A Review on Enabling Waste and Carbon Reduction with Battery Management Systems for Second-Life Batteries

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Abstract

The rapid rise of electric vehicles has sparked a parallel challenge: the sustainable management of end-of-life lithium-ion batteries. While no longer suitable for automotive applications, these batteries often retain a considerable amount of usable capacity, making them strong candidates for second-life deployment in stationary energy storage systems. As the world advances toward circular economy models and low-carbon energy systems, repurposing electric vehicle batteries offers a strategic solution to reduce both electronic waste and lifecycle greenhouse gas emissions. However, second-life batteries face inherent challenges chiefly aging, uneven degradation, and variable state-of-health that threaten their safety, performance, and reliability. In this context, battery management systems emerge as critical enablers for successful second life batteries integration. Intelligent battery management system technologies can continuously monitor battery health, detect faults, optimize energy throughput, and adapt system control to extend battery lifespan and improve performance. This review presents a comprehensive examination of recent advancements in battery management system technologies specifically designed for second-life battery applications. Key areas include state of health estimation, fault diagnostics, adaptive control algorithms, and battery management system integration with renewable sources. The paper analyzes the impact of battery management system on system-level metrics such as reliability, degradation rate, and environmental performance, with studies indicating notable gains in battery longevity and emission reductions. Future research directions are identified in artificial intelligence-based health prediction, modular battery management system architectures, and real-time diagnostics. Overall, this review underscores the essential role of battery management system in enabling scalable, efficient, and sustainable second-life battery systems. By addressing technical barriers and improving lifecycle management, battery management system technologies unlock the full environmental and economic potential of second life battery in modern energy infrastructures.

Keywords

Energy storage systems, Second-life batteries, Battery management systems (BMS), Battery degradation, State of health estimation, Sustainable energy systems, Carbon emissions reduction, Circular economy.

1 Introduction

The future of sustainable transportation is closely tied to the widespread adoption of electric vehicles (EVs). As the transportation sector remains one of the largest contributors to greenhouse gas emissions, the European Union (EU) has set ambitious targets to reduce CO_2 emissions from this sector by up to 37.5% by 2030 [1]. In response to global climate goals, EVs are increasingly replacing internal combustion engine (ICE) vehicles [2]. The global EV fleet has expanded rapidly, surpassing 7 million vehicles by 2019 [3]. According to the Bloomberg EV Outlook 2022, this growth is expected to accelerate, with projections of 700 million passenger EVs and an additional 750 million two- and three-wheeler EVs on the road by 2040 [4]. Lithium-ion batteries (LIBs) are widely used in electric vehicles due to their high energy density (200–250 Wh/kg), excellent coulombic efficiency (nearly 100%), and minimal memory effect. In the automotive sector, a LIB is typically deemed unsuitable for continued use once its capacity drops below 80% of the nominal value [5]. With the rapid expansion of the EV market, the number of retired batteries are increasing significantly, leading to growing environmental concerns. Notably, the total potential storage capacity of second-life batteries (SLBs) is projected to reach approximately 1,000 gigawatt-hours by 2030 [6]. The disposal of these large volumes of battery packs poses significant environmental risks and leads to the loss of valuable chemical materials. Although lithium-ion battery recycling is gaining attention, it remains an emerging sector that faces various economic, logistical, and regulatory obstacles, limiting its commercial feasibility. In contrast, repurposing these battery packs for second-life applications presents a practical and environmentally sustainable alternative [2]. Concurrently, the global push to reduce carbon emissions has fueled a surge in renewable energy installations. Yet, the intermittent nature of renewables like solar and wind introduces variability into power generation, posing challenges for grid integration. Energy storage systems (ESS), especially those utilizing batteries, play a crucial role in addressing these challenges by stabilizing voltage, improving reliability, and enhancing grid flexibility. The convergence of these trends the surge in EV battery retirement and growing demand for stationary storage presents an opportunity to repurpose end of life of LIBs for second-life applications. This not only mitigates environmental harm and resource depletion but also contributes significantly to zero-waste and zero-carbon goals. Nevertheless, safe and efficient reuse of these batteries requires intelligent oversight, which is where battery management systems (BMS) become essential. By monitoring and optimizing performance, BMS technologies are pivotal to enabling the sustainable deployment of second-life batteries [5]. This paper reviews the technological advances in BMS for second-life LIB applications, highlighting their role in reducing waste and carbon emissions, and supporting a circular energy economy.

