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Second-Life Battery Energy Storage Solutions for Charging Infrastructure: A SWOT-based Review

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Executive Summary

The rise of electric vehicles and increasing demand for energy storage have created a growing opportunity for second-life batteries—repurposed lithium-ion batteries retired from electric vehicles. Second-life batteries help reduce waste and conserve resources. These second-life battery energy storage systems (SLBESS) offer a cost-effective, reliable means of supporting charging infrastructure through improved renewable energy integration and grid stability. Despite their potential, significant research gaps remain, particularly around regulatory barriers, market feasibility, and long-term performance. A focused SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a structured approach to identify and synthesize the key factors influencing the adoption of SLBESS, addressing a lack of strategic assessments in existing literature. This paper presents a SWOT analysis of using SLBESS for improving charging infrastructure. It identifies strengths such as cost savings; weaknesses including policy barriers; opportunities in renewable energy; and threats from market volatility. The analysis concludes with strategic recommendations—including standardization, policy support, and industry collaboration—to advance the SLBESS adoption.

Keywords: Second-life batteries, energy storage systems, circular economy, lithium-ion batteries, SWOT analysis

1 Introduction

The transition toward clean energy and sustainable transportation is accelerating, with electric vehicles (EVs) and renewable energy systems driving significant change. Central to this shift is the widespread deployment of lithium-ion batteries (LIBs), which, after losing about 20–30% of their original capacity, become unsuitable for automotive use but retain substantial potential for secondary applications [1]. Rather than recycling or discarding these batteries, second-life battery energy storage systems (SLBESS) are emerging as viable solutions, repurposing them for stationary energy storage applications [3,5]. As EVs adoption accelerates, the demand for robust and scalable charging infrastructure becomes increasingly critical. However, grid limitations, peak demand spikes, and insufficient energy storage pose significant challenges to deploying fast-charging stations at scale. SLBESS offers a promising solution by enabling local energy buffering and load leveling, thereby alleviating pressure on the grid and supporting the deployment of rapid EV charging networks [4]. By storing off-peak energy or renewable generation and discharging during high-demand periods, SLBESS can enhance charging efficiency and reduce reliance on costly grid upgrades [9]. Research demonstrates that repurposed batteries, when properly tested, assessed, sorted, and reconditioned for SLBESS, can provide an additional 5–10 years of useful life while significantly maximizing both environmental and economic benefits [1,10].

SLBESS supports circular economy principles by extending battery lifespans, reducing waste, and conserving critical resources like lithium and cobalt [2,4]. Studies highlight that repurposing EV batteries can lower carbon emissions and system costs, making second-life storage attractive both environmentally and economically [3,5]. Policy frameworks are also advancing to support reuse and repurposing of batteries. In Europe, regulations like the EU Battery Directive promote second-life initiatives, while China has implemented mandatory battery tracking and collection systems to ensure structured repurposing [2,6]. Industrial players such as Nissan and Daimler have launched initiatives like xStorage and large-scale second-life grid systems, demonstrating the technical and commercial viability of SLBESS [1,4].

Nonetheless, significant barriers remain. Technical challenges—such as performance variability, degradation over time, and the lack of standardized testing—complicate the reliable deployment of SLBESS [5]. Economic uncertainties and the absence of harmonized global standards further constrain investment and scalability [2,6]. While advances in battery management systems, predictive health diagnostics, and cross-sector collaboration offer promising solutions, these developments alone are not sufficient. Despite growing interest in second-life battery applications, critical research gaps persist. Systematic literature reviews (SLRs) to date have often focused narrowly on individual aspects, such as technical degradation patterns, environmental impacts, or economic models [10, 24]. However, few studies provide a comprehensive perspective that integrates these technical and economic factors with considerations of market readiness, regulatory frameworks, and scalable business models [20,29]. Moreover, the increasing variety of use cases—from residential storage to grid-level support—demands a more strategic understanding of the ecosystem, which traditional techno-economic analyses alone cannot provide [24,31].

This growing complexity underscores the need for a strategic understanding of SLBESS from both academic and industry perspectives. Stakeholders must consider not only technical and economic factors but also the broader market, regulatory, and operational contexts shaping SLBESS deployment. This makes a systematic literature review (SLR) not only timely but essential to synthesize fragmented knowledge into actionable insights. In this context, applying a SWOT (Strengths, Weaknesses, Opportunities, and Threats) framework becomes especially relevant. A focused SWOT analysis provides a structured method to identify and synthesize the key factors influencing SLBESS deployment, addressing the current lack of integrated strategic assessments in the literature [10,19]. SWOT has proven effective in sustainability research and innovation strategy by highlighting multi-dimensional challenges and identifying strategic entry points [19, 27]. Unlike isolated techno-economic metrics, it enables a holistic assessment of SLBESS, capturing systemic enablers and constraints while informing future directions for research, policy, and commercialization.

