore implicitly assume a known and uniform SoH at the point of certification, a single, well-characterized chemistry and form factor within a given pack, and a predictable, approximately linear aging trajectory over the certified service life. None of these assumptions hold for SLBs. Retired EV batteries enter second-life service already degraded, with cell-to-cell and pack-to-pack heterogeneity arising from unknown and undocumented first-life duty cycles, and are frequently regrouped across mixed chemistries, form factors, and manufacturing vintages to meet second-life pack requirements. Furthermore, their remaining safety margins and internal resistance evolve dynamically with continued cycling, meaning that thresholds fixed at the time of first-life certification may no longer bound safe operation once a cell has undergone substantial aging. Consequently, first-life LiB standards remain necessary but not sufficient for SLBs: they establish a baseline verification of cell and pack integrity but do not address the additional risks introduced specifically by reuse, namely unverifiable degradation history, heterogeneous regrouping, and shifting safety thresholds. This gap is what necessitates the supplementary, stage-specific protocols, spanning SoH screening, sorting and regrouping, remanufacturing, and requalification, that have no direct equivalent in first-life certification frameworks and are mapped explicitly below.

Thus, thermal runaway still remains a dominant safety risk for SLBs and the degradation in battery severely alters its safety limits during its lifetime. This creates the need for advanced monitoring methods and state of safety diagnostics to improve the detection of

Table 12
Global safety standards for LiBs and how can they be applied to SLBs.

Standard	Organization	Scope	Application to second-life batteries	Refs.
UL 1974	Underwriters Laboratories (USA)	Evaluation process for repurposing EV batteries	Defines testing procedures for reuse and repurposing of batteries	[81]
UL 9540	Underwriters Laboratories	Safety standard for ESS	Certification of battery storage systems using repurposed batteries	[135]
UL 9540A	Underwriters Laboratories	Test method for thermal runaway fire propagation	Fire safety validation of ESS	[136]
IEC 62619	International Electrotechnical Commission	Safety requirements for lithium batteries used in industrial applications	Applicable to stationary ESS using SLBs	[137]
IEC 62933-5-3	IEC	Safety requirements for electrical ESS	Defines safety requirements for grid-scale battery storage	[138]
IEC 62933-2-1	IEC	Unit parameters and performance testing of ESS	Defines operational performance parameters for ESS	[139]
IEC 62620	IEC	Performance testing for industrial lithium batteries	Used for capacity and lifecycle evaluation of reused batteries	[140]
IEC 62133	IEC	Safety testing for portable lithium batteries	Provides baseline safety test procedures	[141]
IEC 61960	IEC	Performance testing of lithium-ion cells and batteries	Used for electrical performance evaluation before repurposing	[142]
ISO 26262	International Organization for Standardization	Functional safety of automotive electrical systems	Used to ensure safety in EV battery systems before second-life reuse	[143]
ISO 12405	ISO	Test specification for lithium-ion traction batteries	Used to assess EV battery safety before reuse	[144]
UN 38.3	United Nations	Transport safety testing for lithium batteries	Required for shipping used or repurposed lithium batteries	[145]
NFPA 855	National Fire Protection Association	Installation standard for ESS	Fire safety and building installation requirements	[146]
NFPA 13	National Fire Protection Association	Fire protection systems	Sprinkler system requirements for battery storage facilities	[147]
IEEE 1547	IEEE	Standard for interconnection of distributed energy resources	Required for integrating battery storage into the grid	[148]
IEEE 1679	IEEE	Guide for characterization and evaluation of emerging energy storage technologies	Performance evaluation framework for battery technologies	[149]
IEEE 2030.2.1	IEEE	Guide for interoperability of ESS	Integration of storage systems with smart grids	[150]
EU Battery Regulation 2023/1542	European Union	Sustainability and safety regulation for batteries	Introduces battery passport and lifecycle traceability	[151]
EN 50604-1	CENELEC	Safety requirements for EV batteries	Battery safety testing before repurposing	[152]
EN 62619 (EU adoption)	CENELEC	Safety of lithium batteries for industrial use	Applies IEC safety standard in European markets	[153]
GB/T 36276	China National Standard	Safety standard for lithium batteries used in energy storage	Widely used for stationary energy storage deployment	[154]
GB/T 31467	China National Standard	Safety and performance testing of EV battery packs	Used for evaluating EV battery packs before reuse	[155]
JIS C8715-2	Japanese Industrial Standards	Safety testing for lithium batteries	Used in stationary battery energy storage	[82]

failures along with comprehensive testing and certification frameworks before repurposing. Global safety standards such as UL 1974 [81], IEC 62619 [137] and EU Battery Regulation 2023/1542 [151] are critical for safe deployment of repurposed battery systems. The standards catalogued are intended to function as a staged protocol mapped to SLB repurposing pipeline and not as a decision tree or a checklist applied uniformly at a single point. At the testing and SoH screening stage, UL 1974 [81] and ISO 12405 [144] govern the procedures for evaluation of capacity, resistances and safety characterization of retired EV batteries. For sorting and grading stage, IEC 62619 [137], IEC 62620 [140], and GB/T 31467 [155] provide safety and performance benchmarks, which can be used to classify the cells before regrouping. In the remanufacturing and module reconfiguration stage, EN 50604-1 [152] and IEC 62133 [141] govern the safety requirements for reassembled packs and modules. At safety and BMS adaptation stage, the IEC 62933-5-3 [138], IEC 62933-2-1 [139] and NFPA 855 [146] define the system level requirements for ESS. For transportation of batteries between repurposing stages, UN 38.3 [145] governs the shipping safety requirements. At grid-connection and deployment stage, IEEE 1547 [148], IEEE 2030.2.1 [150], and the EU Battery Regulation 2023/1542 [151] govern the interconnection compliance and lifecycle traceability. This staged mapping clarifies that no single standard governs the end-to-end SLB deployment, and their cumulative and sequential compliance can ensure safety and reliability for SLB deployment.

9. Environmental impact and sustainability assessment

SLBs offer a major environmental advantage of utilization of resources until their entire resource life is consumed and preventing

Table 13
Safety, failure mechanisms, and reliability findings for SLBs.

Authors/Year/Refs.	What the paper studies	Failure mechanisms/Safety findings	Safety methods/Monitoring	Implication for SLBs
Chen et al. (2021) [156]	Review of lithium-ion battery safety issues and standards	Thermal runaway triggered by thermal, electrical, and mechanical abuse	Cell design improvements, cooling systems, safety testing standards	Safety depends on battery chemistry, operating environment, and voltage limits
Dai & Panahi (2025) [157]	Review of thermal runaway mechanisms	TR caused by overcharge, short circuit, or mechanical damage	Material design and safety protocols	Understanding TR mechanisms is critical for safe energy storage deployment
Wang et al. (2025) [158]	Hazard characteristics of battery ESS	TR propagation, flammable gas release, and explosion risk in BESS	Fire suppression strategies and hazard analysis	Large-scale battery storage requires advanced suppression technologies
Deng et al. (2025) [159]	Safety techniques for preventing thermal runaway	LiBs prone to fires and explosions due to TR reactions	PTC thermistors, safety vents, thermal management systems	Active and passive mitigation methods are required for safe battery deployment
Gu et al. (2025) [160]	Early warning system for thermal runaway	Thermal runaway caused by chain reactions and heat accumulation	State-of-Safety (SOS) monitoring using temperature, voltage and strain	Early detection systems can warn several hours before failure
Zhou et al. (2023) [161]	Experimental safety evaluation of overcharge behavior	Overcharge leads to expansion forces, heat generation and TR	Monitoring voltage, temperature and mechanical stress	BMSs must detect overcharge conditions
Tschirschwitz et al. (2023) [162]	Experimental TR propagation in second-life battery modules	TR releases large heat, toxic gases and jet flames	Explosion protection strategies and module testing	Thermal runaway can propagate from single cells to entire modules
Börner et al. (2022) [163]	Challenges of second-life EV batteries	Safety depends on battery history, SoH and heterogeneity	Advanced diagnostics required before repurposing	Lack of standardized design information complicates safety assessment
Manaia et al. (2025) [164]	Certification framework for repurposed batteries	Testing required for capacity, resistance, insulation and BMS functionality	Certification methodology based on UL 1974 and EU regulations	Standardized testing ensures safe second-life deployment
Patel et al. (2024) [72]	Review of second-life battery pathways	Lack of unified policies and standards for repurposing	Standardization of battery design and lifecycle processes	Policies and standards are needed for safe second-life battery ecosystems
Son & Du (2019) [165]	Fault detection algorithms for LiBs	Abnormal thermal behavior leads to safety risks	Model-based fault detection and diagnosis algorithms	BMS diagnostic algorithms improve reliability and safety

wastage of retired EV batteries. They help in the reduction of the carbon footprint, resource conservation, minimization of waste generation, and support circular economy models. Thus, to form policies with respect to their utilization in microgrids, government agencies and regulatory authorities rely on environmental impact and sustainability assessments to create standards for battery reuse, recycling, and disposal. It also helps in the identification of environmental trade-offs, assessment of energy efficiency, and leads toward a lower carbon footprint, explaining the reliable advantages of using SLBs over new batteries in stationary storage applications in microgrids [166–168]. Various assessments, their methods, and their key findings are tabulated in Table 14, and they give a holistic view of the advantages showcased by SLBs consolidating environmental sustainability findings from fifteen LCA and material flow studies, covering carbon footprint reduction, resource conservation, waste minimization, and circular economy alignment. Quantitative results show carbon emission reductions of 3%–38% and potential cumulative GHG savings exceeding 55.8 Mt CO_2 eq by 2050, strongly supporting SLB reuse over immediate recycling [169].