2 Literature Review

2.1 Overview of Second-Life Batteries

A second-life battery refers to a retired EV battery that retains 70–80% of its original capacity and can be repurposed for energy storage applications. As shown in Fig. 1, the typical EV battery lifecycle includes three phases: Phase 1 (First Life): Active use in EVs with 100–80% capacity retention. Phase 2 (Second Life): After falling below 80%, the battery is retired from EV use but remains viable for stationary energy storage. Phase 3 (Recycling): Once capacity drops below 30%, the battery is fully recycled [7]. Recycling, especially for lithium, remains expensive recycled lithium can cost up to five times more than newly mined material, with overall recycling costs ranging from 17–75 $/kWh. As cobalt usage declines, recovering it becomes less economical. Without large-scale recycling, rising demand for lithium, nickel, and cobalt could surpass global reserves. Extending battery life through second-life applications not only delays recycling expenses but also maximizes resource use and supports environmental sustainability [8]. SLBs offer a sustainable, cost-effective solution for energy storage. They support resource conservation, reduce overall battery costs through extended use, and provide flexible performance across diverse applications [7]. Life cycle assessment (LCA) compared reuse and repurpose scenarios, showing higher climate change (CC)

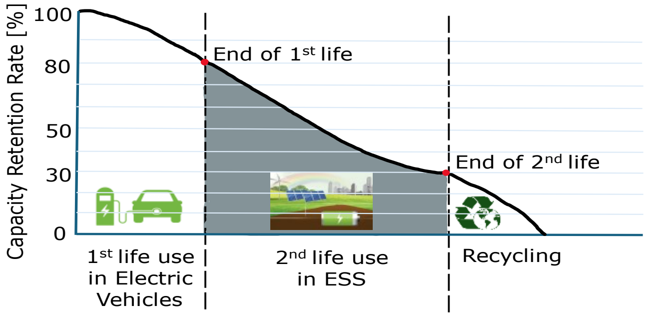

Figure 1. Lifespan phases of an EV battery.

impact during manufacturing due to energy-intensive processes and metal refining. Despite this, repurposing reduced emissions to 0.22 $kgCO_2eq/kWh$ (vs. 0.27 for reuse), with up to 25% benefits in acidification impact. Sensitivity analysis highlighted that reuse only lowers CC impact if the electricity mix is below 113 gCO_2eq/kWh, and that shorter second-life duration significantly increases environmental burden. Combining long-lasting battery chemistries with low-carbon electricity and eco-driving practices maximizes environmental benefits [9]. Second-life applications of LIBs significantly reduce environmental impacts across most categories. Compared to EV-only use, cascaded (EV + stationary) use lowers impacts such as freshwater ecotoxicity, eutrophication, human toxicity, and metal depletion by over 30%, mainly due to extended electricity delivery over the battery's lifetime as shown in Table 1, the data were collected from [9]. These benefits are more pronounced in impact categories less influenced by electricity production. High-energy-density LIBs (e.g., NMC, NCA) generally show better environmental performance due to lower material use, but they gain fewer additional benefits from second-life applications [10]. From an environmental perspective, SLBs help lower emissions by delaying resource intensive mining and recycling. Repurposing can reduce peak emissions by up to 56%, cut metal depletion by over 30%, and reduce GHG emissions by 15–70% depending on application. With an expected 300 GWh of end-of-life (EoL) battery capacity by 2030 and only 5% currently recycled, reuse before recycling is both environmentally and economically advantageous [8].

The SLBs market is rapidly growing beyond the United States, as global companies recognize its potential to reduce waste and extend battery life. In Europe, firms like Zenobe, Relion, and Second Life Batteries are advancing SLB solutions for grid storage, backup power, and mobility. In Asia, with high EV adoption, companies such as Hitachi, Fortum, ION Energy Inc., and Enel X are actively repurposing retired batteries. Supportive government policies such as EU recycling targets and Chinese subsidies are fostering innovation and investment, creating a favorable environment for SLB industry growth worldwide [2]. The main types of SLBs on the market include lead-acid, nickel-metal hydride (NiMH), and lithium-ion batteries, primarily sourced from two-wheelers, electric buses, and EVs. Their economic viability plays a key role in determining suitability for grid applications as shown in Table, the data were sourced from [15]. However, the SLB market is still emerging and influenced by many variables.

Table 1: Per-kWh environmental impact of reused and repurposed applications.