The purpose of this study is to map and consolidate insights from the literature on the use of SLBESS for improving charging infrastructure by organizing them within a SWOT framework. In doing so, the study aims to unify dispersed findings, inform decision-making, and support the development of more coherent industry strategies for sustainable battery reuse and repurposing. This paper contributes to both theory and practice by offering a strategic framework for understanding SLBESS within the broader context of the circular economy and clean mobility transitions.

Theoretically, it contributes to the literature on second-life batteries and their applications [10, 26] expand the use of the SWOT framework in circular economy [20, 29] and energy systems research [14, 30]—specifically in the context of SLBESS. Practically, it supports decision-making for industry stakeholders, policymakers, and infrastructure developers. The choice of SWOT was informed by its proven effectiveness in evaluating emerging technologies and sustainability-oriented innovations by linking internal capabilities with external contextual factors [20]. SWOT, as a strategic planning and evaluation framework, enables the structured identification of internal factors (strengths and weaknesses) and external influences (opportunities and threats) impacting a system or innovation. It provides a versatile tool for synthesizing complex and interdisciplinary information, helping researchers and decision-makers assess both enabling factors and barriers to implementation. Its application in sustainability and technological innovation studies has proven valuable in capturing multi-dimensional dynamics across technical, economic, regulatory, and social contexts. In the case of second-life battery energy storage systems (SLBESS), SWOT supports a cross-sectoral understanding by integrating insights from engineering performance, business model feasibility, environmental impact, and policy support. It helps bridge the gap between theoretical potential and practical deployment, consolidating fragmented knowledge and highlighting areas where intervention is most needed. This makes it particularly useful for informing a range of stakeholders including policymakers, industry actors, and infrastructure planners about strategic pathways, aligning innovation opportunities with institutional capabilities, regulatory readiness, and evolving market conditions.

The remainder of the article is structured as follows: Section 2 outlines key concepts, including energy storage solutions, second-life applications, and SWOT. Section 3 presents the research methodology. Section 4 describes the results of the SWOT analysis. Section 5 provides a critical discussion, and Section 6 concludes with limitations and directions for future research.

2 Research method

This study employs a systematic literature review (SLR) as its primary research method to critically examine the strategic potential of SLBESS. The SLR approach is widely recognized in academic research for its structured, transparent, and reproducible nature, which allows researchers to synthesize existing knowledge across various disciplines in a methodical way [18]. In the context of SLBESS—a subject that intersects engineering, environmental science, energy policy, and business strategy—this method is particularly well-suited to capturing the multi-dimensional characteristics of the field. By aggregating evidence from diverse sources, the review aims to develop a holistic understanding of how second-life lithium-ion batteries can be effectively repurposed for charging infrastructure applications such as grid balancing and sustainable energy storage, all within the broader framework of circular economy principles.

To ensure the rigor of the review, Scopus was selected as the primary academic database due to its extensive coverage of peer-reviewed journals across relevant disciplines. A comprehensive search was conducted using carefully selected keywords:

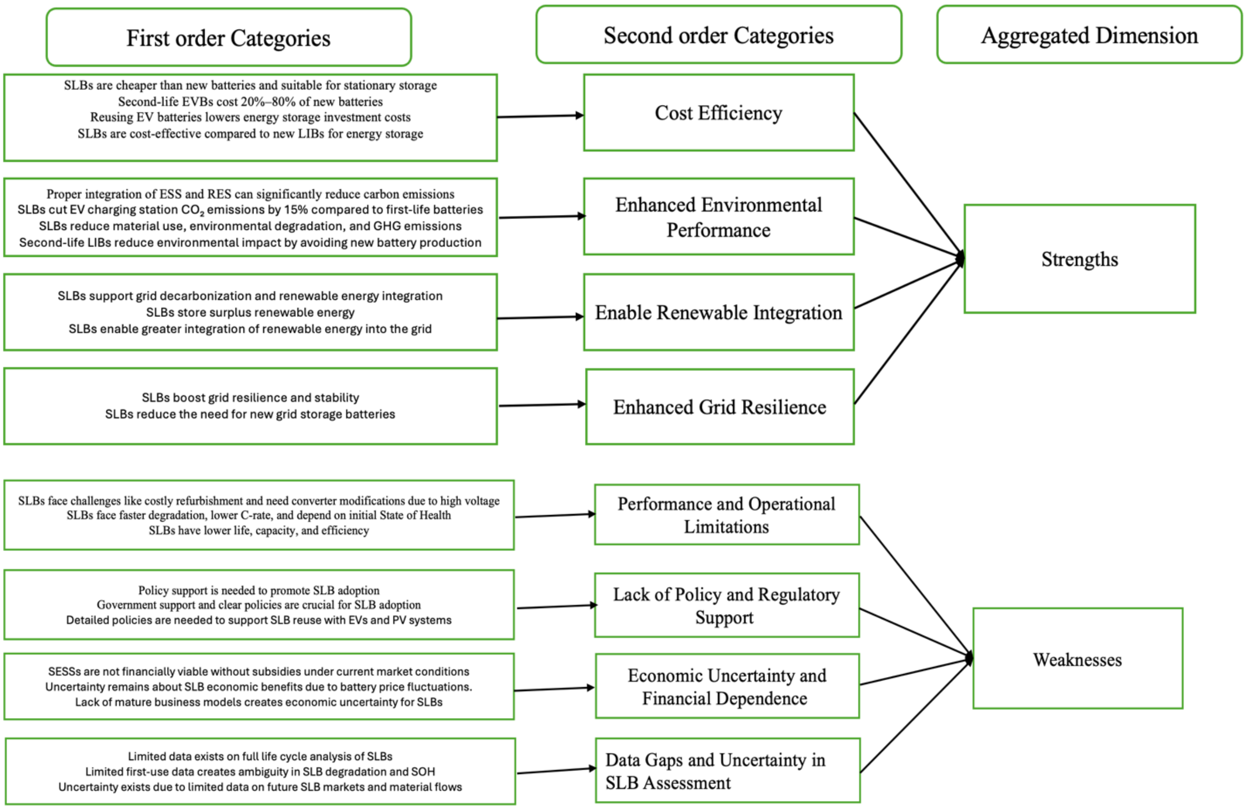
(TITLE-ABS-KEY ("batter*" OR "EV batter*") AND TITLE-ABS-KEY ("second* life*" OR "repurpos*" OR "circular*" OR "reus*" OR "remanufactur*") AND TITLE-ABS-KEY ("energy* storag*" OR "ESS" OR "charg*"))

These terms were chosen to ensure the inclusion of a broad yet focused literature set addressing technical, economic, environmental, and regulatory aspects of SLBESS. The search yielded a total of 137 peer-reviewed articles, technical reports, and conference papers. A multi-stage filtering process followed, which included screening based on titles, abstracts, and full-text relevance. The final selection included 27 studies that were directly relevant to the research purpose. Inclusion criteria prioritized empirical research, conceptual paper, modeling and simulation studies, systematic reviews, and industry case studies that offered insights into the real-world deployment, performance, and policy conditions surrounding SLBESS.

For the analytical phase, a thematic synthesis was conducted using the SWOT framework dimensions. Each article was coded using content analysis to align its findings with the four SWOT dimensions. (X) To analyze the data systematically and derive strategic insights, this study applied the Gioia methodology [32], which structures qualitative data into a three-tiered coding hierarchy: first-order concepts, second-order themes, and aggregate dimensions. The analysis began by extracting first-order categories from the literature and empirical insights—specific statements from various academic sources that identify benefits, challenges, opportunities, or risks of second-life battery energy storage systems (SLBESS). These were then grouped into second-order themes based on conceptual similarities. Finally, the themes were synthesized into four aggregated SWOT dimensions: Strengths, Weaknesses, Opportunities, and Threats (see Figure 1). For instance, statements such as “SLBs are cheaper than new batteries,” “Second-life EVBs cost 20%–80% of new batteries,” and “Reusing EV batteries lowers energy storage investment costs” were categorized under the second-order theme Cost-Effective, which was then assigned to the SWOT dimension Strengths. A similar qualitative coding structure was adopted in the study by Chirumalla [33] to explore technology adoption in circular economy contexts, reinforcing the methodological robustness of this approach. This structured coding process helped validate findings across sources and ensure theoretical rigor in linking fragmented literature into a cohesive strategic framework. This included identifying themes such as economic feasibility, performance variability, environmental benefits, and policy constraints. To systematically derive strategic insights, this study employed a structured qualitative coding process using Microsoft Excel to organize data from various academic publications on second-life battery energy storage systems (SLBESS). For each publication, relevant information was extracted and categorized into predefined columns corresponding to the SWOT framework—Strengths, Weaknesses, Opportunities, and Threats. These entries formed the first-order concepts, representing direct observations or findings from the literature. Similar items were grouped into second-order themes based on conceptual similarity, and from these, aggregate dimensions were developed that aligned with the core SWOT categories. For instance, cost-saving data points were grouped under broader themes like cost efficiency, which were ultimately classified as a strength. The coding process underwent multiple rounds of validation through meetings with the research team, where entries were reviewed, disagreements were resolved, and classifications were refined to ensure consistency and reliability. This iterative and collaborative approach ensured a robust synthesis of qualitative data and helped translate diverse literature findings into a coherent strategic framework.