Second-life applications reduce the environmental burden that is linked with the manufacturing of batteries. Authors in [166] demonstrated that SLBs have a substantially reduced manufacturing-related emission rate in comparison to new batteries when deployed in microgrid ESS by distributing the impact across a longer operational lifetime [170]. All of these strategies collectively indicate that lifetime extension has turned out to be one of the most effective and suitable strategies to compensate for the footprint of LiBs. Several studies have also tried to quantify the carbon emission reduction that is achieved by the reuse of batteries. Kang et al. [171] indicated that the reuse of EV batteries as stationary ESS in microgrids and buildings can reduce the annual carbon emission by 2.8%–18.5%. Jiang et al. [174] demonstrated that combining the battery reusage with advanced recycling strategies can reduce this emission by more than one-third. Additionally, Wesselkämper et al. [169] also estimated that the SLB deployment could create a cumulative greenhouse gas savings of more than 55.8 million metric tonnes (55.8 Mt) CO_2 equivalent by 2050 in regional energy systems, henceforth contributing to the climate mitigation efforts.

Another important role that is played by SLB is in enabling a circular economy. Alam et al. [176] emphasized that the repurposed batteries prevent a premature disposal and reduce the demand for newly manufactured batteries thereby conserving critical metals such as lithium, cobalt and nickel. Moreover, these EV batteries, after retirement from the EV application generally have just 20%–30% of their original capacity utilized, making them highly suitable for less demanding stationary applications [72]. By using the remaining capacity, SLB systems optimally maximize the utilization of resources and reduce the environmental impact associated with the extraction of raw materials. Despite several environmental benefits, several trade-offs have been identified by distinct studies between the second life applications and recycling. Dunn et al. [173] demonstrated by studying the life cycle analysis that repurposing the batteries could produce lower environmental impacts than immediate recycling, reinforcing the waste hierarchy that gives priority to re-use of resources before recycling them. However, this could be an important factor in delaying the recovery of valuable materials from recycling processes [172].

Fig. 6 presents a comparative overview of key environmental sustainability indicators for SLB systems, including global warming potential (GWP), carbon emission savings, and lifecycle impact reductions relative to both new battery manufacturing and direct recycling pathways. The data collectively demonstrate that second-life deployment reduces per-kWh carbon emissions by 3%–38% depending on application context and grid mix, reinforcing the role of SLBs as an effective instrument within circular economy strategies for the energy storage sector.

Table 14
Environmental and LCA findings for second-life battery systems.

Paper	Environmental assessment method	Key sustainability findings	Quantitative results/Indicators	Implications
E. de Godoy Antunes et. al (2023) [166]	Life Cycle Assessment (LCA) for microgrid battery systems	SLBs reduce manufacturing impacts compared with new batteries when reused in stationary microgrids	Manufacturing impact reduced from 15 $kgCO_2$ eq/kg to ~3.5 kg CO_2 eq/kg for refurbished batteries	Reusing EV batteries in microgrids can significantly reduce environmental burdens associated with new battery manufacturing
Brunström (2022) [170]	LCA combined with energy system modeling	Environmental performance strongly depends on energy throughput during second life	SLBs can relieve 15%–29% of manufacturing emissions through lifetime extension	High utilization of storage significantly improves environmental performance
Kang et al. (2025) [171]	Probabilistic LCA with Monte-Carlo analysis	Reusing EV batteries in building energy storage reduces overall carbon emissions compared with new battery installations	2.8%–18.5% reduction in annual CO_2 emissions	Battery reuse contributes to decarbonization in energy communities and building-integrated energy systems
Tao et al. (2021) [172]	LCA combined with material flow and recycling analysis	Second-life use followed by recycling improves sustainability compared with direct recycling	Carbon footprint reduction 8%–17%, energy use reduction 2%–6%	Cascaded use of batteries before recycling enhances environmental performance
Kobayashi et al. (2024) [167]	Integrated LCA of reuse and recycling	Combining battery reuse with recycling significantly reduces CO_2 emissions and resource consumption	Method integrates manufacturing, reuse, recycling, and material recovery	Comprehensive lifecycle modeling is required to avoid double counting environmental benefits
Dunn et al. (2023) [173]	Life-cycle assessment of battery repurposing vs. immediate recycling	Repurposing batteries generally yields lower environmental impacts than direct recycling	Reuse remains preferable in the waste hierarchy	Prioritizing reuse before recycling maximizes environmental benefits
Jiang et al. (2025) [174]	National-scale lifecycle carbon and material flow modeling	Recycling and reuse of EV batteries significantly reduce raw material demand	Up to 36%–38% reduction in lifecycle carbon emissions	Circular battery management reduces dependence on critical materials
Wesselkämper et al. (2025) [169]	Material flow analysis and climate impact modeling	SLBs can supply large portions of stationary storage demand while reducing emissions	Potential 55.8 Mt CO_2eq emission savings by 2050	Battery reuse can play a major role in future energy storage infrastructure
Gautam et al. (2024) [168]	Sustainability assessment linked with circular economy and SDGs	Second-life EV batteries support sustainable development through resource optimization and reduced waste	Identifies policy and technological barriers to adoption	Repurposing batteries aligns with global sustainability goals
Akram et al. (2024) [175]	Comprehensive sustainability review	Stationary applications of SLBs extend battery life by up to a decade	EV batteries can continue operating in secondary applications for 6–30 years depending on application	Lifetime extension improves environmental performance of the battery lifecycle
Alam et al. (2026) [176]	Circular economy and sustainability framework analysis	Repurposed batteries reduce waste and resource extraction while enabling renewable energy storage	Integrates circular economy, industrial symbiosis, and technology transfer frameworks	SLBs contribute to climate mitigation and resource conservation
Patel et al. (2024) [72]	Review of reuse and recycling pathways	Second-life applications reduce environmental impacts by extending battery service life and reducing material demand	Batteries often reach end-of-vehicle-life at 70%–80% capacity and still retain usable energy	Repurposing batteries before recycling enhances lifecycle sustainability
Pellow et al. (2020) [177]	Review of environmental LCA studies for battery storage systems	Current LCA research on stationary battery systems lacks consistent methodology and system boundaries	Highlights need for standardized lifecycle modeling approaches	Future research should incorporate operational and end-of-life phases in environmental assessments

An important observation across all the papers is that an accurate environmental assessment requires comprehensive life cycle modeling of the battery. Kobayashi et al. [167] proposed an integrated LCA framework that considers manufacturing, reuse and recycling processes simultaneously. On the other hand, Pellow et al. [177] highlighted that the existing studies often used inconsistent system boundaries and modeling assumptions, which led to difficulty in comparison of results across studies. Thus, there is a need for standardization in LCA methodologies for SLBs.

Across the reviewed literature, it can be concluded that SLBs significantly reduce the lifecycle environmental impacts and also contribute to the reduction in carbon emissions by 3 to 38% depending upon the application and the operating conditions. Battery reuse supports circular economy strategies and reduces resource extraction and waste generation. Reuse followed by recycling processes, once the capacity reduces below the usable range, produces much better environmental outcomes than direct recycling however future models must integrate LCA with techno-economic operational models for more accurate and reliable sustainability assessments.

10. Key findings and future research directions

Among the emerging applications, this review emphasizes the potential of SLBs for integration into microgrid applications, which represent one of the most promising pathways for their large-scale utilization. SLB-based energy storage systems can provide cost-effective and sustainable solutions for renewable energy integration, particularly in rural and remote electrification projects, while reducing environmental impacts through extended battery utilization after their first life in EVs. The effective reuse of EV batteries can minimize waste generation, reduce the demand for new battery production, and support circular economy principles. Below are the identified key findings, challenges, and future research directions in this review that can serve as a valuable roadmap for researchers and stakeholders working toward the effective

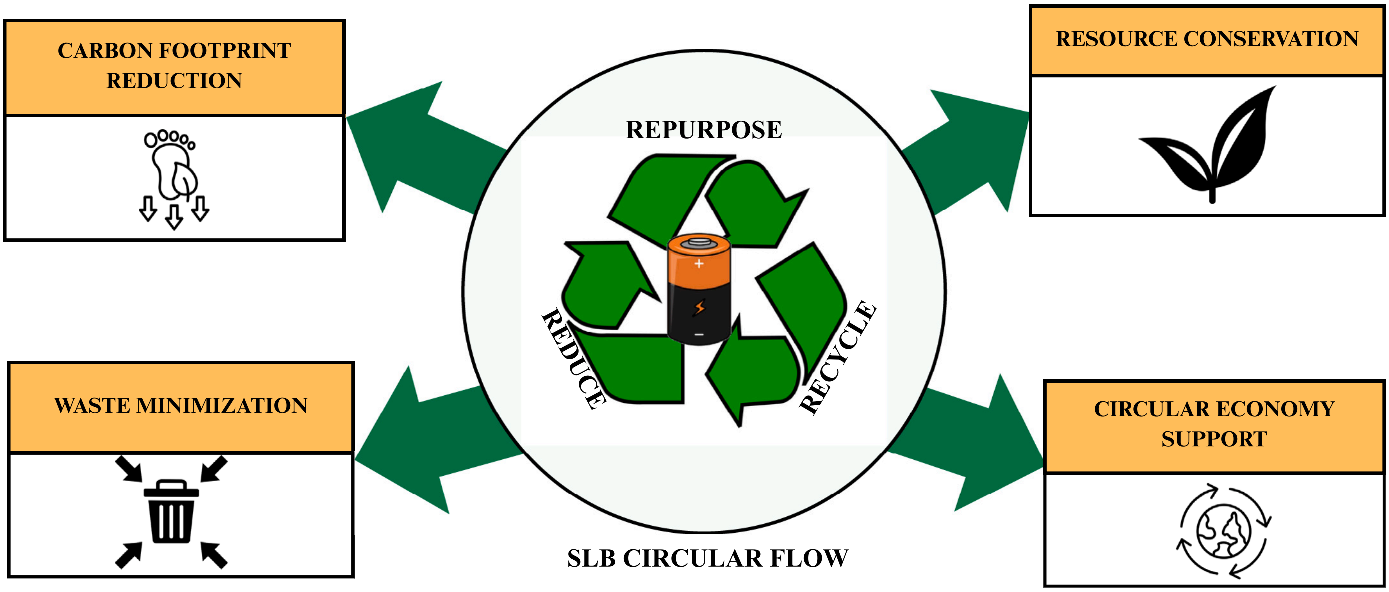

Fig. 6. Environmental sustainability indicators for SLBs.

utilization of SLBs in microgrid applications. Future efforts addressing these critical areas will be essential to accelerate SLB adoption, enhance sustainable energy storage solutions, minimize waste generation, reduce reliance on new battery production, and strengthen circular economy approaches in the battery lifecycle.