Impact Categories	Unit	Reuse Application	Repurpose Application
Climate Change	kg CO_2eq	0.27	0.22
Ionizing Radiation	kBqU-235eq	0.41	0.23
Ozone Depletion	kg CFC11eq	5.45E-08	3.62E-08
Human toxicity, noncancer	CTUh	3.27E-09	6.27E-09
Acidification	MolH*eq	7.28E-04	1.11E-03
Eutrophication, freshwater	kg Peq	7.12E-05	9.94E-05
Land use	Pt	2.76	1.80
Water use	m^3depriv	0.10	0.11
Resource use, minerals and metals	kg Sbeq	3.45E-06	1.06E-05
Resource use, fossils	Mj	10.4	6.60
Photochemical ozone formation	kg NMVOCeq	4.43E-04	5.55E-04
Particulate matter	disease inc.	4.95E-09	7.86E-09

It faces strong competition from battery recyclers driven by high demand for critical materials like cobalt, nickel, and lithium as well as from alternative technologies like flow batteries, which are often favored for grid-scale energy storage [2], [11].

Preliminary studies show that, cathode nanomaterials can be toxic, but replacing cobalt and nickel with less harmful metals like manganese may improve safety and sustainability. Fires, explosions, and chemical leaks are the most frequent hazards, releasing toxic substances such as HF, CO, HCN, metal nano-oxides (e.g., NMC, LMO), and electrolyte degradation products. These pollutants can contaminate soil, water, and air, with potentially severe impacts on wildlife and human health especially during EV fires involving HF exposure [12].

One major application area of SLBs is grid energy storage, especially as power systems integrate more intermittent renewable sources like solar and wind. SLBs can support grid reliability by providing essential services such as [2]:

a) **Power Smoothing:** Mitigating the variability of renewable generation by stabilizing short-term fluctuations.

b) **Peak Shaving:** Reducing demand spikes during peak hours, which lowers grid strain and generation costs.

c) **Energy Arbitrage:** Enabling users to store electricity when prices are low and discharge when prices are high, improving economic viability.

d) **Frequency Regulation:** Maintaining grid frequency stability through fast response services, crucial in regions with high renewable penetration.

Their cost-effectiveness and environmental benefits make SLBs a valuable asset for advancing the sustainable energy infrastructures, provided technical challenges like degradation, state-of-health variability and system integration are addressed through robust battery management systems [2], [5], [8].

Table 2: Potential applications of second-life batteries.

Second Life Battery Applications	Residential	Commercial	Industrial
Renewables Integration	0-150 kWh	0-500 kWh	0-10MWh
Energy Arbitrage	0-60 kWh	0-500 kWh	-
Peak Load Shaving	0-60 kWh	500-4,500 kWh	0- 4 MWh
Back-up Power	0-40 kWh	0-700 kWh	0-4 MWh
Small Mobility Vehicles	0-15.3 kWh	0-8 kWh	11-25 kWh
EV Charging	0-20 kWh	0-1 MWh	0-5 MWh
Demand Response	-	0-2 MWh	0-4 MWh
Microgrid	0.02-2 MWh	2-6 MWh	6-20 MWh

2.2 SLB vs New Batteries: A Comparison

Second-life batteries present a compelling economic alternative to new lithium-ion batteries, with estimated costs between 90–105 $/kWh nearly 50% lower than new LIBs, which average around 209 $/kWh. This cost advantage makes SLBs particularly attractive for stationary energy storage applications. However, this benefit must be weighed against key challenges such as uncertain remaining useful life (RUL), variable performance, and additional refurbishment or testing costs [8]. However, as LIB prices continue to decline projected to reach 40–70 $/kWh by 2030 the economic advantage of SLBs may narrow. Cost estimates for SLBs range from 38–300 $/kWh depending on remaining capacity, chemistry, and intended use. Refurbishment adds 12–50 $/kWh, with disassembly and state of health (SoH) testing contributing significantly to cost [13]. SLBs also ease the integration of renewable energy sources (RES). Second-life battery energy storage systems (SLBESSs) offer similar performance to new systems at a fraction of the cost estimated at 31.7% in one study enabling broader RES adoption and affordable grid support as shown in Table 3, the data were summarized from [26]. They also increase the residual value of EVs. For example, the Nissan Leaf's battery was valued at $15,000, with $3,040 attributed to second-life applications [14]. However, early adopters may benefit less due to the rapid decline in battery prices (up to 70% since 2011). Battery costs have consistently dropped: from 732 $/kWh in 2013 to 151 $/kWh in 2022, with forecasts predicting 40–70 $/kWh by 2030 and 40–50 $/kWh by 2050 [13]. SLB prices vary widely from 38-300 $/kWh depending on remaining capacity, chemistry, and usage. Refurbishment adds 12–50 $/kWh, with SoH testing and disassembly accounting for up to 13% of costs. Studies suggest using cost-benefit frameworks to determine when refurbishing becomes less viable than recycling [13], [15].