3 Results

Our analysis identifies the following strengths, weaknesses, opportunities, and threats related to the development and implementation of SLBESS for improving charging infrastructure. Figure 1 illustrates the coding of the SWOT dimensions, from the first-order categories to second-order and aggregated dimensions. Below, each of these SWOT dimensions is explained in detail:



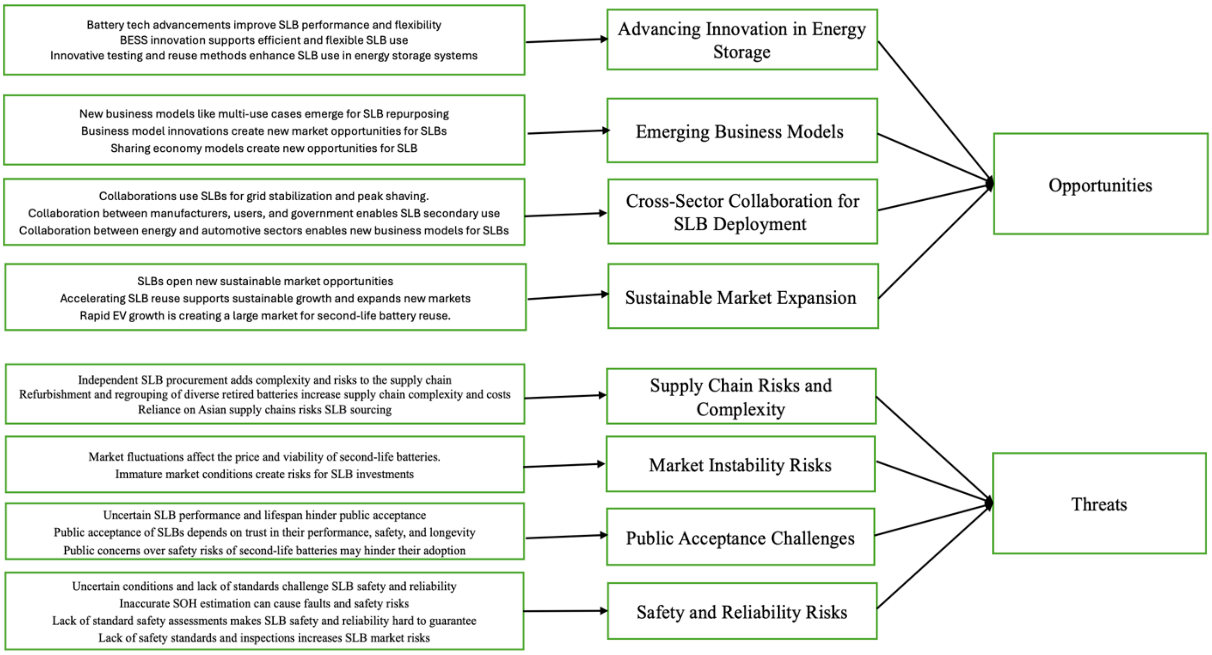


Figure 1. SWOT analysis

4.1 **Strengths**

The literature analysis shows four **Strengths(S)** categories such as Cost efficiency, Enhanced environmental performance, Enable renewable integration, and Enhanced grid resilience.
The first category of strengths is **Cost efficiency.** Second-life batteries (SLBs) offer significant cost advantages compared to new batteries, making them an attractive solution for stationary energy storage applications. SLBs cost less than original batteries and can effectively serve niche markets such as stationary storage [13]. It was estimated that the cost of second-life EV batteries ranges from 20% to 80% of the price of new batteries [11], further reinforcing their economic feasibility. Obrecht et al. [20] highlight that reusing EV batteries beyond their end-of-life can substantially reduces the investment cost of energy storage systems. Supporting this, Iqbal et al. [24] conducted a cost-effectiveness and carbon emissions analysis in the United States comparing SLBs to new LIBs across three energy storage applications: domestic rooftop photovoltaic (PV), utility-level PV firming, and utility-level peak shaving, concluding that SLBs present a more affordable alternative.

