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Second Life EV Battery Degradation: A Techno-Economic Analysis

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Abstract

Batteries from Electric Vehicles often retain much of their capacity after they are considered at their end-of-life, so they can be transplanted instead to a different application. Studying the properties of these second-life batteries allows for more sustainable practices by introducing circularity in the life cycle of a battery. Investigating the degradation of SLBs gives crucial information regarding their lifespans, efficacy, and costs. This study examines the core parameters involved with SLB degradation namely state of charge, depth of discharge, C-Rate, solid electrolyte interphase, temperature, lithium plating, electrode decomposition and electrolyte conductivity. Then, technical, economic, and environmental analyses are performed to determine capacity fade, round-trip efficiency, and remaining cycling life. Considering our investigations, we then discuss the intricacies and required considerations involved with SLB use, thus providing stakeholders with practical knowledge regarding the benefits and cautions of integrating SLBs into infrastructure.

Keywords
Second Life battery; degradation; electric vehicle; lithium-ion battery.

1. Introduction
As the global adoption of electric vehicles (EVs) continues to increase, it is essential to tackle battery degradation to boost consumer confidence, support long-term sustainability, and guarantee the economic feasibility of electric mobility. Predictions made by Akram and Abdul-Kader (2021) indicate that the lithium-ion batteries (LIBs) used in these vehicles can function for as long as 12 years. As a result, millions of EV batteries will annually reach the end of their operational lifespans. Utilizing these batteries for a secondary life presents a more economical and environmentally friendly alternative compared to direct recycling them for material recovery. These retired batteries retain 70-80% of their storage capacity and can be repurposed for various applications, including area regulation, fast EV charging, self-consumption, microgrid, renewable energy (RE) system, residential and commercial building, and slow-moving transportation, among others (Akram and Abdul-Kader, 2024). Many important challenges exist that must be addressed considering these batteries and their various parameters, such as aging mechanisms, degradation, remaining capacity, remaining number of cycles, round trip efficiency, and remaining useful life (RUL).

Numerous factors influence a battery's performance and efficiency throughout its life cycle, indicating the remaining capacity of a battery at any given moment and the extent of its discharged capacity. Maintaining these factors within controlled limits aids in decelerating the battery degradation. The alternate method of reducing fast degradation and aging is optimal charging and discharging, which decelerates wear. State of Health (SOH) is a ratio between the current health of the storage system to its original health. The main factors that impact SOH are its internal mechanical and chemical processes within the battery. Degradation, a natural phenomenon of electrodes that leads to electrolyte decomposition, occurs when any battery is used (Edge et al., 2021).

So, besides many other drawbacks of degradation, the SOH of a battery is reduced along with its RUL. RUL estimates the remaining life of a battery and provides information about when replacement is necessary in a storage system. A Battery management system (BMS) is used to monitor the factors that degrade the battery, making it a crucial component. Among other factors, by managing the state of charge (SOC), controlling surrounding temperature, dynamic cells system, preventing critical condition, the BMS ensures all operating conditions are optimal to prolong the lifespan of the battery (Akram and Abdul-Kader, 2021). To analyze the technical, economic, and environmental viabilities of EVs, considering battery aging mechanisms is necessary. Four main factors of EV degradation are Capacity Loss, resulting from an interface layer produced from aging electrodes, Cyclable Lithium Loss , caused by the number of charging and discharging cycles that cause lithium depletion, Calendar Capacity Loss, due to internal mechanisms such as self-discharging and internal side reactions, and Aging Time, related to battery aging time specifically due to high temperature (Barre et al 2013).

A significant amount of research has been conducted on the degradation of new batteries; however, it is essential to understand the degradation behavior of second-life batteries (SLB) when utilized in stationary applications. This study concentrates on the factors that cause degradation of SLBs such as state of charge, depth of discharge, C-Rate, solid electrolyte interphase, temperature, lithium plating, electrode decomposition, and electrolyte conductivity. Also, we provide an analysis of capacity loss, cycling capacity loss, and round-trip efficiency reduction by utilizing data from published research, along with an analysis of the economic and environmental impact. The remaining sections of the paper are organized as follows: Section 2 presents the degradation mechanism of SLBs, Section 3 describes the technical analysis, Section 4 presents the economic and environmental analysis of SLBs, Section 5 presents the discussion, and Section 6 concludes whole work.

2. SLB Degradation Mechanism

Degradation refers to the process by which all LIBs experience a reduction in their lifespan. Each cycle of charging and discharging leads to the deterioration of battery components via a layer known as the Solid Electrolyte Interphase (SEI) that is usually developed on the surface of the battery electrodes. This growth results in increased internal resistance, thereby accelerating the overall decline in capacity. In Figure 1 the main factors that cause degradation, especially for SLBs, are shown.