10.1. Major findings and emerging insights

Across the literature reviewed in this paper, SLBs have the potential to show strong technical, economic, and environmental performance in microgrid applications. Technically, retired batteries retain 70%–80% of their original capacity, operate at 92%–99% energy efficiency, and have been shown in real deployments to reduce peak demand by up to 60% and peak-time energy use by up to 39%. Economically, SLBs become an attractive alternative to new batteries once their acquisition cost drops below about 40% of a new battery's price, at which point they deliver 13%–40% lower storage costs, IRR above 41%, and NPV improvements approaching 49.2% in commercial deployments, with frequency regulation standing out as the most profitable use case. Environmentally, reusing batteries instead of recycling them immediately cuts lifecycle carbon emissions by 3%–38%, supports up to 18.5% annual CO_2 reduction, and could save close to 55.8 Mt of CO_2-equivalent emissions by 2050 in regional projections. At the same time, safety and control remain the weaker links in the picture. Thermal runaway is still the most serious safety concern, and because SLBs age unevenly, fixed safety thresholds designed for new batteries do not always hold up over time. More than twenty global standards exist for battery safety and testing, yet none of them cover the entire second-life journey from EV retirement through microgrid deployment. On the modeling and control side, newer AI-based and hybrid approaches are proving far faster and more accurate than traditional physics-based models, and smarter, SoH-aware control strategies are already showing real improvements in system stability and battery balancing. Taken together, these findings confirm that SLBs are technically ready and economically and environmentally rewarding, but wider adoption in microgrids still depends on closing the gaps in standardization and degradation-aware control that this review identifies and addresses through its unified grading, modeling, and control frameworks.

10.2. Challenges and research needs

Even though extensive research has been carried out regarding the integration of SLBs and their usage, several research gaps pertain and are yet to be addressed and are presented in Fig. 7. Research studies still lack assessments relevant solely for microgrids. The uncertainty in SLB performance, which is highly relevant for microgrid-based assessments is still unaddressed. The performance of SLBs is highly dependent on DoD, cycling frequency and a new generation variability. However, the existing studies simplify the assumptions and real-world performance characteristics for usability in microgrids still remains limited. Moreover, studies lack microgrid-specific LCA studies. Although it is widely used for the evaluation of environmental consequences of batteries, only a few studies specifically address SLBs operating within renewable-integrated microgrids; more comprehensive assessments remain needed for mapping characteristics and behavior of SLBs in a proper manner. In addition to this, their integration with the fluctuating power generation because of the intermittent nature of RES and the irregularities caused by them in charging and discharging patterns is yet to be studied in depth, as it accelerates degradation, reduces system inertia, and also reduces reliability.

In addition, most of the degradation models for LiBs are developed for EV applications. Post their first life, when they are integrated in microgrids, their operational behavior and characteristics tend to change. The battery aging mechanisms tend to enhance degradation due to frequent cycling and partial charge operation, and the behavior under these circumstances is not yet fully understood. One important problem in the utilization of SLBs is that they originate from different types of vehicles, patterns of usage, and chemistries, which result in significant variations in capacities, resistances, and remaining useful lives. This heterogeneity complicates the design and control implementations in microgrid systems. Adaptive and AI-driven SoH estimation techniques and using advanced BMS capable of handling heterogeneous battery modules for effective coordinated operation in microgrids are yet to be implemented. Existing microgrid energy management strategies generally assume ideal performance characteristics of the battery and do not incorporate the degradation and health constraints for second life. A more advanced optimization framework enhanced with both operational efficiency and battery longevity is still lacking, which can address the way the SLB would behave when actually connected in a microgrid.

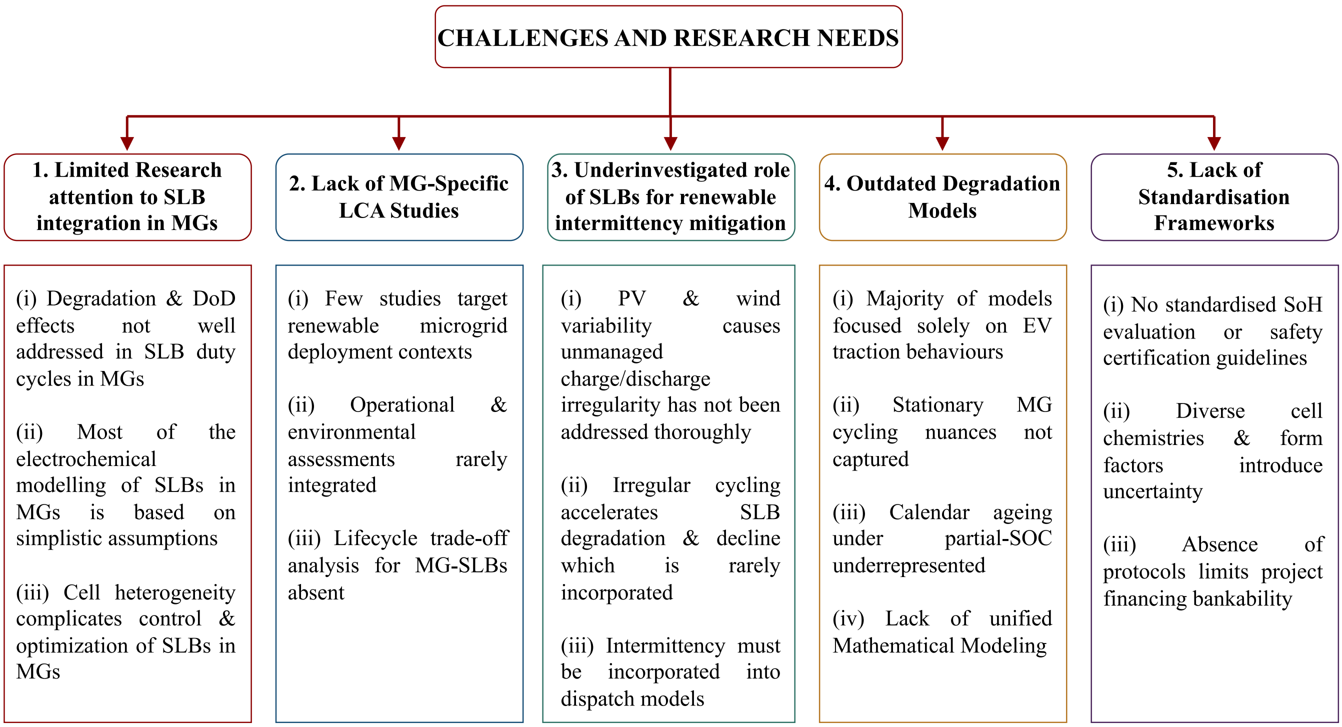

Fig. 7. Key challenges and research needs in the integration of SLBs.

Moreover, techno-economic and environmental trade-off analysis and gains dependent on parameters such as charging electricity sources and battery energy throughput to assess the sustainability benefits in microgrids are still missing. Also, SLBs may exhibit increased risks of thermal runaway, short circuits, capacity fading, or capacity imbalance due to aging. Ensuring safe and sound operation in distributed microgrids still requires improved diagnostics and monitoring techniques that can correctly evaluate the performance metrics and usefulness in microgrid operations. Beyond all the above-stated issues, the most critical problem is the lack of standardization frameworks for microgrid deployment: there is no universally accepted framework for evaluating, testing, and certifying the SLBs before integrating them into microgrids. Thus, standardized guidelines for large-scale deployment are the crucial requirement of SLB integration into microgrids.

11. Conclusion

This paper comprehensively examined the potential of Second-Life lithium-ion batteries (SLBs) for microgrid applications by integrating perspectives on battery degradation, repurposing methodologies, mathematical modeling, techno-economic assessment, control strategies, safety, reliability, and standardization. The SLB grading framework has been proposed based on existing battery standards that provide a structured basis for battery selection, facilitating reliable and application-specific integration into microgrid systems. The detailed mathematical modeling approaches enable researchers to accurately represent and analyze SLB behavior in microgrid and other applications. The study also described techno-economic and environmental impacts of SLBs, indicating significant cost reduction, improvement of energy access, and carbon footprint reduction, confirming the importance of circular economy principles in energy storage. Some key limitations hindering large-scale SLB implementation include uncertain degradation, absence of clear regulations, testing, sorting, and repurposing processes; a lack of a comprehensive framework addressing aspects of technical feasibility, cost-effectiveness, sustainability, and legislative restrictions has been discussed. Overall, this work provides a unified and scalable framework for understanding, evaluating, and deploying SLBs in microgrid environments. By bridging gaps across degradation modeling, system integration, control, and sustainability assessment, the paper not only consolidates existing knowledge but also establishes a clear roadmap for future research and industrial implementation. SLBs, when supported by robust standardization, intelligent control, and integrated techno-economic frameworks, have the potential to transform microgrid energy storage, enabling resilient, cost-effective, and low-carbon power systems for the next generation of energy infrastructure.