The second category is **Enhanced environmental performance.** SLBs offer significant environmental benefits by reducing emissions, resource use, and environmental degradation. Terkes et al. [12] found that SLBs, similar to fresh batteries, can reduce peak demand by 60%, lower the global warming potential, and decrease the levelized cost of energy by 35%, while also cutting grid dependency by 23.3% and increasing energy self-sufficiency by upto 25%. The cumulative CO_2 emissions from EV charging stations can be reduced by 15% compared to first-life batteries and by 10% compared to systems without stationary storage [14]. Thakur et al. [13] emphasized that SLBs contribute to efficient resource utilization by reducing the need for raw material extraction, lowering environmental degradation, and supporting the circular economy. Similarly, extending battery life reduces greenhouse gas emissions and mining impacts. SLBs not only reduce the cost of battery energy storage systems (BESS) but also mitigates the environmental impact of new battery production and helps promote renewable energy adoption [1]. These findings collectively reinforce the role of SLBs in enhancing environmental sustainability across the energy storage lifecycle.

The third category is **Enable Renewable Integration**. SLBs play a crucial role in enabling greater integration of renewable energy sources into the power grid. Battery technology is a key enabler for electrified transportation and serves as a core component in supporting grid decarbonization and low-carbon energy systems powered by renewables [21]. Loni et al. [15] further emphasize that EVs, and by extension their second-life batteries, enhance power system resilience by storing surplus renewable energy, supplying backup power during outages, and supporting grid functions such as frequency regulation and voltage stability. SLBs, functioning as stationary energy storage systems, contribute to integrating more renewables into the grid by offering enhanced flexibility, capability, and stability [13]. Together, these insights demonstrate how SLBs facilitate a more robust and renewable-ready energy infrastructure.

The fourth category is **Enhanced grid resilience.** SLBs significantly contribute to enhancing grid resilience by supporting backup power, grid services, and storage capacity. EVs and their SLBs improve power system resilience by supplying backup power during outages, storing surplus renewable energy, and delivering essential grid services such as frequency regulation and voltage stability [15]. Kamran et al. [16] highlight that repurposing end-of-life vehicle batteries for grid storage could eliminate the need for purpose-built grid storage batteries, with projections estimating over 50 GWh of such repurposed capacity by 2050. These contributions underline the role of SLBs in strengthening grid stability and reliability while reducing infrastructure demands.

4.2 **Weaknesses**

The literature analysis shows four **Weaknesses(W)** categories such as Performance and operational limitations, Lack of policy and regulatory support, Economic uncertainty and financial dependence, and Data gaps and uncertainty in SLB assessment.

The first category is **Performance and operational limitations**. SLBs face several performance and operational limitations that may hinder their widespread adoption. One major technical obstacle is their high voltage, which often requires modifications to existing hybrid converters for effective integration into current systems [17]. Additionally, SLB performance is strongly influenced by the State of Health (SOH) of the battery cells at the end of their first life. Bartolucci et al. [14] note that SLBs typically experience faster degradation rates and lower maximum charge/discharge (C-rate) capacities, although they offer the benefit of a lower footprint and cost. Yang et al. [22] further emphasize that, even under ideal conditions, SLBs generally have a shorter service life, reduced rated capacity, and lower charge/discharge efficiency compared to fresh batteries. These limitations present important technical challenges that must be addressed to improve the operational reliability and performance of SLBESS.

The second category is **Lack of policy and regulatory support**. The adoption of SLBs is hindered by a lack of comprehensive policy and regulatory support. There is a need for policymakers to recognize the potential of battery reuse schemes not only for profit margins but also for environmental preservation [17]. Gu et al. [23] underline that inter-industry collaboration and policy frameworks are critical, noting that government support is the most influential factor in facilitating battery secondary use. Obrecht et al. [20] further argue for a synergistic policy approach that aligns EV growth with renewable energy expansion. They call for detailed, ground-level policies that enable practical implementation of battery reuse, particularly in coordination with PV power systems and relevant stakeholders. Without targeted regulatory backing and structured policy mechanisms, the full potential of SLBs in sustainable energy systems remains constrained.

The third category is **Economic uncertainty and financial dependence**. SLB systems face significant economic uncertainty and often rely on external financial support to be viable. Rallo et al. [4] report that SLBESS are not currently financially sustainable under prevailing market conditions without subsidies or payments from grid controllers. Similarly, Iqbal et al. [24] highlight that fluctuating battery prices and limited generalizability of economic analyses contribute to ongoing doubt about the profitability of SLBESS solutions. Sun et al. [25] further emphasize that the lack of a dominant market position, clear compensation mechanisms, and sufficient operational experience means there is no mature business model for BESS using repurposed LIBs. Consequently, most investment projects remain in pilot or demonstration phases, indicating a high level of financial risk and dependence on policy-driven incentives or institutional support.