Studies suggest implementing cost-benefit frameworks to determine the economic cut off for refurbishment versus recycling, as beyond certain thresholds, recycling becomes the more viable option [15]. The economic viability of SLBs is highly application dependent and influenced by factors including solar irradiance, local electricity tariffs, and control strategies. Simulation studies suggest that SLBs are profitable when procured and repurposed at less than 60% of the cost of new batteries, especially if advanced control algorithms are implemented to prolong lifespan. Without optimized control, new batteries often offer better returns unless SLBs are nearly cost-free [8]. Nevertheless, SLBs can achieve a benefit cost ratio ≥1 under favorable conditions and generate post automotive value, thereby reducing the total cost of electric vehicle ownership. From an environmental perspective, SLBs significantly reduce lifecycle emissions compared to new batteries. The global warming potential (GWP) of second-life battery applications varies depending on energy sources and use cases. First-use phases contribute consistently (~35,000 kg CO_2e over 10 years), while second-life emissions range widely for instance, as high as ~60,341 kg CO_2e for fossil-based island systems, but reduced by up to 32% in renewable-powered applications [16]. Notably, applications such as energy arbitrage increase GWP due to intensive cycling and energy losses, while renewable-integrated systems offer significant net reductions in emissions.

Battery chemistry and operating depth-of-discharge (DOD) greatly influence SLB feasibility. Energy-intensive use cases (e.g., arbitrage) demand stable chemistries; lithium titanate (LTO) anodes offer improved cycle stability and safety over graphite, although at lower energy density. Cathode materials such as lithium nickel manganese (NMC) offer high energy density, while lithium iron phosphate (LFP) and lithium manganese oxide (LMO) are safer but degrade faster. In contrast, applications with shallower cycling requirements (e.g., Renewable energy source-based systems) can accommodate both graphite and LTO chemistries effectively [16]. Life cycle assessments (LCAs) demonstrate that SLBs reduce the environmental burden of new battery manufacturing. Compared to lead acid (PbA) batteries, SLBs and new LIBs (LFP, NMC-811) exhibit higher round-trip efficiency (~97.5% vs. ~85.5%) and longer service life [31]. Moreover, reusing EV batteries can reduce global warming potential by 15–70%, metal depletion by over 30%, and conserve critical resources like lithium, cobalt, and nickel [5], [8]. LCA comparing SLBs, new LIBs, and internal combustion engine (ICE) vehicles across manufacturing, use, and disposal phases consistently show environmental benefits. In California, SLBs used for renewable energy integration could supply 15 TWh/year by 2050, avoiding 7 million metric tons of CO_2 emissions. Replacing gas peaker plants with SLB-based ESS yields benefits comparable to transitioning from ICE vehicles to plug-in hybrids [5]. SLBs support a circular battery economy, conserving lithium, cobalt, and nickel while reducing dependence on new mining. However, complete material recovery remains a challenge due to processing inefficiencies and surging demand. Effective policies and incentives are essential to encourage adoption, especially as high costs remain a barrier [8].

Table 3: Comparison between new battery vs SLB.

Parameters	1st life Battery	2nd life Battery
Battery chemistry of cathode	NMC111	NMC111
State of Health (SoH)	100%	70%
Capacity	14.4 kWh	14.4 kWh
Number of modules	6	9
Weight	162 kg	231.43 kg
Lifespan (until capacity = 8.7 kWh)	2934 cycles	3739 cycles

2.3 Technical Challenges of SLBs

Second-life batteries (SLBs) offer a sustainable and economical energy storage option but face technical hurdles due to degradation from initial EV use. Common issues include reduced capacity, thermal instability, and cell imbalance, which affect safety and reliability. Pack-level differences and integration of varied cells require accurate SoH data and cost-effective maintenance strategies [7]. Challenges include diverse chemistries, uncertain SoH, and lack of standardized testing, worsened by unpredictable new battery prices. Solutions proposed involve fast, non-invasive diagnostics, standardized protocols, and second-life-optimized battery designs. Tools like battery passports can improve traceability and reuse safety. Defining battery end-of-life remains complex and should rely on measurable BMS-based or simple external methods. Accurate SoH estimation is essential for safe repurposing [13], [17]. Though some aged batteries may still power low-demand vehicles, "second life" typically refers to non-automotive storage applications. SLB system design is complicated by variation in size, chemistry, and degradation. Imbalances in resistance, capacity, or self-discharge reduce performance and challenge traditional balancing. Aged Li-ion batteries may be thermally safer under moderate charging e.g., 68% capacity cells are less flammable than 92.5% ones—but this adds complexity to system design. While safety standards like UL 1974 and IEC 62933-5-3 exist, they lack chemistry-specific guidance, emphasizing the need for more detailed assessment protocols [13].