CRediT authorship contribution statement

Vansh Suri: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Sandeep Dhundhara:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Florimond Guéniat:** Writing – review & editing, Visualization, Validation, Supervision. **Ravi Sharma:** Validation, Supervision, Methodology, Conceptualization.

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

No data was used for the research described in the article.

References

[1] X. Ma, R. Xie, L. Guo, S. Niu, L. Cheng, R. Hu, Range anxiety of battery electric vehicles: Quantification and determinants using real-world data, Transp. Res. D 146 (2025) 104837, http://dx.doi.org/10.1016/j.trd.2025.104837.

[2] A.A. Mostaghi, N. Mirzaei, H. Yousefi, A. Hajinezhad, M. Abdoos, Comprehensive bibliometric analysis of electric vehicle research: Trends, emerging topics, and sustainability insights, Energy Strategy Rev. 62 (2025) 101963, http://dx.doi.org/10.1016/j.esr.2025.101963.

[3] International Energy Agency (IEA), Global EV Outlook 2025: Executive Summary, Paris, France, 2025, [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2025/executive-summary. (Accessed 28 July 2026).

[4] McKinsey & Company, Electric Vehicles—What's Ahead, McKinsey Center for Future Mobility, 2023, Available: https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/our-insights/electric-vehicles-whats-ahead (accessed 15 April 2026).

[5] F. Lambert, Global EV Sales Jump 21% in 2025 as Europe Surges and the US Stalls, Electrek, 2025, https://electrek.co/2025/12/11/global-ev-sales-jump-21-in-2025-as-europe-surges-and-the-us-stalls/.

[6] J. Dow, Contrary to Popular Belief, EV Sales Growth Continued to Accelerate in 2025, Electrek, 2026, [Online]. Available: https://electrek.co/2026/01/14/contrary-to-popular-belief-ev-sales-growth-continued-to-accelerate-in-2025/.

[7] T. Sutikno, W. Arsadiando, H.S. Purnama, Battery types and recent developments for energy storage in electric vehicles: Technical criteria and battery management system, Clean Energy 9 (6) (2025) 293–322, http://dx.doi.org/10.1093/ce/zkaf048.

[8] J.M. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries, Nature 414 (6861) (2001) 359–367, http://dx.doi.org/10.1038/35104644.

[9] A. Hassan, S.A. Khan, R. Li, W. Su, X. Zhou, M. Wang, B. Wang, Second-life batteries: A review on power grid applications, degradation mechanisms, and power electronics interface architectures, Batteries 9 (12) (2023) 571, http://dx.doi.org/10.3390/batteries9120571.

[10] C.A. Rufino Junior, E.R. Sanseverino, P. Gallo, M.M. Amaral, D. Koch, Y. Kotake, H.-G. Schweiger, H. Zanin, A comprehensive review of EV lithium-ion battery degradation, 2023, http://dx.doi.org/10.20944/preprints202306.0228.v1, Preprints.

[11] A. Tankou, G. Bieker, D. Hall, Scaling Up Reuse and Recycling of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches, White Paper, International Council on Clean Transportation (ICCT), Washington, DC, USA, 2023, Available: https://theicct.org.

[12] L.C. Casals, B. Amante García, C. Canal, Second life batteries lifespan: Rest of useful life and environmental analysis, J. Environ. Manag. 232 (2019) 354–363, http://dx.doi.org/10.1016/j.jenvman.2018.11.046.

[13] Reuters Events, Battery Storage Outlook Boosted by Thirst for Firm Power, Reuters Events Energy Transition, 2026, Available: https://www.reutersevents.com/renewables/solar-pv/battery-storage-outlook-boosted-thirst-firm-power.

[14] International Energy Agency (IEA), Batteries and Secure Energy Transitions, World Energy Outlook Special Report, IEA Publications, Paris, France, 2024, Available at: https://www.iea.org/reports/batteries-and-secure-energy-transitions. (Accessed 28 July 2026).

[15] IRENA, Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi, 2017, Available at: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets. (accessed 15 April 2026).

[16] World Bank, Tracking SDG7: The Energy Progress Report 2025, World Bank, Washington, DC, 2025, Available at: https://www.worldbank.org/en/topic/energy/publication/tracking-sdg-7-the-energy-progress-report-2025. (accessed 15 April 2026).

[17] J. Lacap, J.W. Park, L. Beslow, Development and demonstration of microgrid system utilizing second-life electric vehicle batteries, J. Energy Storage 41 (2021) http://dx.doi.org/10.1016/j.est.2021.102837.

[18] X. Hu, X. Deng, F. Wang, Z. Deng, X. Lin, R. Teodorescu, M.G. Pecht, A review of second-life lithium-ion batteries for stationary energy storage applications, Proc. IEEE 110 (6) (2022) 735–753, http://dx.doi.org/10.1109/JPROC.2022.3175614.

[19] K. Neigum, Z. Wang, Technology and economic analysis of second-life batteries as stationary energy storage: A review, in: Canadian Conference on Electrical and Computer Engineering, Institute of Electrical and Electronics Engineers Inc., 2023, pp. 583–587, http://dx.doi.org/10.1109/CCECE58730.2023.10288704.

[20] X. Gu, H. Bai, X. Cui, J. Zhu, W. Zhuang, Z. Li, X. Hu, Z. Song, Challenges and opportunities for second-life batteries: Key technologies and economy, Renew. Sustain. Energy Rev. 192 (2024) 114191, http://dx.doi.org/10.1016/j.rser.2023.114191.

[21] H. Iqbal, S. Sarwar, D. Kirli, J.K.H. Shek, A.E. Kiprakis, A survey of second-life batteries based on techno-economic perspective and applications-based analysis, Carbon Neutrality 2 (2023) http://dx.doi.org/10.1007/s43979-023-00049-5.

[22] M.K. Al-Alawi, J. Cugley, H. Hassanin, Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review, Energy Clim. Chang. 3 (2022) 100086, http://dx.doi.org/10.1016/j.egycc.2022.100086.

[23] S. Azizighalehsari, P. Venugopal, D. Pratap Singh, T. Batista Soeiro, G. Rietveld, Empowering electric vehicles batteries: A comprehensive look at the application and challenges of second-life batteries, Batteries 10 (5) (2024) 161, http://dx.doi.org/10.3390/batteries10050161.

[24] F. Salek, S. Resalati, M. Babaie, P. Henshall, D. Morrey, L. Yao, A review of the technical challenges and solutions in maximising the potential use of second life batteries from electric vehicles, Batteries 10 (3) (2024) 79, http://dx.doi.org/10.3390/batteries10030079.

[25] H. Song, H. Chen, Y. Wang, X.-E. Sun, An overview about second-life battery utilization for energy storage: Key challenges and solutions, Energies 17 (23) (2024) 6163, http://dx.doi.org/10.3390/en17236163.

[26] P. Eleftheriadis, et al., Second life batteries: Current regulatory framework, evaluation methods, and economic assessment: Reuse, refurbish, or recycle, IEEE Ind. Appl. Mag. 30 (1) (2024) 46–58, http://dx.doi.org/10.1109/MIAS.2023.3325091.

[27] M.H.S.M. Haram, J.W. Lee, G. Ramasamy, E.E. Ngu, S.P. Thiagarajah, Y.H. Lee, Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges, Alex. Eng. J. 60 (5) (2021) 4517–4536, http://dx.doi.org/10.1016/j.aej.2021.03.021.

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

[29] I. Kulkov, K. Chirumalla, I. Stefan, E. Dahlquist, G. Johansson, Business models for second life batteries: A comprehensive framework for selecting sustainable business options, J. Eng. Technol. Manag. - JET-M 76 (2025) http://dx.doi.org/10.1016/j.jengtecman.2025.101874.

[30] R. Toorajipour, K. Chirumalla, G. Johansson, E. Dahlquist, F. Wallin, Implementing circular business models for the second-life battery of electric vehicles: Challenges and enablers from an ecosystem perspective, Bus. Strategy Environ. 33 (8) (2024) 8637–8655, http://dx.doi.org/10.1002/bse.3941.

[31] M. Gharebaghi, O. Rezaei, C. Li, Z. Wang, Y. Tang, A survey on using second-life batteries in stationary energy storage applications, Energies 18 (1) (2025) 42, http://dx.doi.org/10.3390/en18010042.

[32] M. Shahjalal, P.K. Roy, T. Shams, A. Fly, J.I. Chowdhury, M.R. Ahmed, K. Liu, A review on second-life of Li-ion batteries: Prospects, challenges, and issues, Energy 241 (2022) 122881, http://dx.doi.org/10.1016/j.energy.2021.122881.

[33] A. Varzi, R. Raccichini, S. Passerini, B. Scrosati, Challenges and prospects of the role of solid electrolytes in the revitalization of lithium metal batteries, J. Mater. Chem. A Mater. 4 (44) (2016) 17251–17259, http://dx.doi.org/10.1039/c6ta07384k.

[34] A. Mondal, H.T. Das, Energy storage batteries: Basic feature and applications, in: K.P. Misra, R.D.K. Misra (Eds.), Ceramic Science and Engineering, in: Elsevier Series in Advanced Ceramic Materials, Elsevier, Amsterdam, The Netherlands, 2022, pp. 323–351, http://dx.doi.org/10.1016/B978-0-323-89956-7.00008-5, ch. 13.

[35] P.U. Nzereogu, A.D. Omah, F.I. Ezema, E.I. Iwuoha, A.C. Nwanya, Anode materials for lithium-ion batteries: A review, Appl. Surf. Sci. Adv. 9 (2022) 100233, http://dx.doi.org/10.1016/j.apsadv.2022.100233.