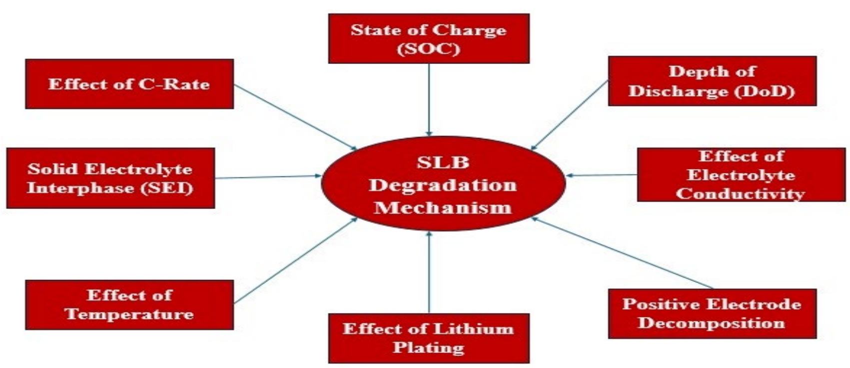

Figure 1. Factors Causing SLB Degradation

2.1 Effect of State of Charge (SOC)

The state of charge (SOC) at which a battery is kept influences its degradation. Maintaining a battery at a full 100% SOC leads to increased side reactions, which subsequently diminishes its capacity over time. Conversely, a battery maintained at a 0% SOC has demonstrated minimal capacity loss over a span of 12 months. Although electric vehicles (EVs) are not stored for extended durations, the average SOC can still fluctuate significantly (Wu et al., 2017).

2.2 Effect of Depth of Discharge (DOD)

The depth of discharge (DOD) is crucial in determining the degradation of batteries during their first life in EVs and their second life in stationary applications. In the context of battery lifetimes in EVs, the BMS does not monitor DOD. This factor remains not only untracked, but also shows considerable variability among different users, and inconsistency in individual usage patterns. Mathews et al. (2020) conducted a study on SLB and found that using a DOD of 65% and SOC ranging from 20% to 85% resulting in an increased battery degradation. On the other hand, operating the battery within the lower SOC range of 15% to 65%, resulting in a 50% DOD, helped reduce degradation. This is because staying within a lower SOC range puts less stress on the battery, which slows down degradation. The findings indicate that to extend the lifespan of a storage system, it is necessary to maintain the DOD for a SLB lower than for new batteries. It is advisable to maintain the battery's SOC above 20% and below 90% to avoid excessive depletion of the battery.

2.3 C- Rate of Battery

This parameter expresses the speed of battery charging and discharging considering the capacity of the battery, thus having a significant impact on the aging rate of LIBs. Elevated C-rates expose the battery to higher currents, resulting in increased internal heat production, mechanical stress on electrode materials, and hastened deterioration of the electrolyte and SEI layer. These consequences stimulate capacity loss and become a cause of increasing internal resistance and diminished overall life. Conversely, operating at lower C-rates typically fosters more stable electrochemical conditions, thereby decelerating aging processes and prolonging battery lifespan. Consequently, it is essential to manage C-rates effectively in applications that demand long-term battery performance and reliability (Gao et al., 2024).

2.4 Effect of Solid Electrolyte Interphase (SEI)

The solid electrolyte interphase (SEI) is vital in investigating the performance and deterioration of LIBs. Over time, the SEI may expand uncontrollably due to ongoing side reactions between the electrolyte and the electrode, which depletes active lithium and increases the thickness of the layer. This results in heightened internal resistance, diminished lithium-ion mobility, and a gradual decline in capacity. Furthermore, mechanical stress from repeated cycling can cause cracks in the SEI, revealing new electrode surfaces and prompting additional SEI formation, which further accelerates degradation. Consequently, it is crucial to manage SEI stability to enhance battery longevity and efficiency (Sordi et al., 2025).