The fourth category is **Data gaps and uncertainty in SLB assessment**. A major barrier to the large-scale adoption of SLBs lies in the significant data gaps and uncertainties surrounding their assessment. It is pointed out that despite growing interest in smart charging and battery reuse for demand-side management, the literature lacks comprehensive studies that quantify economic and energy savings across the full life cycle of a battery in varied end-user settings [13]. Li et al. [26] further emphasize that limited access to degradation data from a battery's first use creates ambiguity in assessing the SOH, which is critical for ensuring safe and effective second-life applications. Additionally, it highlights uncertainties related to the future market behavior of recycled LIB metals and the potential expansion of LIB applications beyond the transportation sector [16]. These data and assessment limitations hinder the reliability of SLB forecasting, evaluation, and investment decision-making.

4.3 Opportunities

The literature analysis shows four **Opportunities(O)** categories such as Advancing innovation in energy storage, Emerging business models, Cross sector collaboration for SLB deployment, and Sustainable market expansion.
The first category is **Advancing innovation in energy storage**. Rapid advancements in energy storage technology present significant opportunities for the development and deployment of SLBs. Wangsupphaphol et al. [17] highlight how ongoing innovations in battery technology are enhancing the capability of batteries to supply or recapture power among varying loads while maintaining essential qualities such as safety, efficiency, and endurance. Dong et al. [11] emphasize that BESS are increasingly attractive due to their high efficiency, energy density, rapid response times, modularity, and flexibility in installation and construction. These characteristics align well with the evolving demands of modern energy systems. Furthermore, Gao et al. [1] demonstrate that whole battery packs can be feasibly reused in second-life applications through advanced analysis of cell aging, and they offer practical guidelines to prolong battery life. Collectively, these technological advancements support more effective, reliable, and scalable SLBESS, reinforcing SLBs as a future-ready component of innovative energy systems.

The second category is **Emerging business models**. The rise of emerging business models offers promising opportunities to expand the adoption and value generation of SLBs. It was emphasized that new models for LIB repurposing—such as multi-use cases—demand deeper exploration of how SLBESS function from the end-user's perspective, particularly in terms of flexibility and utility [31]. Costa et al. [27] underline that business model innovation involves redefining how value is created and captured, including non-monetary benefits such as sustainability and sectoral integration. Such innovation often transcends traditional industry boundaries, unlocking significant market opportunities tied to technological progress. Wu et al. (2020) also highlight the potential of sharing economy models, which support collaborative and cost-effective deployment of SLBs in distributed energy storage networks. These evolving models create diverse pathways for SLBs to enter the market and generate both economic and environmental value across sectors.

The third category is **Cross sector collaboration for SLB deployment**. Cross-sector collaboration is emerging as a key enabler for the successful deployment of SLBs in energy storage systems. Zahoor et al. (2024) highlight the 'JUMP' project, a collaboration between the Dutch startup Alfen, Renault, and The Mobility House, which demonstrates the potential of SLBs for grid stabilization and peak shaving through partnerships between the automotive and energy sectors. Gu et al. (2021) reinforce the importance of coordinated action by presenting a closed-loop supply chain model involving battery manufacturers, secondary users, and governmental bodies, emphasizing how collaboration across stakeholders can streamline battery reuse systems. A growing intersection of interests between the electricity and mobility sectors is not only shaping policy but also fostering new business model innovations [27]. These examples collectively show how cross-sector partnerships can accelerate SLB adoption, enhance system integration, and open new pathways for sustainable energy solutions.

The fourth category is **Sustainable market expansion**. The rapid growth of the EV sector is creating significant opportunities for sustainable market expansion through the reuse of SLBs. SLBs open new avenues in both the EV battery reuse and energy storage markets, offering environmentally sustainable alternatives to battery disposal [24]. The first wave of EV batteries approaching end-of-life, the anticipated ‘scrap tide’ presents an urgent need—and opportunity—to accelerate the industrialization of battery repurposing as a foundation for a healthy, circular new energy vehicle ecosystem [25]. Li et al. (2023) highlight that global EV adoption is growing rapidly, with a 43% increase in sales in 2020 alone and a notable 137% rise in the European market. This surge has resulted in more than 10 million EVs on the road globally, amplifying the challenge of managing a growing volume of retired batteries. The confluence of environmental necessity and market growth presents a compelling case for scaling SLB applications as a key component of sustainable development in the energy and mobility sectors.

4.4 Threats

The literature analysis shows four **Threats(T)** categories such as Supply chain risks and complexity, Market instability risks, Public acceptance challenges, and Safety and reliability risks.