[36] S. Dhundhara, Y.P. Verma, A. Williams, Techno-economic analysis of the lithium-ion and lead–acid battery in microgrid systems, Energy Convers. Manage. 177 (2018) 122–142, http://dx.doi.org/10.1016/j.enconman.2018.09.030.

[37] A. Purwanto, S. Nisa, I.P. Lestari, M.N. Ikhsanudin, C.S. Yudha, H. Widiyandari, High performance nickel based electrodes in state-of-the-art lithium-ion batteries: Morphological perspectives, KONA Powder Part. J. 39 (2022) 130–149, http://dx.doi.org/10.14356/kona.2022015.

[38] X. Zeng, C. Zhan, J. Lu, K. Amine, Stabilization of a high-capacity and high-power nickel-based cathode for Li-ion batteries, Chem 4 (4) (2018) 690–704, http://dx.doi.org/10.1016/j.chempr.2017.12.027.

[39] A. Ghosh, J.M. Foster, G. Offer, M. Marinescu, A shrinking-core model for the degradation of high-nickel cathodes (NMC811) in li-ion batteries: Passivation layer growth and oxygen evolution, J. Electrochem. Soc. 168 (2) (2021) 020509, http://dx.doi.org/10.1149/1945-7111/abdc71.

[40] Y. Yang, R. Wang, Z. Shen, Q. Yu, R. Xiong, W. Shen, Towards a safer lithium-ion batteries: A critical review on cause, characteristics, warning and disposal strategy for thermal runaway, Adv. Appl. Energy 11 (2023) 100146, http://dx.doi.org/10.1016/j.adapen.2023.100146.

[41] A.K. Koech, G. Mwandila, F. Mulolani, A.K. Koech, G. Mwandila, F. Mulolani, A review of improvements on electric vehicle battery, Heliyon 10 (15) (2024) e34806, http://dx.doi.org/10.1016/j.heliyon.2024.e34806.

[42] R. Satpathy, V. Pamuru, Solar PV Power: Design, Manufacturing and Applications from Sand to Systems, Academic Press, Cambridge, MA, USA, 2020, http://dx.doi.org/10.1016/C2018-0-02530-X.

[43] B. Chu, Y.-J. Guo, J.-L. Shi, Y.-X. Yin, T. Huang, H. Su, A. Yu, Y.-G. Guo, Y. Li, Cobalt in high-energy-density layered cathode materials for lithium ion batteries, J. Power Sources 544 (2022) 231873, http://dx.doi.org/10.1016/j.jpowsour.2022.231873.

[44] Z.W. Lebens-Higgins, et al., Surface chemistry dependence on aluminum doping in Ni-rich LiNi0.8Co0.2−yAlyO2 cathodes, Sci. Rep. 9 (1) (2019) http://dx.doi.org/10.1038/s41598-019-53932-6.

[45] A. Mauger, C.M. Julien, Olivine positive electrodes for Li-ion batteries: Status and perspectives, Batteries 4 (3) (2018) 39, http://dx.doi.org/10.3390/batteries4030039.

[46] J.B. Goodenough, K.-S. Park, The li-ion rechargeable battery: A perspective, J. Am. Chem. Soc. 135 (4) (2013) 1167–1176, http://dx.doi.org/10.1021/ja3091438.

[47] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: Present and future, Mater. Today 18 (5) (2015) 252–264, http://dx.doi.org/10.1016/j.mattod.2014.10.040.

[48] M. Armand, J.-M. Tarascon, Building better batteries, Nature 451 (7179) (2008) 652–657, http://dx.doi.org/10.1038/451652a.

[49] K. Xu, Nonaqueous liquid electrolytes for lithium-based rechargeable batteries, Chem. Rev. 104 (10) (2004) 4303–4418, http://dx.doi.org/10.1021/cr030203g.

[50] P. Arora, Z. Zhang, Battery separators, Chem. Rev. 104 (10) (2004) 4419–4462, http://dx.doi.org/10.1021/cr020738u.

[51] D. Bresser, D. Buchholz, A. Moretti, A. Varzi, S. Passerini, Alternative binders for sustainable electrochemical energy storage-the transition to aqueous electrode processing and bio-derived polymers, Energy Environ. Sci. 11 (11) (2018) 3096–3127, http://dx.doi.org/10.1039/c8ee00640g.

[52] G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines, P. Anderson, Recycling lithium-ion batteries from electric vehicles, Nature 575 (7781) (2019) 75–86, http://dx.doi.org/10.1038/s41586-019-1682-5.

[53] A. Bello, R.A. Ahmed, R.K. Koech, K. Orisekeh, D.M. Sanni, M. Kigozi, V. Anye, O.K. Oyewole, W.O. Soboyejo, The mechanical properties of batteries and supercapacitors, in: Comprehensive Structural Integrity, second ed., Vol. 10, Elsevier, 2023, pp. V10–308–V10–348, http://dx.doi.org/10.1016/B978-0-12-822944-6.00050-5.

[54] R. Jacobs, D. Morgan, S. Attarian, J. Meng, C. Shen, Z. Wu, C.Y. Xie, J.H. Yang, N. Artrith, B. Blaiszik, et al., A practical guide to machine learning interatomic potentials – Status and future, Curr. Opin. Solid State Mater. Sci. 35 (2025) 101214, http://dx.doi.org/10.1016/j.cossms.2025.101214.

[55] J.S. Menye, M.-B. Camara, B. Dakyo, Lithium battery degradation and failure mechanisms: A state-of-the-art review, Energies 18 (2) (2025) 342, http://dx.doi.org/10.3390/en18020342.

[56] Y. Zhang, D. Fraggedakis, T. Gao, S. Pathak, D. Zhuang, C. Grosu, Y. Samantaray, A.R.C. Neto, S.R. Duggirala, B. Huang, Y.G. Zhu, L. Giordano, R. Tatara, H. Agarwal, R.M. Stephens, M.Z. Bazant, Y. Shao-Horn, Lithium-ion intercalation by coupled ion-electron transfer, Science 390 (6768) (2025) http://dx.doi.org/10.1126/science.adq2541.

[57] R. Zhang, B. Xia, B. Li, Y. Lai, W. Zheng, H. Wang, W. Wang, M. Wang, Study on the characteristics of a high capacity nickel manganese cobalt oxide (NMC) lithium-ion battery—An experimental investigation, Energies 11 (9) (2018) 2275, http://dx.doi.org/10.3390/en11092275.

[58] S. Liu, J. Chen, C. Zhang, L. Jin, Q. Yang, Experimental study on lithium-ion cell characteristics at different discharge rates, J. Energy Storage 45 (2022) http://dx.doi.org/10.1016/j.est.2021.103418.

[59] J. Li, E. Murphy, J. Winnick, P.A. Kohl, Studies on the cycle life of commercial lithium ion batteries during rapid charge–discharge cycling, J. Power Sources 102 (1–2) (2001) 294–301, http://dx.doi.org/10.1016/S0378-7753(01)00821-7.

[60] S.S. Zhang, The effect of the charging protocol on the cycle life of a Li-ion battery, J. Power Sources 161 (2) (2006) 1385–1391, http://dx.doi.org/10.1016/j.jpowsour.2006.06.040.

[61] N. Kirkaldy, M.A. Samieian, G.J. Offer, M. Marinescu, Y. Patel, Lithium-ion battery degradation: Comprehensive cycle ageing data and analysis for commercial 21700 cells, J. Power Sources 603 (2024) http://dx.doi.org/10.1016/j.jpowsour.2024.234185.

[62] M.A. Khan, S. Thatipamula, S. Onori, Onboard health estimation using distribution of relaxation times for lithium-ion batteries, IFAC-PapersOnLine 58 (28) (2024) 917–922, http://dx.doi.org/10.1016/j.ifacol.2024.12.074.

[63] Q. Zhang, D. Wang, E. Schaltz, D.I. Stroe, A. Gismero, B. Yang, Lithium-ion battery calendar aging mechanism analysis and impedance-based State-of-Health estimation method, J. Energy Storage 64 (2023) http://dx.doi.org/10.1016/j.est.2023.107029.

[64] J. Vetter, P. Novák, M.R. Wagner, C. Veit, K.-C. Möller, J.O. Besenhard, M. Winter, M. Wohlfahrt-Mehrens, C. Vogler, A. Hammouche, Ageing mechanisms in lithium-ion batteries, J. Power Sources 147 (1–2) (2005) 269–281, http://dx.doi.org/10.1016/j.jpowsour.2005.01.006.

[65] X. Han, L. Lu, Y. Zheng, X. Feng, Z. Li, J. Li, M. Ouyang, A review on the key issues of the lithium ion battery degradation among the whole life cycle, eTransportation 1 (2019) 100005, http://dx.doi.org/10.1016/j.etran.2019.100005.

[66] S. Rout, S.K. Samal, D.J. Gelmecha, S. Mishra, Estimation of state of health for lithium-ion batteries using advanced data-driven techniques, Sci. Rep. 15 (1) (2025) http://dx.doi.org/10.1038/s41598-025-93775-y.

[67] K. Chen, J. Li, K. Liu, C. Bai, J. Zhu, G. Gao, G. Wu, S. Laghrouche, State of health estimation for lithium-ion battery based on particle swarm optimization algorithm and extreme learning machine, Green Energy Intell. Transp. 3 (1) (2024) 100151, http://dx.doi.org/10.1016/j.geits.2024.100151.

[68] S. Zhu, et al., State of health and remaining useful life estimation of lithium-ion battery based on parallel deep learning methods, Int. J. Electrochem. Sci. 20 (5) (2025) http://dx.doi.org/10.1016/j.ijoes.2025.100988.