2.5 Effect of Temperature

Degradation is also linked to the surrounding temperature. Research indicates that at a high temperature, the rate of internal side reactions increases and leads to a loss of cyclable lithium, causing a decline in capacity over time. Conversely, lower storage temperatures can decelerate the diffusion rate, potentially resulting in lithium plating, a metallic process occurring in the anode of a battery, which subsequently contributes to capacity loss (Hossain et al., 2019). Furthermore, storage temperature influences the self-discharge rate of the battery, which typically ranges from 1% to 3% per month when stored at approximately normal temperature of the battery i.e. 20 ◦C. On the other hand, it increases exponentially at the high temperatures of the battery (Moreira et al., 2021). In terms of battery performance, the most significant capacity degradation over cycles has been observed at lower operating temperatures. EVs are designed considering thermal and battery management systems to alleviate these impacts by maintaining an optimal range of temperature for LIBs, between −20 ◦C and 60 ◦C (Met et al., 2018).

2.6 Degradation Effect of Lithium Plating

A significant factor contributing to the degradation of LIB is lithium plating, particularly under low temperature and overcharging. This phenomenon occurs when there is a decrease in lithium ions, leading to their deposition on the anode surface as metallic lithium rather than intercalating into the graphite structure. As a result of this process, the amount of active lithium diminishes, which leads to a loss of capacity, an increase in internal resistance, and poses safety risks. The growth of this SEI can lead to electrical isolation of residual lithium, known as 'dead lithium', which is irreversible. Similarly, the increased SEI formation and the presence of dead lithium significantly reduce the lithium catalogue and lessen conductivity due to pore obstruction (Edge et al., 2021).

2.7 Effect of Positive Electrode Decomposition

The degradation of positive electrodes is significantly influenced by their chemical composition. At present, different transition-metal oxide materials are widely used as cathodes in LIBs. These include layered oxides (e.g., $LiCoO_2$ and $LiNixMnyCozO_2$, commonly known as NMC), spinel-structured oxides such as $LiMn_2O_4$, and polyanion-based oxides like $LiFePO_4$. NMC materials can exhibit considerable variation in their composition, with differing proportions of metals such as nickel, manganese, and cobalt that are used in cell compositions. Each material has distinct characteristics that critically affect the aging and degradation of the positive electrode. The primary mechanisms of degradation in the aforementioned NMC layer can be expressed as follows: first phase transformation, oxidation of lattice hydrogen, decomposition and loss of the electrolyte, exchange of transition metal/Li+ sites, and acid corrosion (Li et al., 2018).

2.8 Effect of Electrolyte Conductivity

The conductivity of electrolytes is observed to diminish linearly with the number of cycles. It can be inferred that there is notable consumption. Electrolyte conductivity tends to decrease progressively with cycling. This pattern of decline suggests that a significant percentage of the electrolyte is consumed primarily due to the development of SEI or through gas generation. So, in this way the SEI is anticipated to develop in all cells, albeit at varying rates and with differing characteristics. Additionally, the decomposition of the electrolyte contributes significantly to the increase in impedance and the overpotentials during discharge (Strauss et al., 2020).

3. Technical Analysis of SLB

The degradation of LIBs can be characterized through three levels of detail: physical, chemical, and mechanical. Degradation mechanisms describe the underlying physical, mechanical and chemical changes that occur inside a battery cell. Although they offer the most complete understanding of aging, these processes are often difficult to directly observe during real-time operation. Instead, what can be monitored are their outcomes, such as reduced capacity, lower power delivery, cycling inefficiencies, and a drop in round-trip efficiency. Capacity fade reflects the gradual loss of usable energy storage, whereas power fade corresponds to the decline in the cell's ability to supply high output power (Akram and Abdul-Kader, 2025)

The concept of cycling loss pertains to the cumulative number of cycles a battery has diminished over its lifetime round trip efficiency denotes the performance degradation of an SLB. These observable consequences represent the least detailed perspective on degradation, although they are still considered simplified to quantify it. Thus, the practical analysis of cell degradation usually considers a battery's capacity fade, its efficiency (round-trip), and primarily cycling loss.

3.1 Capacity Degradation of SLB

The phenomenon of capacity degradation in LIBs pertains to the gradual decline in the battery capability to store and deliver charges throughout numerous charge discharge cycles. This deterioration arises from several factors, such as the development of a SEI layer on the anode, lithium plating, structural damage to the electro materials, and the decomposition of the electrolyte (Lianpo et al., 2025). These mechanisms deplete active lithium and hinder ion mobility, leading to a reduction in the battery capacity and efficiency. Extreme temperatures, elevated charging rates, and deep discharges can expedite capacity fade, thereby affecting the overall performance and longevity of the battery (Edge et al., 2021). The capacity fade loss for an SLB is 1.8% per year as stated by Argue (2025). Thus, when a battery is retired from an EV it has 80% SOH, and we can calculate capacity loss of an SLB at time (t) by using Equation (1). Figure 2 presents the trend of this equation for a duration of 15 years.