The first category is **Supply chain risks and complexity**. The deployment of SLBs faces considerable supply chain risks and operational complexity, which can hinder scalability and cost-effectiveness. Managing SLB systems requires a broad and well-coordinated network involving numerous activities and specialized competencies [12]. This includes the need for long-term procurement contracts and navigating additional complexities when sourcing batteries independently of original equipment manufacturers (OEMs). Xu et al. (2023) highlight the logistical and cost challenges posed by refurbishing and regrouping multiple heterogeneous battery packs, which often leads to increased unit prices for retired batteries. Moreover, Bonsu et al. [21] point out that the UK's heavy dependence on China and other Asian countries for battery cell manufacturing and raw material sourcing, raising concerns over geopolitical vulnerability and supply chain resilience. These interconnected issues collectively pose strategic threats to the consistent, affordable, and secure deployment of SLBs at scale.

The second category is **Market instability risks**. SLBs are exposed to significant market instability risks that could hinder their broader adoption and commercial viability. Meyer et al. [29] highlight that fluctuations in market dynamics—such as demand uncertainty, raw material pricing, and regulatory shifts—can impact the pricing, availability, and long-term economic feasibility of second-life EV batteries. The lack of a market-dominant position, undefined compensation mechanisms, and limited experience with system dispatching contribute to an underdeveloped market [25], where most investment projects remain in the demonstration phase. The absence of standardized safety assessment and inspection protocols for SLBs creates bottlenecks in scaling battery reuse across sectors [13]. In parallel, public acceptance remains a critical barrier. Pagliaro et al. (2019) point out that uncertainties in SLB performance and service life challenge market confidence. The success of SLBs largely hinges on building trust in their safety, longevity, and reliability among both consumers and businesses [12]. Kastanaki et al. [28] reinforce this view by noting that perceived safety risks linked to aged or second-hand batteries may limit SLB adoption in the energy storage market. Together, these concerns reflect how economic, technical, and social uncertainties converge to threaten market stability for SLB deployment.

The third category is **Public acceptance challenges**. Public acceptance remains a key challenge in the widespread adoption of SLBs, primarily due to concerns over their performance, safety, and longevity. Pagliaro et al. [2] point out that the uncertain service life and performance reliability of retired batteries continue to pose barriers within the reuse market. Building trust among consumers and businesses is crucial [12], as the acceptance and integration of SLBs depend heavily on user confidence in their operational safety and durability. Kastanaki et al. [28] further highlight that public perception of safety risks associated with aged or second-hand batteries can significantly limit their use in the energy storage sector. Without effective communication, education, and standardization to address these concerns, public skepticism may continue to hinder market growth for SLB solutions.

Table 1. SWOT analysis of SLBESS for improving charging infrastructure

Strengths (S) Cost efficiency Enhanced environmental performance Enable renewable integration Enhanced grid resilience	**Weaknesses (W)** Performance and operational limitations Lack of policy and regulatory support Economic uncertainty and financial dependence Data gaps and uncertainty in SLB assessment
Opportunities (O) Advancing innovation in energy storage Emerging business models Cross sector collaboration for SLB deployment Sustainable market expansion	**Threats (T)** Supply chain risks and complexity Market instability risks Public acceptance challenges Safety and reliability risks

The final category is **Safety and reliability risks.** Safety and reliability risks pose a significant threat to the deployment of SLBs, primarily due to uncertainties in battery condition and the lack of standardized assessment methods. It was emphasized that these uncertainties make it difficult to ensure consistent safety and reliability throughout SLB applications [30]. Inaccurate estimation of a battery's SOH can lead to misconceptions about its operational capacity, increasing the risk of faults and serious safety hazards [24]. Li et al. [26] further reinforce that battery safety, which is fundamentally determined by electrochemical system stability, is essential for reuse. However, the absence of mature safety assessment protocols and effective screening and inspection measures continues to hinder confidence in SLB reliability. These technical limitations underscore the pressing need for standardized procedures to ensure safe and dependable SLB usage across applications. Table 1 outlines the outcome of our analysis in SWOT dimensions.

4 Discussion

This study offers a comprehensive perspective on second-life battery energy storage systems (SLB ESS) by employing a SWOT framework to explore their strategic potential within circular economy and sustainable energy solutions. Theoretically, the paper extends existing knowledge by integrating multiple dimensions such as technical, economic, environmental, and regulatory into a single analytical framework. While prior research has often examined second-life battery use through isolated lenses such as techno-economic assessments, business models, lifecycle performance or environmental impact, this study contributes by situating SLBESS within a broader systems perspective that accounts for their dynamic interactions with market forces, regulatory policies, and grid infrastructures. The SWOT analysis in this research extends understanding of SLBs in applications like charging infrastructure, grid balancing, and residential storage, highlighting cost savings, environmental benefits, and alignment with sustainability goals. By identifying opportunities such as supportive policies and advancements in battery monitoring, this study underscores the potential for SLBs to play a vital role in ESS. Managerially, it emphasizes the need for standardized testing, performance benchmarks, and supportive regulations to address challenges like degradation and competition from newer battery technologies. The results contribute to the circular economy literature on batteries [2, 13, 20, 21] providing insights into how SLBESS can support sustainable resource use, reduce waste, and create economic value through battery repurposing and integration into energy systems. The study provides a detailed overview of strengths, weaknesses, opportunities, and threats for designing and implementing SLBESS, which will guide battery ecosystem actors to strategically prepare and plan the circular activities in an effective way.