2.3.1 SLBs Aging Mechanisms

Battery aging is driven by several key factors, notably the degradation, remaining useful life (RUL), state of charge (SOC), depth of discharge, and state of health as shown in Fig. 2. SOC and DOD indicate a battery's usage and remaining capacity, and maintaining them within safe limits can slow degradation. However, repeated charge/discharge cycles accelerate wear and reduce capacity. SOH reflects the battery's condition relative to its original state, and it declines as chemical and mechanical changes occur during cycling [18].

a) Degradation: Degradation is a natural process involving electrode damage and electrolyte breakdown further lowers SOH and shortens the battery's remaining useful life (RUL), which estimates its functional time left [18]. Understanding battery degradation is essential for estimating state of health. Usage patterns vary widely between users and are often confidential, making SoH prediction for SLBs challenging. Limited access to historical data requires establishing reliable correlations between degradation and minimal available data. As shown in Fig. 3, key ageing factors include: phase transitions in electrode materials, decline in electrode reaction kinetics, electrolyte decomposition, formation of the SEI (solid electrolyte interphase) layer. In NMC batteries, lithium-ion movement is disrupted by SEI growth and electrolyte contamination, leading to capacity loss and reduced electrochemical performance [19]. Key degradation mechanisms include:

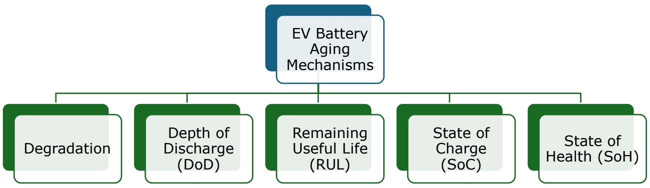

Figure 2: Key factors influencing SLB aging.

1) SEI Layer Growth: A passivating layer forms between the electrode and electrolyte, reducing battery capacity over time as shown in Fig. 3. This growth occurs via solvent diffusion, electron conduction, and lithium-ion diffusion, all contributing to performance loss [2]. The solid SEI layer forms on the anode during early cycling. It traps lithium-ions, decreasing capacity and increasing resistance. With aging, the SEI thickens and can reach the separator, risking internal short circuits. SLBs often lack SEI history, complicating SoH estimation [19].

2) Lithium Plating: Occurs mainly during fast charging or low temperatures, where lithium deposits on the anode instead of intercalating, reducing battery life [2]. This forms dendrites, which may pierce the separator and create short circuits. Lithium plating reduces usable capacity and worsens battery safety and performance [19].

3) Particle Fracture: Mechanical stress from volume changes during cycling leads to fractures in electrode particles, disrupting electrical connectivity and degrading capacity [2]. Cracks develop in electrode particles due to stress from cycling and SEI growth. These cracks block lithium-ion flow and reduce the number of active particles. Over time, this leads to performance drop and capacity fade. Dead lithium zones intensify the problem in aged cells [19].

b) Depth of Discharge (DOD): DOD refers to how much energy has been used from the battery. For example, using 80 kWh from a 100-kWh battery equals 80% DOD. Lower DOD levels help preserve battery health and extend overall lifespan [18].

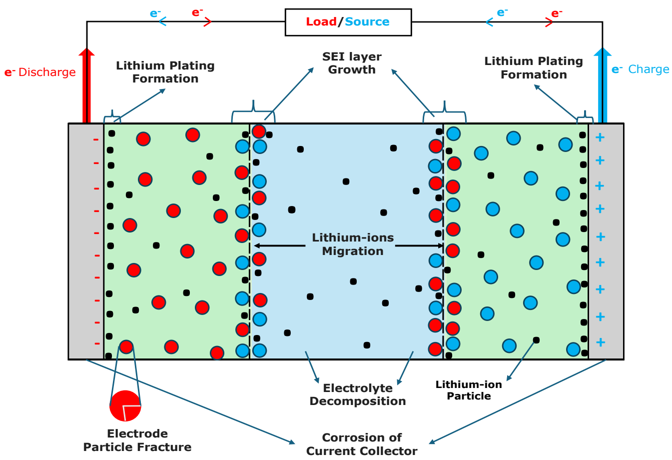

Figure 3: Cross-sectional view of SLB architecture.

c) Remaining Useful Life (RUL): RUL estimates how much operational time is left before a battery requires replacement. Since lithium-ion batteries degrade with each charge cycle, accurate RUL prediction is essential for performance planning and cost-effective battery use in applications like EVs, smart grids, and renewable energy systems [18].