[69] Q. Li, R. Song, Y. Wei, A review of state-of-health estimation for lithium-ion battery packs, J. Energy Storage 118 (2025) 116078, http://dx.doi.org/10.1016/j.est.2025.116078.

[70] X. Lei, F. Xie, J. Wang, C. Zhang, A Review of Lithium-Ion Battery State of Health and Remaining Useful Life Estimation Methods Based on Bibliometric Analysis, KeAi Communications Co., 2024, http://dx.doi.org/10.1016/j.jtte.2024.09.004.

[71] A.A. Pesaran, Lithium-ion battery technologies for electric vehicles: Progress and challenges, IEEE Electrif. Mag. 11 (2) (2023) 35–43, http://dx.doi.org/10.1109/MELE.2023.3264919.

[72] A.N. Patel, L. Lander, J. Ahuja, J. Bulman, J.K.H. Lum, J.O.D. Pople, A. Hales, Y. Patel, J.S. Edge, Lithium-ion battery second life: Pathways, challenges and outlook, Front. Chem. 12 (2024) 1358417, http://dx.doi.org/10.3389/fchem.2024.1358417.

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

[74] J. Campoverde-Pillco, D. Ochoa-Correa, E. Villa-ávila, P. Astudillo-Salinas, Reuse of electrical vehicle batteries for second life applications in power systems with a high penetration of renewable energy: A systematic literature review, Ingenius 2024 (31) (2024) 95–105, http://dx.doi.org/10.17163/ings.n31.2024.08.

[75] C.H. Illa Font, H.V. Siqueira, J.E. Machado Neto, J.L.F. dos Santos, S.L. Stevan Jr., A. Converti, F.C. Corrêa, Second life of lithium-ion batteries of electric vehicles: A short review and perspectives, Energies 16 (2) (2023) 953, http://dx.doi.org/10.3390/en16020953.

[76] T. Jaradat, T. Khatib, A review of battery energy storage system for renewable energy penetration in electrical power system: Environmental impact, sizing methods, market features, and policy frameworks, Future Batter. 7 (2025) 100106, http://dx.doi.org/10.1016/j.fub.2025.100106.

[77] W. Zhou, Q. Lu, Y. Zheng, Review on the selection of health indicator for lithium ion batteries, Machines 10 (7) (2022) 512, http://dx.doi.org/10.3390/machines10070512.

[78] S. Tsianikas, J. Zhou, N. Yousefi, D.W. Coit, Battery selection for optimal grid-outage resilient photovoltaic and battery systems, in: Proceedings of the 2019 IISE Annual Conference, 2019, pp. 1042–1047.

[79] N. Pang, Q. Meng, M. Nan, Multi-criteria evaluation and selection of renewable energy battery energy storage system-a case study of Tibet, China, IEEE Access 9 (2021) 119857–119870, http://dx.doi.org/10.1109/ACCESS.2021.3107192.

[80] M.K. Loganathan, B. Mishra, C.M. Tan, T. Kongsvik, R.N. Rai, Multi-criteria decision making (MCDM) for the selection of Li-ion batteries used in electric vehicles (EVs), in: Materials Today: Proceedings, Elsevier Ltd, 2019, pp. 1073–1077, http://dx.doi.org/10.1016/j.matpr.2020.07.179.

[81] UL Standards & Engagement, UL 1974: Standard for Evaluation for Repurposing Batteries, second ed., Northbrook, IL, USA, 2024.

[82] JIS C 8715-2:2024, Secondary Lithium Cells and Batteries for Use in Industrial Applications – Part 2: Safety Requirements, Japanese Standards Association (JSA), Tokyo, Japan, 2024.

[83] R. Li, A. Hassan, N. Gupte, W. Su, X. Zhou, Degradation prediction and cost optimization of second-life battery used for energy arbitrage and peak-shaving in an electric grid, Energies (Basel) 16 (17) (2023) http://dx.doi.org/10.3390/en16176200.

[84] K.B. Samal, M. Mahapatra, S. Pati, M.K. Debnath, A Review on Microgrid Control: Conventional, Advanced and Intelligent Control Approaches, KeAi Communications Co., 2026, http://dx.doi.org/10.1016/j.uncres.2025.100297.

[85] J.H. He, J.H. Lin, Review of microgrids to enhance power system resilience, Eng. Proc. 92 (1) (2025) http://dx.doi.org/10.3390/engproc2025092082.

[86] M.I. Hossain, H.Z. Anonto, A. Shufian, B.B. Pathik, M.A. Mannan, A. Rashid, P. Biswas, Enhancing microgrid resilience through integrated grid-forming and grid-following inverter strategies for solar PV battery control and fault ride-through, Sci. Rep. 15 (2025) 40078, http://dx.doi.org/10.1038/s41598-025-18767-4.

[87] S. Tajjour, S.S. Chandel, A comprehensive review on sustainable energy management systems for optimal operation of future-generation of solar microgrids, Sustain. Energy Technol. Assess. 58 (2023) 103377, http://dx.doi.org/10.1016/j.seta.2023.103377.

[88] K. Kumar, P. Kumar, S. Kar, A review of microgrid protection for addressing challenges and solutions, Renew. Energy Focus 49 (2024) 100572, http://dx.doi.org/10.1016/j.ref.2024.100572.

[89] A. Dosa, O.A. Olanrewaju, F. Mora-Camino, A comprehensive review of hybrid renewable microgrids: Key design parameters, optimization techniques, and the role of demand response in enhancing system flexibility, Energies 18 (19) (2025) 5154, http://dx.doi.org/10.3390/en18195154.

[90] M. Cheng, A. Ran, X. Zheng, X. Zhang, G. Wei, G. Zhou, H. Sun, Sustainability evaluation of second-life battery applications in grid-connected PV-battery systems, J. Power Sources 550 (2022) 232132, http://dx.doi.org/10.1016/j.jpowsour.2022.232132.

[91] A. Farakhor, D. Wu, P. Chen, J. Wang, Y. Wang, H. Fang, Economic optimal power management of second-life battery energy storage systems, J. Energy Storage 133 (2025) http://dx.doi.org/10.1016/j.est.2025.117680.

[92] Y. Gao, Y. Cai, C. Liu, Annual operating characteristics analysis of photovoltaic-energy storage microgrid based on retired lithium iron phosphate batteries, J. Energy Storage 45 (2022) http://dx.doi.org/10.1016/j.est.2021.103769.

[93] M. Cheng, X. Zhang, A. Ran, G. Wei, H. Sun, Optimal dispatch approach for second-life batteries considering degradation with online SoH estimation, Renew. Sustain. Energy Rev. 173 (2023) http://dx.doi.org/10.1016/j.rser.2022.113053.

[94] M.T. Sarker, M.S. Hossen, G. Ramasamy, M. Al Qwaid, H.A. Karim, Techno economic and environmental evaluation of second life battery PV hybrid charging stations for sustainable e-mobility in tropical regions, Sci. Rep. 16 (2026) 8195, http://dx.doi.org/10.1038/s41598-026-39034-0.

[95] M. Abdoos, Y. Noorollahi, A. Shahee, H. Yousefi, M. Rezaeifard, R. Moltames, Energy PLAN-based evaluation of renewable energy scenarios in semi-arid contexts, Results Eng. 27 (2025) 107007, http://dx.doi.org/10.1016/j.rineng.2025.107007.

[96] M. Gautam, D. Wu, P. Chen, H. Fang, Techno-economic assessments of second-life batteries for electric vehicle charging stations, in: 2025 IEEE Electrical Energy Storage Applications and Technologies Conference, EESAT, Charlotte, NC, USA, 2025, pp. 1–5, http://dx.doi.org/10.1109/EESAT62935.2025.10891225.

[97] C. White, B. Thompson, L.G. Swan, Repurposed electric vehicle battery performance in second-life electricity grid frequency regulation service, J. Energy Storage 28 (2020) http://dx.doi.org/10.1016/j.est.2020.101278.

[98] M.F. Roslan, P.R. Satpathy, T. Prasankumar, V.K. Ramachandaramurthy, M. Mansor, S.L. Walker, Second-life battery energy storage system for energy sustainability: Recent advancements, key takeaways and future perspectives, J. Energy Storage 123 (2025) 116808, http://dx.doi.org/10.1016/j.est.2025.116808.

[99] Z. Cao, N. Vosoughi Kurdkandi, C. Mi, Techno-economic and environmental viability of second-life EV batteries in commercial buildings: An analysis using real-world data, Batteries 11 (11) (2025) http://dx.doi.org/10.3390/batteries11110412.

[100] J. Zhuang, A. Bach, B.H.C. van Vlijmen, S.J. Reichelstein, W. Chueh, S. Onori, S.M. Benson, Technoeconomic decision support for second-life batteries, Appl. Energy 390 (2025) 125800, http://dx.doi.org/10.1016/j.apenergy.2025.125800.

[101] S. Lieskoski, J. Tuuf, M. Björklund-Sänkiaho, Techno-economic analysis of the business potential of second-life batteries in Ostrobothnia, Finland, Batteries 10 (1) (2024) http://dx.doi.org/10.3390/batteries10010036.

[102] A. Wangsupphaphol, S. Chaitusaney, M. Salem, A techno-economic assessment of a second-life battery and photovoltaics hybrid power source for sustainable electric vehicle home charging, Sustain. (Switz.) 15 (7) (2023) http://dx.doi.org/10.3390/su15075866.

[103] I. Mathews, B. Xu, W. He, V. Barreto, T. Buonassisi, I.M. Peters, Technoeconomic model of second-life batteries for utility-scale solar considering calendar and cycle aging, Appl. Energy 269 (2020) http://dx.doi.org/10.1016/j.apenergy.2020.115127.