$$\text{Capacity of ESS at } (t) = (\text{SLB Initial SOH}) - (1.8 \times t) \qquad (1)$$

Where:

Initial SOH of SLB = 80%
Capacity Loss =1.8% per year
Life Span of SLB = 15 years

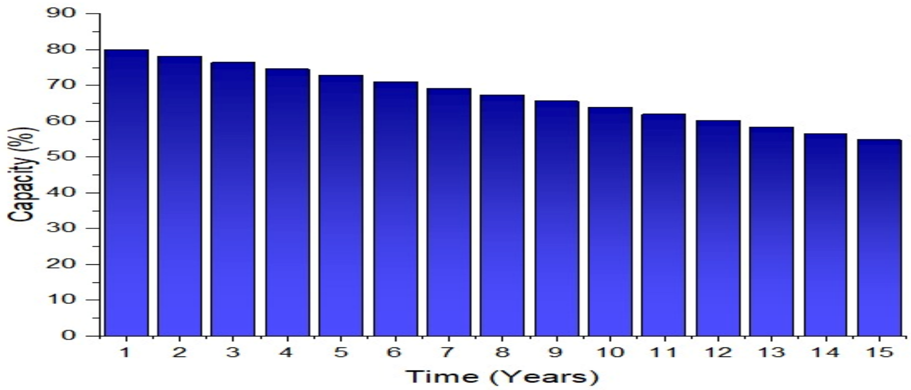

Figure 2. Capacity Loss of SLB

3.2 Cycles Loss of SLB

The cycle of an LIB encompasses a full charge and discharge process, wherein lithium ions migrate from the anode to the cathode during discharge and return from the cathode to the anode during charging. Each cycle results in a slight degradation of the battery due to physical and chemical alterations within the cells, including electrode wear and side reactions. Several factors, such as temperature, DOD, charge rate, and overall battery management, affect the number of effective cycles a battery can deliver (Fan et al., 2023). According to Geo et al. (2024), a new EV battery has a cycle count between 1500 and 2500, and when using these batteries in second life applications, they can run approximately two thousand cycles, with a cycling loss of these SLBs being 2% per year. By using equation (2) we can calculate the remaining number of cycles of an SLB for a span of 15 years, presented in Figure 3.

$$\text{SLB Remaining Number of Cycles} = (\text{SLB Initial Number of Cycles}) - (0.02 \times t) \qquad (2)$$

Where:

Initial Number of Cycles of SLB = 2000 cycles
Cycling Loss = 2% per year
Lifetime of SLB = 15 years

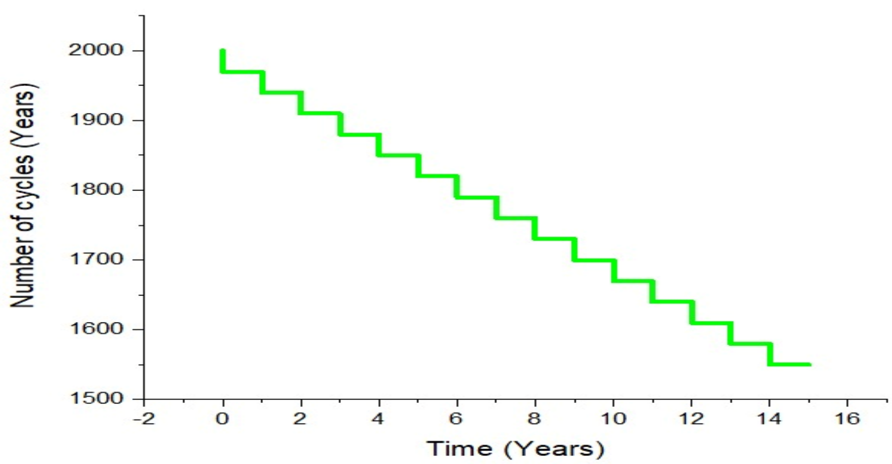

Figure 3. Remaining Number of Cycles of SLB

3.3 Round Trip Efficiency Loss

The round-trip efficiency of an LIB describes how much of the energy stored during charging can be recovered during discharge, typically expressed as a percentage. This metric evaluates the battery's effectiveness in storing and delivering energy, while considering losses from internal resistance, heat production, and side reactions. Adhering to appropriate charging methods and functioning within ideal temperature ranges can aid in maintaining this efficiency over time (Ma et al., 2018). The initial efficiency of an SLB is between 80% and 90%, with an annual efficiency loss of 0.86% (Beckers et al., 2024). By using these values, we can calculate the roundtrip efficiency loss of an SLB by using Equation 3 resulting in the graph shown in Figure 4.