2.3.2 SOC and SOH Estimation

SOC represents the ratio of a battery's current charge to its full capacity. It is critical for estimating available energy and is a core parameter managed by the BMS. Accurate SOC monitoring ensures efficient operation and is key to maximizing battery lifespan [18]. A comparative review of balancing strategies for second-life batteries highlights trade-offs in cost, complexity, and performance. Passive Equalizers (PEQ) are simple and economical, suitable for batteries with >80% capacity. bilevel equalizers (BEQ), combining PEQ and active equalizers (AEQ), provide better efficiency for second-life use. While active balancing is more complex and costly, it reduces aging and improves capacity retention. Advanced methods such as DC/DC-based balancing, electro-thermal optimization, 3D thermal monitoring, and AI-driven capacity estimation offer improved management of heterogeneous cells. Other innovations include modular reconfiguration, dual-level charging, and ripple-cancellation systems. However, most techniques require further validation, particularly in large, diverse battery packs [7].

A core technical challenge in repurposing EV batteries is accurately estimating the state of health, which reflects a battery's remaining capacity and performance. SoH is affected by factors such as C-rate, temperature, internal resistance (IR), and open-circuit voltage (OCV), all of which vary with EV usage patterns. While EV manufacturers often use 80% of initial capacity as an end-of-life threshold, second-life applications may lower this to 40–60% depending on safety requirements, such as avoiding thermal runaway due to internal shorts as shown in Fig. 4 [19]. SoH estimation methods fall into three main categories: physics-based models, equivalent circuit models, and data-driven approaches. However, predicting future degradation in second-life batteries is difficult due to missing first-life usage data and nonlinear aging, especially near the aging knee point. Models like the Enhanced Single Particle Model (ESPM) help simulate long-term behavior, but validation remains a challenge. This is especially relevant as repurposes lack universal SoH thresholds and must develop their own criteria based on application safety and performance [2], [20]. The paper [19], highlights both experimental and computational, non-destructive SoH assessment techniques relevant to SLB evaluation. State of Health (SoH) can be defined using different parameters as shown in equation (1), (2) and (3):

A) Capacity-based SoH: Reflects how much charge the battery can hold compared to when it was new.

$$SoH = \frac{\text{Current capacity}}{\text{Nominal capacity}} \tag{1}$$

B) Internal Resistance (IR)-based SoH: Indicates how resistance has increased over time.

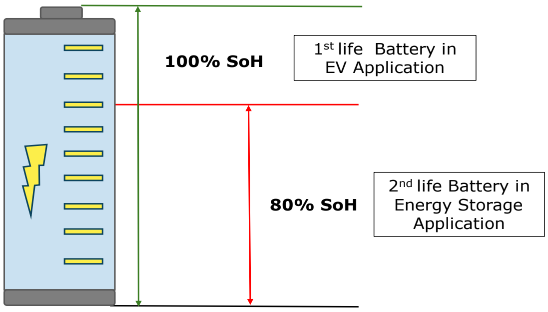

Figure 4: Comparative SoH roles in EV and ESS use cases.

$$SoH = \frac{EoL_{IR} - Now_{IR}}{EoL_{IR} - New_{IR}} \quad (2)$$

C) Electrolyte Concentration-based SoH: Indicates how electrolyte concentration changes over time.

$$SoH = \frac{Electrolyte_{currentbatteryconcentration}}{Electrolyte_{newbatteryconcentration}} \quad (3)$$

While capacity-based SoH is most common, IR and electrolyte changes also provide valuable health indicators. In the context of second-life batteries, SoH estimation is less explored and remains challenging. Accurate SoH measurement is critical for determining battery suitability in low-power applications. Repurposes must define upper and lower SoH limits and ensure reliable certification for second-life use as shown in Fig. 5 [19]. Other diagnostic techniques like Coulomb counting, incremental capacity analysis (ICA), and differential voltage analysis (DVA) help identify degradation mechanisms but may lack predictive capabilities. Electrochemical impedance spectroscopy (EIS), while accurate, is expensive and invasive, making it less practical for large-scale second-life applications [19]. Cloud-based systems and digital battery passports could help track first-life history, improving SoH estimation and matching batteries to appropriate uses [19], [20]. Currently, a standardized grading system for retired batteries is still developing. UL 1974 is emerging in North America, while companies like 4R Energy use A–D qualitative grades to sort batteries by degradation level [15]. Other Factors includes salt precipitation, current collector corrosion, and binder or separator failures. Battery degradation is nonlinear, typically starting slow and accelerating after a "knee point," where performance drops rapidly. Understanding the first-life usage profile is key to predicting second-life behavior [2]. However, large-scale SoH assessment remains a bottleneck for widespread adoption.