[104] Q. Dong, S. Liang, J. Li, H.C. Kim, W. Shen, T.J. Wallington, Cost, energy, and carbon footprint benefits of second-life electric vehicle battery use, iScience 26 (7) (2023) 107195, http://dx.doi.org/10.1016/j.isci.2023.107195.

[105] S. S., N. Srivastava, J. Hristov, Mathematical modelling of ion diffusion and state of charge prediction in sodium ion batteries with time series analysis, Sci. Rep. 16 (2026) 7534, http://dx.doi.org/10.1038/s41598-026-37522-x.

[106] B. Zheng, Z. Deng, Z. Luo, S. Mao, M. Ouyang, X. Han, H. Wang, Y. Li, Y. Sun, D. Wang, Y. Yuan, L. He, Z. Yang, Y. Zhu, A comprehensive review of lithium-ion battery modelling research and prospects: In-depth analysis of current research and future directions, Appl. Energy 401 (pt. B) (2025) 126688, http://dx.doi.org/10.1016/j.apenergy.2025.126688.

[107] MathWorks, Battery Second Life App – SOH Estimation. [Online]. Available: https://www.mathworks.com/help/predmaint/ug/battery-second-life-app-soh-estimation.html.

[108] F. Salek, A. Azizi, S. Resalati, P. Henshall, D. Morrey, Mathematical modelling and simulation of second life battery pack with heterogeneous state of health, Mathematics 10 (20) (2022) http://dx.doi.org/10.3390/math10203843.

[109] M. Hassini, E. Redondo-Iglesias, P. Venet, Second-life batteries modeling for performance tracking in a mobile charging station, World Electr. Veh. J. 14 (4) (2023) http://dx.doi.org/10.3390/wevj14040094.

[110] G. Pozzato, S.B. Lee, S. Onori, Modeling degradation of Lithium-ion batteries for second-life applications: preliminary results, in: CCTA 2021-5th IEEE Conference on Control Technology and Applications, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 826–831, http://dx.doi.org/10.1109/CCTA48906.2021.9659267.

[111] S.V. Ganesh, M. D'Arpino, Critical comparison of li-ion aging models for second life battery applications, Energies (Basel) 16 (7) (2023) http://dx.doi.org/10.3390/en16073023.

[112] A. Pérez, I. San Martín, P. Sanchis, A. Ursúa, A novel aging modeling approach for second-life lithium-ion batteries, eTransportation 24 (2025) 100400, http://dx.doi.org/10.1016/j.etran.2025.100400.

[113] L.S. Teixeira, Modelling Lithium-Ion Battery Degradation for Second Life Stationary Applications (M.Sc. Thesis), Universidade Federal de Minas Gerais, Belo Horizonte, Brazil, 2024, Available: https://repositorio.ufmg.br/server/api/core/bitstreams/d4a82651-277c-45ee-8601-a7408e0fbd04/content.

[114] V. Bhattacharjee, I. Khan, A non-linear convex cost model for economic dispatch in microgrids, Appl. Energy 222 (2018) 637–648, http://dx.doi.org/10.1016/j.apenergy.2018.04.001.

[115] M.M. Camboim, A.C. Moreira, M. de F. N. C. Rosolem, R.F. Beck, V.T. Arioli, C. Omae, H. Ding, State of health estimation of second-life batteries through electrochemical impedance spectroscopy and dimensionality reduction, J. Energy Storage 78 (2024) 110063, http://dx.doi.org/10.1016/j.est.2023.110063.

[116] A. Takahashi, A. Allam, S. Onori, Evaluating the feasibility of batteries for second-life applications using machine learning, iScience 26 (4) (2023) http://dx.doi.org/10.1016/j.isci.2023.106547.

[117] S.M. Jameel, J.M. Altmemi, A.A. Oglah, M.A. Abbas, A.H. Sabry, Predicting batteries second-life state-of-health with first-life data and on-board voltage measurements using support vector regression, J. Energy Storage 104 (2024) http://dx.doi.org/10.1016/j.est.2024.114554.

[118] A.H. Alqahtani, H.M. Hasanien, H.M. Fahmy, M. Tostado-Véliz, F. Jurado, Machine learning approach for lifespan prediction of second-life lithium-ion batteries, Results Eng. (2025) 108925, http://dx.doi.org/10.1016/j.rineng.2025.108925.

[119] K. Li, X. Chen, Machine learning-based lithium battery state of health prediction research, Appl. Sci. (Switz.) 15 (2) (2025) http://dx.doi.org/10.3390/app15020516.

[120] F. Wang, Z. Zhai, Z. Zhao, Y. Di, X. Chen, Physics-informed neural network for lithium-ion battery degradation stable modeling and prognosis, Nat. Commun. 15 (1) (2024) http://dx.doi.org/10.1038/s41467-024-48779-z.

[121] J. Luque, B. Schroeder, A. Carrasco, H. Heidarabadi, C. León, H. Hesse, Machine learning estimation of battery state of health in residential photovoltaic systems, Future Batter. 5 (2025) 100039, http://dx.doi.org/10.1016/j.fub.2025.100039.

[122] F. Marasciuolo, M. Dicorato, G. Tricarico, G. Forte, R. Sbrizzai, Second life EV batteries use in microgrid application, in: 2024 7th IEEE International Humanitarian Technologies Conference, IHTC 2024, Institute of Electrical and Electronics Engineers Inc., 2024, http://dx.doi.org/10.1109/IHTC61819.2024.10855032.

[123] N. Hassanpour, A. Chub, N. Yadav, A. Blinov, D. Vinnikov, High-efficiency partial power converter for integration of second-life battery energy storage systems in DC microgrids, IEEE Open J. Ind. Electron. Soc. 5 (2024) 847–860, http://dx.doi.org/10.1109/OJIES.2024.3389466.

[124] Y. Zhang, F. Luo, Y. Mu, Hierarchical Energy Management for Community Microgrids with Integration of Second-Life Battery Energy Storage Systems and Photovoltaic Solar Energy, United States Patent and Trademark Office (USPTO), 2025, U.S. Patent US12422800B2.

[125] E. Nunes, G. Liang, E. Rodriguez, H.W. Yan, G.G. Farivar, P. Vorobev, Optimal distributed SoH balancing of second-life battery energy storage systems in a dc microgrid, in: Proc. 2025 IEEE 7th Int. Conf. DC Microgrids, ICDCM, Tallinn, Estonia, 2025, http://dx.doi.org/10.1109/ICDCM63994.2025.111447377.

[126] N. Wang, Y. Jiang, Y. Wang, D. Mou, Y. Liu, W. Hu, Advanced operation and control schemes of retired batteries in DC microgrid for secondary usage, IEEE Trans. Smart Grid 16 (4) (2025) 3155–3166, http://dx.doi.org/10.1109/TSG.2025.3555181.

[127] T.A. Fagundes, G.H.F. Fuzato, L.J.R. Silva, A.M. dos Santos Alonso, J.C. Vasquez, J.M. Guerrero, Battery energy storage systems in microgrids: A review of SoC balancing and perspectives, IEEE Open J. Ind. Electron. Soc. 5 (2024) 961–992, http://dx.doi.org/10.1109/OJIES.2024.3455239.

[128] C. Yuan, C. Liu, S. Chen, W. Xu, J. Gou, K. Xu, Z. Li, Y. Liu, Second-life battery energy storage system capacity planning and power dispatch via model-free adaptive control-embedded heuristic optimization, Energy Eng. 122 (9) (2025) 3573–3593, http://dx.doi.org/10.32604/ee.2025.067785.

[129] H. Bai, S. Lei, S. Geng, X. Hu, Z. Li, Z. Song, Techno-economic assessment of isolated micro-grids with second-life batteries: A reliability-oriented iterative design framework, Appl. Energy 364 (2024) 123068, http://dx.doi.org/10.1016/j.apenergy.2024.123068.

[130] European Commission, Battery Management System and System Design for Stationary Energy Storage with 2nd Life Batteries (Battery2Life), Horizon Europe Project, Grant Agreement No. 101137615, 2024, [Online]. Available: https://cordis.europa.eu/project/id/101137615.

[131] Fraunhofer, Designing the Next-Generation BMS for BIG LEAP, BIG LEAP Project, 2025, Available: https://bigleapproject.eu/where-innovation-meets-reality-eatons-second-life-battery-demonstrator-2/.

[132] M. Šuňal, A. Stupka, T. Kulhánek, D. Šišmišová, J. Matušov, BMS controller architecture for second-life batteries, in: 2024 ELEKTRO, ELEKTRO, IEEE, 2024, pp. 1–6, http://dx.doi.org/10.1109/ELEKTRO60337.2024.10557113.

[133] J.Y. Lee, A.K. Ramasamy, K.H. Ong, R. Verayiah, H. Mokhlis, A logic-driven battery balancing technique for second-life battery application in small-scale grid system, Energy Technol. 13 (8) (2025) http://dx.doi.org/10.1002/ente.202401473.

[134] E. Sutton, Energy Management Strategies for Second Life Battery Energy Storage Systems in Grid Applications, University of Tennessee, [Online]. Available: https://trace.tennessee.edu/utk_gradthes.

[135] UL Standards & Engagement, UL 9540: Standard for Energy Storage Systems and Equipment, third ed., Northbrook, IL, USA, 2023.

[136] UL Standards & Engagement, UL 9540 A: Standard Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, fifth ed., Northbrook, IL, USA, 2025.

[137] International Electrotechnical Commission, IEC 62619:2022 — Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes: Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications, second ed., IEC, Geneva, Switzerland, 2022, TC 21/SC 21A. https://webstore.iec.ch/publication/IEC62619.