$$\text{Efficiency at any time } \eta(t) = (\text{SLB Initial Efficiency}) - (0.86 \times t) \quad (3)$$

Where:

SLB Initial efficiency = 80% per year
Round trip efficiency Los =0.86%
Lifetime of SLB = 15 years

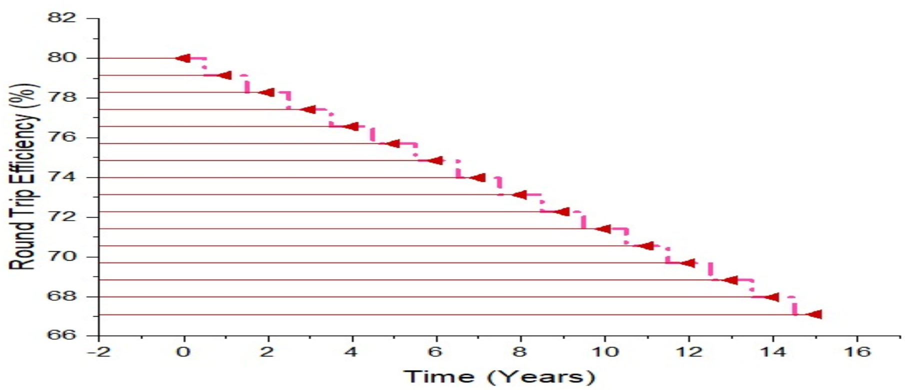

Figure 4. Round Trip Efficiency Loss of SLB

3.4 Performance of SLB Pack

The performance of battery packs varies considerably based on their aging condition, with significant distinctions between new batteries and SLBs. New battery packs generally demonstrate optimal capacity, high round-trip efficiency, and low internal resistance, which guarantees robust performance in energy storage applications. SLBs, however, are reused after their initial deployment in EVs and have experienced some degradation, leading to diminished capacity, heightened internal resistance, and possible inconsistencies in cell performance (Lianpo et al., 2025) Nevertheless, despite these drawbacks, SLBs can still provide dependable performance in less energy demanding stationary storage applications, such as load shifting or backup power, where high energy density is not as crucial. It is essential to thoroughly assess performance across various aging states to appropriately align battery packs with suitable applications, thereby ensuring both technical feasibility and economic efficiency throughout their second life. (Akram and Abdul-Kader (2025). Table 1 below presents the performance of new batteries and SLB at different states.

Table 1. Specification of SLB and New EV Battery

Parameters	Lithium-ion Battery New	Second Life EV Battery	Sources
State of Health (SOH)	Typically, close to 100% at the beginning of use	Around 75–80% at the start of second-life phase	(Neigum and Wang, 2024)
Round-trip Efficiency Degradation	Efficiency drops estimated at ~0.86% annually	Similar yearly reduction of ~0.86%	(Beckers et al., 2024)

Capacity Loss per 1000 Cycles	About 6–12% reduction after 1000 charge/discharge cycles	About 1.5% loss over the same number of cycles	(Gao et al., 2024)
Annual Capacity Decrease	Typically 1.5–2.5% per year	Around 1.5% per year	(Gao et al., 2024)
Internal Impedance	Average impedance ~1 mΩ	Ranges between 1.5–3.0 mΩ	(Gao et al., 2024)
Cycle Life Expectancy	1500–2500 cycles depending on usage	Around 2000 cycles	(Akram and Abdul-Kader, 2025)
Lifetime	Usually 10–15 years	10-15 years	(Akram and Abdul-Kader, 2025)
Efficiency	Ranged 77–85%	70–80%	May et al., 2018
CO2 Emission	Usually very High	Low	May et al., 2018
Cost	High	Low	(Mongird et al., 2019)

3.5 Pack Degradation Categories

In North America, the evaluation and categorization of EV batteries for second-life use follows the UL 1974 standard (Evaluation for Repurposing Batteries) (UL, 1974; 2018). A practical example can be seen at 4R Energy Corporation, a joint venture between Nissan and Sumitomo Corporation recognized as a pioneer in SLB technology. They classify end-of-life (EOL) Nissan LEAF batteries into four groups:

- **Category A:** Batteries with little to no degradation, suitable for reuse in electric vehicles.
- **Category B:** Batteries that show moderate aging but remain viable for most stationary storage applications.
- **Category C:** Heavily degraded batteries that can still provide service, typically in low demand uses such as emergency backup power (Hill, 2021).
- **Category D:** Units that are no longer safe or effective for reuse and are directed toward recycling.