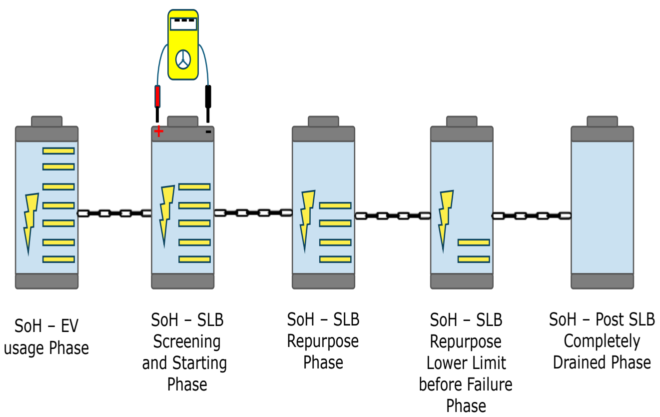

Figure 5: Battery SoH degradation from EV use to EoL.

Ultimately, accurate, scalable, and non-invasive SoH assessment, along with adaptive BMS, standardized protocols, and application-specific degradation models, are critical for safely deploying second-life batteries. Technical and economic uncertainty especially from missing usage data, inconsistent testing standards, and market variability continues to limit SLB adoption without stronger regulatory support and improved evaluation tools [8], [15], [19], [20]. A battery management system plays a critical role in controlling these parameters by balancing cells, regulating temperature, and preventing extreme conditions. By doing so, it enhances battery performance and extends lifespan crucial for both economic and environmental sustainability [18].

2.4 Role of BMS in SLB Integration

SLBs have diverse degradation profiles, requiring accurate, real-time state-of-health estimation [21]. A battery management system is vital for the safe, efficient, and reliable operation of second-life batteries, which often contain cells with varied conditions due to prior use. BMS monitors cell voltage, temperature, and state of charge, performs cell balancing, and ensures thermal safety by activating cooling or shutdown mechanisms when needed. It also estimates state of health, detects anomalies, and isolates faulty cells to prevent failures. Advanced BMS technologies enable remote monitoring, active balancing to address SOH differences, and integration with energy management systems. Key challenges in SLB BMS development include the need for predictive models that account for aging behavior, non-invasive fault detection methods, and optimization algorithms. Successful integration with renewable energy sources also requires handling power fluctuations and ensuring grid stability. To scale SLBs sustainably, efforts must address standardization, safety, lifecycle assessment, and user adaptability. Overcoming these technical and economic challenges will enhance SLB deployment in modern energy storage systems [2]. Accurate charge/discharge control and cell balancing by the BMS extend battery life, reduce replacement costs, and enhance EV performance and efficiency. Real-time monitoring of temperature, voltage, and current helps prevent overheating, short circuits, and enables fast, safe charging without harming battery health [22].

By maintaining optimal operating conditions, the BMS improves energy efficiency, lowering electricity use and indirectly reducing CO_2 emissions. In second-life applications, it enables safe and effective battery reuse in stationary storage, further decreasing environmental impact across the battery lifecycle [23]. The battery management system significantly contributes to the carbon footprint of battery pack production, mainly due to the use of printed wiring boards and aluminium casings. While essential for safe operation, the BMS also influences end-of-life treatment outcomes. Its design and materials impact both carbon footprint and recycling efficiency, underlining the need for BMS designs that support easier disassembly and second-life use. To further reduce environmental impacts, improving recycling efficiency, suppressing graphite combustion, and avoiding solvent-intensive processes (like NMP recovery) are recommended. Additionally, optimizing BMS design and developing harmonized testing standards will support more sustainable second-life battery systems [10]. Several studies have proposed BMS strategies for second-life batteries. One approach used a non-invasive method for parameter estimation and thermal balancing, though its applicability across battery chemistries remains limited. Another implemented an air-cooled system to reduce cell temperature variation, but its scalability is uncertain. Passive thermal control using DC resistance showed limited effectiveness. A low-cost BMS predicted key metrics from voltage, current, and temperature data, but struggled with nonlinear aging. A flexible controller was proposed to manage cell-level thermal inconsistencies, while another topology introduced self-healing via wear balancing, requiring robust electrical infrastructure. Overall, SLB BMS design must address varied cell conditions, detect faults accurately, and ensure safe, efficient operation [7].