The application of SWOT as an analytical tool in this context provides theoretical value by capturing the complex interplay between internal attributes—such as battery degradation patterns, cost-performance trade-offs, and modular design—and external influences, including market dynamics, regulatory incentives, and supply chain constraints. It highlights how SLB deployment cannot be evaluated solely on technical merits but must be assessed through a multidimensional framework that includes socio-technical systems, stakeholder alignment, and long-term economic feasibility. This theoretical approach aligns with the broader literature on sustainability transitions [21, 27]. where technology implementation is influenced by both innovation capabilities and institutional readiness.

Managerially, the findings underscore several key imperatives for actors within the battery ecosystem. The SWOT results provide a structured tool that companies—ranging from battery manufacturers and EV producers to energy service providers and recyclers—can use to inform decision-making across different operational stages. Strengths such as cost efficiency and environmental benefits highlight value propositions that firms can leverage to target sustainability-conscious customers and cost-sensitive markets. Weaknesses, including performance degradation and lack of standardization, signal the need for technical upgrades, rigorous diagnostics, and strategic R&D investments. Identified opportunities such as emerging circular business models and policy incentives encourage firms to collaborate across sectors and explore innovative service offerings. Meanwhile, threats like supply chain complexity and market volatility point to the importance of risk mitigation strategies, diversified procurement, and adaptive planning. The SWOT framework can be employed by product development teams during system design, by strategy departments to align with long-term sustainability goals, and by policy and compliance units to ensure regulatory alignment. Overall, this framework equips stakeholders with an integrative perspective to evaluate the feasibility, readiness, and impact of SLBESS initiatives within the evolving energy and mobility landscape.

The SWOT analysis serves not only as a descriptive assessment but also as a strategic planning tool to navigate the challenges and leverage the opportunities associated with SLBESS. The need for standardized testing protocols, clear certification systems, and transparent data-sharing mechanisms is particularly urgent to build trust in SLB safety and performance. Currently, many SLBESS projects remain at the demonstration stage due to inconsistent assessments of battery state-of-health and limited access to usage histories from the first life. Firms involved in battery production, EV manufacturing, and energy storage integration must collaborate to

address these information asymmetries and technical inconsistencies through improved digital diagnostics, traceability platforms, and cross-sectoral knowledge exchange. In parallel, business models need to evolve to accommodate the unique risks and opportunities associated with SLBESS. The development of battery-as-a-service offerings, integration into virtual power plants, and localized community energy solutions are emerging as viable strategies to capture both monetary and environmental value. These models require flexible financial structures and adaptive policy frameworks that can respond to uncertainties in battery availability, evolving safety standards, and rapidly shifting market demands. Policymakers also play a critical role by fostering environments that incentivize reuse, such as through extended producer responsibility schemes, tax credits, and public-private partnerships that promote innovation in battery reuse and energy decentralization.
SLBESS.

5 Limitations and future research

While this study presents a structured SWOT analysis of SLBESS, it is based primarily on academic literature. This reliance limits the depth of insight into real-world operational challenges and regional deployment differences. The SWOT framework, while effective in mapping strategic factors, does not capture the dynamic trade-offs or interdependencies between categories, suggesting that future research should consider hybrid approaches such as multi-criteria decision analysis or techno-economic modeling to enrich the analysis [10]. To deepen understanding and validate the theoretical findings of the SWOT analysis, future research will focus on three interconnected strands. First, an empirical SWOT study will be conducted through semi-structured interviews with key stakeholders across the battery value chain including manufacturers, recyclers, energy providers, and policymakers for exploring context-specific insights on the strengths, weaknesses, opportunities, and threats of SLBESS. Second, further investigation will assess the preconditions necessary for the successful development and implementation of SLBESS, particularly in relation to regulatory frameworks, technical infrastructure, and cross-sector collaboration. Third, research will examine viable and scalable business models tailored to various use cases such as residential storage, commercial peak shaving, and EV fast-charging support. These efforts will help bridge the gap between theoretical insights and real-world application, facilitating the sustainable expansion of second-life battery solutions in diverse energy systems.

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