Although this approach by 4R Energy is qualitative in nature, it provides a useful baseline for grading. Moving forward, the key challenge lies in scaling up quantitative SOH testing from individual cells to full battery packs, which would enable a more precise and industry-wide standardized framework.

4. Economic Analysis of Second Life Battery

Reusing an EV battery can enhance its longevity, defer recycling expenses, and minimize immediate resource consumption, all of which offer potential advantages.

4.1 Cost Analysis of New and SLB

The initial expense of an Energy Storage System (ESS) is a crucial factor in any application. Mathews et al., (2020) present some results about SLB investment costs, indicating that the investment cost of an SLB is 104.5 USD/kWh, while the investment cost of new batteries is 209 USD/kWh. Moreira et al (2021) reported a cost for SLBs at about 90 USD/kWh. Like LIBs, the pricing of SLBs varies significantly in literature. Nevertheless, additional factors must be considered, including RUL, performance, maintenance, testing and refurbishment, which are more challenging to quantify. Another issue with SLBs is that their economic viability may vary depending on the application, akin to new batteries. Kamath et al. (2020) highlighted in his study that the financial viability of adding battery storage to a solar array is mainly dependent on some local factors such as solar irradiance levels and the energy tariff structures of utilities. Thus, using SLBs can facilitate an additional economic return which would otherwise be lost if these batteries were simply wasted. In this way, this reuse option can benefit EV owners as well, since the resale or reuse value of retired batteries effectively lowers the total ownership cost of the vehicle.

One major challenge in this context is examining the RUL of SLBs, as it is influenced by some factors such as the EOL and capacity threshold chosen. Since SLBs often show more stable degradation patterns than new batteries, their RUL can appear longer when measured against the same EOL capacity benchmark. For instance, Mathews et al.

(2020) demonstrated that reducing the EOL capacity criterion from 70% to 60% of the original capacity extended the RUL of a new battery from 11.4 years to 17.3 years. On the other hand, for SLBs, the RUL noticed an improvement from 5.1 years to 11 years.

4.2 Refurbishing Cost of SLB

The refurbishment of EV batteries is often a lengthy, laborious, and multi-step process. It typically involves the return of used packs, followed by some inspection, battery disassembly, recycling of unusable parts, and detailed testing of modules and their cells. After detailed sorting and classification, the components are rearranged and reassembled into a functional SLB. A major challenge in this process is the lack of international standardized procedures, which leads to significant variations between battery packs. Additionally, some other challenges such as differences in cell design, levels of dismantling required, and module interconnections all contribute to the complexity and time involved in refurbishment (Gu et al., 2024)

Consequently, the process necessitates manual execution, which considerably escalates both the costs and time required due to the extra labor involved. Similarly, the costs associated with renewing are comprised of the purchase of the battery, labor for the disassembly and reassembly of the battery parts, administrative costs, packing materials, and transportation. Notably, transportation costs constitute only approximately 2% of the total refurbishing expenses. The literature presents a wide range of costs per cell or kilowatt-hour, rendering it challenging to ascertain the economic viability of SLBs within respective design processes, with estimated costs that ranged from approximately 18 USD/kWh to 140 USD/kWh (Ambrose et al., 2014). Hossain et al., (2019) reported that the refurbishing costs of an SLB typically fall within the range of 15 USD/kWh to 62 USD/kWh

4.3 Environmental Analysis of SLB

At the end of their first life cycle, batteries generally face three possible pathways: disposal, recycling, or reuse. According to Philippot et al. (2022), around 185 GWh of EOL battery capacity is expected to be available by 2030. Ambrose et al. (2014) estimated that this capacity, under conservative assumptions of 879 kWh per household annually, could potentially support about 35 million household microgrid systems. This suggests that simply discarding or even recycling such batteries immediately after their initial use is an inefficient and less sustainable approach. Similarly, improper disposal in landfills contributes to environmental pollution, including water acidification, eutrophication, and photochemical smog, which in turn can disrupt ecosystems and harm species reproduction. On the other hand, studies have shown that SLBs used as energy storage systems (ESS) can cut peak demand emissions by up to 56% (Ahmadi et al., 2014) while also reducing pressure on the production of new LIBs. This postpones the need for additional raw material extraction. With each kWh of lithium battery production linked to an estimated 70 kg CO_2 emissions and around 2 million liters of water consumed per ton of lithium extracted, extending battery use into a second life provides significant environmental benefits. Nonetheless, EOL management remains a challenge for our ecosystem, as only around 5% of batteries worldwide are currently recycled (Lakshmi et al., 2023).