Thermal management is a vital BMS function in second-life batteries, minimizing heat build-up and CO_2 emissions. Using sensors, control algorithms, and cooling methods (e.g., liquid or phase-change systems), BMS keeps temperatures within 15°C–35°C, preventing thermal runaway and degradation. This prolongs battery life, reduces replacements, and lowers manufacturing emissions. Advanced techniques like AI-based maintenance and nanomaterial cooling further boost efficiency, enhancing SLB reliability and sustainability across their extended lifecycle. [24]. Unlike traditional BMSs, SLB-tailored systems must offer advanced state-of-health (SOH) diagnostics, real-time monitoring, and adaptive control strategies under varying load and thermal conditions. Industry efforts like ReJoule's smart BMS and Relectrify's cell-level control show progress, but reliable online SOH estimation remains limited. Recent advancements use machine learning (e.g., neural networks, SVR, GPR) to outperform conventional models, though most are based on lab-aged data [21]. BMS-controlled cell balancing via passive or active methods ensures charge uniformity, minimizes overheating and thermal stress, and extends battery life while lowering CO_2 emissions [25]. Using BMS to repurpose full NMC-811 packs (~60% capacity) in wind energy storage shows significantly lower global warming potential (GWP) than new batteries. Life cycle analysis indicates SLBs with BMS emit just ~0.25 kg CO_2/kWh—441 kg CO_2 (LFP) and 181 kg CO_2 (NMC) in total—whereas poor BMS integration shortens life and raises emissions by 111–129 kg CO_2. Extending life to 10 years via BMS reduces emissions by 178–197 kg CO_2 [11]. Compared to immediate recycling, cascading use (EV → second-life ESS → recycling) enabled by BMS reduces CO_2 footprint by 8–17% and energy use by 2–6%, while decreasing ecotoxicity, acidity, human toxicity, and metal depletion by over 30% as shown in Table 4 [1], [10], [13]. Battery management systems are also essential for optimizing second-life battery performance. Model-based BMS, often supported by Kalman filters, are favored due to limited available data. These systems manage charge/discharge cycles, estimate state of health, predict remaining useful life (RUL), and reduce degradation through methods like Coulomb counting and adaptive filtering. Key goals include extended lifespan, high efficiency, and minimal energy loss [8]. Environmental life cycle assessments (LCA) show that reusing components especially battery casings and BMS can significantly cut environmental impacts. For instance, casing reuse reduces emissions during repurposing by 16%, and BMS reuse lowers impacts across multiple categories. End-of-life recycling also offers substantial benefits, with 13–77% impact reduction from cell and BMS processing. Designing batteries with second-life potential, including BMS reset functionality, enhances sustainability [5], [26].

Table 4: Environmental impacts of SLBs with and without BMS integration.

Parameters	With BMS	Without BMS
CO_2 emissions (10 year use)	~0.25 kg CO_2/kWh (net- 178 to 197 kg CO_2e over life)	+111 to +129 kg CO_2e
CO_2 reduction vs New battery	Up to 77% reduction	Negligible or even worse if battery fails early
GWP reduction vs Recycling	8-17% less GWP plus >30% reduction in toxicity, metal depletion	None- Immediate recycling may be better
Battery Lifetime in ESS	7-10 years	<2 years
Waste generation	Significantly reduced, fewer replacements and longer cycle	2-3 times more waste due to earlier failures
Component replacement threshold	Up to 50% component reuse still retains benefits	>50% replacement erodes environmental advantage
SoH/Thermal control	Enables active monitoring, balancing and thermal regulation	Lacking-Higher chance of overheating and fires
System safety and Stability	Safety operation through fault detection, balancing	Unsafe operation-leads to early disposal
Environmental benefit per kWh	High, low emissions and long life	Low or negative due to poor cycle life

3 Conclusion and Future work

The integration of advanced battery management systems is essential for unlocking the full potential of second-life batteries in stationary energy storage and grid applications. Through real-time monitoring, accurate SoH/SOC estimation, thermal regulation, and active cell balancing, BMS ensures operational safety, enhances performance, and extends battery lifespan. These functions contribute to lowering lifecycle greenhouse gas (GHG) emissions, improving energy efficiency, and reducing the environmental impact of battery production and disposal. This leads to significant reductions in lifecycle CO_2 emissions up to 123 kg CO_2e/kWh avoided compared to new battery production and lowers environmental impacts throughout the battery's lifecycle. Furthermore, lifecycle assessments confirm that BMS-enabled SLB repurposing especially whole-pack reuse offers significant economic and ecological advantages compared to immediate recycling or cell-level reuse. Despite these benefits, several technical and practical challenges remain. Future work should focus on developing robust, real-time SoH estimation algorithms tailored to the variable degradation profiles of SLBs. Designing modular and adaptable BMS architectures to support diverse SLB chemistries and configurations. Enhancing thermal management systems using AI, nanomaterials, and predictive modeling to handle fluctuating operating conditions. Establishing standardization protocols for SLB qualification, safety, and integration with renewable energy systems. Expanding open-access datasets and real-world testbeds to validate performance and degradation under dynamic use cases. Advancing BMS technology and supporting frameworks will be critical to ensuring the economic viability, safety, and sustainability of SLBs, ultimately contributing to global decarbonization targets and circular energy systems.

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