[138] International Electrotechnical Commission, IEC 62933-5-3:2023 — Electrical Energy Storage (EES) Systems — Part 5-3: Safety Requirements for Grid-Integrated EES Systems: Performing Unplanned Modification of Electrochemical Based System, first ed., IEC, Geneva, Switzerland, 2023, TC 120. https://webstore.iec.ch/publication/IEC62933-5-3.

[139] IEC 62933-2-1:2017, Ed. 1.0, Electrical Energy Storage (EES) Systems – Part 2-1: Unit Parameters and Testing Methods – General Specification, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2017, (including corrigendum Jan. 2019).

[140] IEC 62620:2014, Ed. 1.0, Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Secondary Lithium Cells and Batteries for Use in Industrial Applications, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2014.

[141] IEC 62133-2:2017, Ed. 1.0, Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications – Part 2: Lithium Systems, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2017.

[142] IEC 61960-4:2024 CMV, Ed. 2.0, Secondary Cells and Batteries Containing Alkaline Or Other Non-Acid Electrolytes – Secondary Lithium Cells and Batteries for Portable Applications – Part 4: Coin Secondary Lithium Cells, and Batteries Made from Them, Commented Version, CMV, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2024.

[143] ISO 26262:2018 (all parts), Road Vehicles – Functional Safety – Parts 1–10, International Organization for Standardization (ISO), Geneva, Switzerland, 2018.

[144] ISO 12405-4:2018, Ed. 1, Electrically Propelled Road Vehicles – Test Specification for Lithium-Ion Traction Battery Packs and Systems – Part 4: Performance Testing, International Organization for Standardization (ISO), Geneva, Switzerland, 2018.

[145] United Nations, Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria, Section 38.3: Lithium Metal and Lithium Ion Batteries, United Nations, New York and Geneva, 2009.

[146] National Fire Protection Association, NFPA 855: Standard for the Installation of Stationary Energy Storage Systems, 2023 ed., National Fire Protection Association, Quincy, MA, USA, 2022.

[147] National Fire Protection Association, NFPA 13: Standard for the Installation of Sprinkler Systems, 2022 ed., National Fire Protection Association, Quincy, MA, USA, 2021.

[148] IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE, 2018, pp. 1–138, http://dx.doi.org/10.1109/IEEESTD.2018.8332112.

[149] IEEE Std 1679-2020 (Revision of IEEE Std 1679-2010), IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications, IEEE, 2020, pp. 1–40, http://dx.doi.org/10.1109/IEEESTD.2020.9063725.

[150] IEEE Std 2030.2.1-2019, IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, Both Stationary and Mobile, and Applications Integrated with Electric Power Systems, IEEE, 2019, pp. 1–45, http://dx.doi.org/10.1109/IEEESTD.2019.8930450.

[151] Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 2023 concerning batteries and waste batteries, amending directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, Off. J. Eur. Union L 191 (2023) 1–117.

[152] CENELEC EN 50604-1:2016, Secondary Lithium Batteries for Light EV (Electric Vehicle) Applications – Part 1: General Safety Requirements and Test Methods, European Committee for Electrotechnical Standardization (CENELEC), Brussels, Belgium, 2016.

[153] CENELEC EN 62619:2017, Secondary Cells and Batteries Containing Alkaline Or Other Non-Acid Electrolytes – Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications, European Committee for Electrotechnical Standardization (CENELEC), Brussels, Belgium, 2017.

[154] GB/T 36276-2023, Lithium Ion Battery for Electrical Energy Storage, National Standard of the People's Republic of China, Beijing, China, 2023.

[155] GB/T 31467-2023, Electrical Performance Test Methods for Lithium-Ion Traction Battery Pack and System of Electric Vehicles, National Standard of the People's Republic of China, Beijing, China, 2023.

[156] Y. Chen, Y. Kang, Y. Zhao, L. Wang, J. Liu, Y. Li, Z. Liang, X. He, X. Li, N. Tavajohi, B. Li, A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards, J. Energy Chem. 59 (2021) 83–99, http://dx.doi.org/10.1016/j.jechem.2020.10.017.

[157] Y. Dai, A. Panahi, Thermal runaway process in lithium-ion batteries: A review, Next Energy 6 (2025) 100186, http://dx.doi.org/10.1016/j.nxener.2024.100186.

[158] Y. Wang, T. Yu, J. Chen, B. Gao, M. Yu, J. Zhu, Advances in safety of lithium-ion batteries for energy storage: Hazard characteristics and active suppression techniques, Energy Rev. 4 (1) (2025) 100117, http://dx.doi.org/10.1016/j.enrev.2024.100117.

[159] J. Deng, Z. Hu, J. Chen, J. Zhao, Z. Bai, Safety methods for mitigating thermal runaway of lithium-ion batteries—A review, Fire 8 (6) (2025) 223, http://dx.doi.org/10.3390/fire8060223.

[160] X. Gu, Y. Shang, J. Li, Y. Zhu, X. Tao, H. Geng, Z. Zhang, C. Zhang, Early warning of thermal runaway based on state of safety for lithium-ion batteries, Commun. Eng. 4 (2025) 106, http://dx.doi.org/10.1038/s44172-025-00442-1.

[161] Y. Zhou, X. Zhu, Z. Wang, T. Shan, J. Zhang, Z. Sun, Safety assessment of thermal runaway behavior of lithium-ion cells with actual installed state, Appl. Therm. Eng. 229 (2023) http://dx.doi.org/10.1016/j.applthermaleng.2023.120617.

[162] R. Tschirschwitz, C. Bernardy, P. Wagner, T. Rappsilber, C. Liebner, S.-K. Hahn, U. Krause, Harmful effects of lithium-ion battery thermal runaway: scale-up tests from cell to second-life modules, RSC Adv. 13 (2023) 20761–20779, http://dx.doi.org/10.1039/d3ra02881j.

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

[164] J.P. Manaia, G. Pedreiro, J.P. Dias, J. Santos, A. Alves, A. Pardal, Sustainable repurposing of EV batteries: A methodology for certification in the EU, Future Batter. 7 (2025) 100101, http://dx.doi.org/10.1016/j.fub.2025.100101.

[165] J. Son, Y. Du, Model-based stochastic fault detection and diagnosis of lithium-ion batteries, Processes 7 (1) (2019) 38, Available: https://doi.org/10.3390/pr7010038.

[166] E. de Godoy Antunes, A. González López, F. Lacressonnière, X. Roboam, B. Sareni, Life cycle assessment of a lithium ion battery: Comparison between first and second life batteries environmental impacts in microgrid applications, in: Proc. Symposium de Génie Électrique, SGE, Lille, France, 2023.

[167] T. Kobayashi, H. Kondo, T. Sasaki, Life cycle assessment integrating the effects of recycling and reuse for battery circulation, J. Power Sources 624 (2024) http://dx.doi.org/10.1016/j.jpowsour.2024.235544.

[168] D. Gautam, N. Bolia, Fostering second-life applications for electric vehicle batteries: A thorough exploration of barriers and solutions within the framework of sustainable energy and resource management, J. Clean. Prod. 456 (2024) http://dx.doi.org/10.1016/j.jclepro.2024.142401.

[169] J. Wesselkämper, T.P. Hendrickson, S. Lux, S. von Delft, Recycling or second use? Supply potentials and climate effects of end-of-life electric vehicle batteries, Environ. Sci. Technol. 59 (30) (2025) 15751–15765, http://dx.doi.org/10.1021/acs.est.5c01823.

[170] M. Brunström, Life-Cycle Assessment and Energy Systems Analysis of Second-Life Li-Ion Batteries (M.Sc. Thesis), Chalmers University of Technology, Gothenburg, Sweden, 2022, Available: https://hdl.handle.net/20.500.12380/304462.

[171] H. Kang, S. Jung, H. Kim, J. An, J. Hong, S. Yeom, T. Hong, Life-cycle environmental impacts of reused batteries of electric vehicles in buildings considering battery uncertainty, Renew. Sustain. Energy Rev. 207 (2025) 114936, http://dx.doi.org/10.1016/j.rser.2024.114936.

[172] Y. Tao, C.D. Rahn, L.A. Archer, F. You, Second life and recycling: energy and environmental sustainability perspectives for high-performance lithium-ion batteries, Sci. Adv. 7 (45) (2021) eabi7633, Available: https://doi.org/10.1126/sciadv.abi7633.

[173] J. Dunn, K. Ritter, J.M. Velázquez, A. Kendall, Should high-cobalt EV batteries be repurposed? Using LCA to assess the impact of technological innovation on the waste hierarchy, J. Ind. Ecol. 27 (5) (2023) 1277–1290, http://dx.doi.org/10.1111/jiec.13414.

[174] R. Jiang, C. Wu, W. Feng, K. You, J. Liu, G. Zhou, L. Liu, H.-M. Cheng, Impact of electric vehicle battery recycling on reducing raw material demand and battery life-cycle carbon emissions in China, Sci. Rep. 15 (2025) 2267, http://dx.doi.org/10.1038/s41598-025-86250-1.

[175] M.N. Akram, W. Abdul-Kader, Repurposing second-life EV batteries to advance sustainable development: A comprehensive review, Batteries 10 (12) (2024) 452, http://dx.doi.org/10.3390/batteries10120452.

[176] Z. Alam, S.H. Gheewala, Recharging the planet: The sustainability potential of second-life electric vehicle batteries, J. Energy Storage 144 (2026) 119720, http://dx.doi.org/10.1016/j.est.2025.119720.

[177] M.A. Pellow, H. Ambrose, D. Mulvaney, R. Betita, S. Shaw, Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues, Sustain. Mater. Technol. 23 (2020) e00120, http://dx.doi.org/10.1016/j.susmat.2019.e00120.