5. Discussion

When employing SLB in stationary applications, it is crucial to consider a variety of factors, including operational safety, post-EOL assessment, and precise evaluation of SOH. These EOL electric vehicle batteries must go through testing procedures, which include visual inspection and detailed pack-level characterization. In the following subsection, we will discuss all these factors in detail.

5.1 Key Considerations for SLB Reuse

Retired EV batteries are required to undergo a comprehensive series of tests to verify their suitability for second life applications. In certain instances, entire battery packs may be repurposed for second life applications; however, this may necessitate new requirements that demand the reconfiguration of the pack. Consequently, additional processes may be involved, such as the disassembly of the battery pack, cell selection, and reconfiguration.

5.1.1 SLB Operational Safety Criteria

The robustness of systems, which is fundamentally connected to safety, represents a significant consideration. Effectively navigating the possible risks arising from an SLB market scarce with regulation is crucial for its success; thus, repurposed batteries need to adhere to rigorous standards to guarantee safe operation. Such standards generally encompass legal outlines for SLB operation, handling, transportation, and storage to reduce risks related to flammability, chemical leakage, and other possible dangers. It is essential to develop and update regulations and testing standards (Yu et al., 2025), and various agencies across the globe, along with private-sector coalitions, including OEMs and SLB companies, are actively engaged in establishing industry-wide safety standards for SLBs. These standards will fundamentally categorize batteries according to their ability to perform both overall, and with respect to their intended application, thereby fostering transparency in product supply and market demand.

5.1.2 Post End-of-Life Battery Assessment

In the post end of life battery assessment, the initial step involves removing the battery from the EV chassis, followed by evaluating the battery packs suitability for repurposing. The procedures may differ depending on the specific case; however, this assessment generally encompasses the following:

a. A visual inspection for any damage.
b. Verification of functionality during both charge and discharge cycles.
c. Comprehensive battery-pack-level characterization.

The outcomes of the battery assessment after EOL are utilized to ascertain the battery pack's appropriateness for deployment in second life applications. Should the battery pack successfully pass this assessment, further tests on SOH will be performed to enhance its deployment. Conversely, if it does not pass the battery assessment, further disassembly will take place to evaluate the pack's individual modules' health, or in more severe instances, the individual cells themselves within each module. The objective is to reuse the maximum number of modules and/or cells from the pack as feasible, while acknowledging that some may be too degraded for any benefit for repurposing in different applications (Patel et al., 2023)

5.1.3 Monitoring and Assessing SOH

The SLB sector has a well-defined procedure, where all battery packs, after successfully completing the post EOL battery evaluation, proceed to additional SOH testing to find the best fit of using. The diverse array of repurposing results in significantly varying requirements. Furthermore, each battery possesses a distinct SOH state, considering all possible degradation mechanisms and the spectrum of operational conditions it may have encountered during its initial life. As a result, optimizing battery selection for a specific second life application is quite intricate. SOH assessment techniques must be capable of providing a thorough overview of anticipated efficacy (considering capacity fade and power fade), all while identifying any potential concerns, most importantly those involved with safety and thermal runaway (Li et al., 2025).

5.1.4 Battery Packs Disassembly

When a battery pack is considered unfit for reuse directly, whether because of degradation, safety concerns, or specific application requirements, it may undergo refurbishment to varying extents. Replacing unfit cells, increasing the system with more battery packs, or disassembling the pack entirely are all possible processes that may be involved. Disassembly involves extracting a variety of parts, including the pack cover, the BMS, electronic and thermal management components, and modules and cells (Lander et al., 2023). Currently, battery disassembly processes have been called into question, such as the disassembly inefficiencies involved with the wide range of structural components and pack designs including robust adhesives and welding. Enhancing and expediting the disassembly process is crucial to managing the anticipated influx of EOL batteries in the coming years. Other design strategies, such as clip fasteners or easily separable tapes, as well as battery pack standardization, may address these challenges. Automation of battery disassembly represents a significant advancement towards achieving a process that is time-efficient and cost-effective

5.2 Approach to Extend Life of SLB

Initially, the range of operational voltage must be established between 3.0V and 4.05V, which is 80% DOD. If the SOH falls under 60%, the range should be reduced further to 3.0V and 4.0V, i.e. 70% DOD. Furthermore, one must maintain battery temperature below 30◦C, and ideally between 15◦C and 25◦C. Although the battery can function at even lower temperatures, such as 10◦C, it is necessary to reduce the current and charging voltage to avoid lithium plating. Moreover, the maximum current should not exceed 0.2C, and the maximum peak current must remain at or below 0.3C. Additionally, it is crucial for the batteries to be utilized daily to preserve their material activity. One should avoid extended periods of inactivity (months) to reduce material activity loss and calendar aging. Furthermore, careful SOC and storage management extended durations of non-use can also help alleviate the impacts of calendar aging (Geo et al., 2024).

5.3 Challenges

Repurposing batteries is a cost-effective and sustainable option with the rising demand for energy storage solutions. Further research and experimentation in battery second life applications can result in increased efficiency, decreased environmental impact, and wider acceptance of sustainability in energy storage solutions. However, major challenges exist regarding the engineering, economics, and regulations around SLBs, and insights between manufacturers, researchers, and stakeholders are required to address these concerns, and ultimately establish battery repurposing standards and best practices across the industry. This would then allow for consistency, interoperability, and safety across many sectors and applications. The following sections outline areas that can be optimized to improve SLB usage (Das, 2025)

5.3.1 Evaluating Battery Usability Limits

The EOL assessment for a LIB that is based on current SOH criteria lacks universal consensus, with differing opinions on the precise threshold. The 80% capacity fade criterion is frequently employed in the current automotive industry; however, there is a persistent discussion regarding the necessity for its re-evaluation, especially given the rapid progress in LIB technology that has resulted in batteries exhibiting enhanced degradation characteristics and extended lifespans (Tang et al., 2025). These technological advancements could potentially make the criterion obsolete or excessively cautious for certain battery chemistries. Furthermore, as various repurpose applications can accommodate lower quantities for SOH without substantial detriment to safety or performance, it is crucial to reassess this threshold to fully optimize the capabilities of a battery.

5.3.2 From Waste to Resource: Circular Approaches

The economics surrounding of SLB involve a delicate balance between the profit margins that are comparable to new LIB, the additional refurbishment costs, and the competition posed by recycling. For SLBs to achieve full economic viability, it is essential that the costs associated with refurbishment and logistics, including transportation and collection, are reduced. Nevertheless, the overall costs are heavily influenced by future advancements in technology, policy changes, and market trends, making them challenging to forecast at this early stage. A more thorough evaluation is required to determine if the economic and environmental advantages of repurposing SLBs surpass the advantages of prolonging the battery's initial life, either by lowering the EOL criterion from 80%, by enhancing battery technology, or by pipelining EOL batteries directly to recycling for the recovery of valuable materials (Akram and Abdul-Kader, 2023).

5.3.3 Cell and Pack Design Structures

It is imperative to design battery packs considering EOL requirements, a practice called eco-design or "Design for Disassembly." Reversible fastening mechanisms reduce times for disassembly, and modularization of battery pack configurations assist with cell or module replacement, thus extending overall battery lifespan and enhancing refurbishment, repurposing, and recycling processes. Furthermore, standardizing battery interfaces and communication protocols allow SLBs to be better integrated into many battery storage systems without needing to consider specific chemistry or the original manufacturer (Patel et al., 2023).

5.3.4 Policies and Regulations

North American governments have predominantly failed to align their policies to facilitate even battery recycling, much less the reuse of secondary batteries. In contrast, while North American governments have been sluggish in supporting the swiftly growing EOL battery supply chain, European and Asian governments have already established policies, objectives, and guidelines for battery recycling and reuse. If support opportunities do not increase, Canada may find itself lagging in this competitive emerging industry. China has started to take the lead in EV markets and is at the forefront of policies regarding EOL batteries and the management of battery recycling (Carey et al., 2023).

6. Conclusion

We have examined SLB degradation with respect to eight core parameters, namely, SOC, DOD, C-Rate, Solid Electrolyte Interphase, Temperature, Lithium Plating, Electrode Decomposition and Electrolyte Conductivity. Using these mechanisms to understand the nuances of degradation, we use data from published research regarding capacity fade, round-trip efficiency, and remaining cycling life to analyze SLBs with respect to their technical capability, economic benefit, and environmental impact. If we consider a default end-of-life battery to have 80% capacity, 2000 number of cycles, 80% round-trip efficiency, our findings show that in 15 years of use, the battery will degrade to 53% capacity, 1550 number of cycles, and 67.1% round-trip efficiency. Our cost analysis further expands on the economic feasibility of using SLBs as opposed to new batteries, considering refurbishing costs. We finally discuss the many nuances that come with SLB use to grant practical insights to stakeholders, such as ideas on their effective use, means to most optimally utilize them, drawbacks and cautions to consider, and thoughts on how to encourage their use through policy.

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