

Preconditions for the Development and Implementation of Second-Life Batteries in Energy Storage Solutions[#]

Suchandra Paul¹, Koteswar Chirumalla¹, Erik Dahlquist¹

¹ Digital and Circular Industrial Services (DigiCircle) Research Group, Mälardalens University, Eskilstuna, Sweden

(Corresponding Author: suchandra.paul@mdu.se)

ABSTRACT

The rising adoption of electric vehicles (EVs) presents an imminent challenge leading to the management of retired lithium-ion batteries. Second-life battery (SLB) solutions reusing EV batteries in stationary storage applications have gained substantial attention due to their potential environmental and economic benefits. However, the successful development and implementation of SLB in a specific context depend heavily on meeting preconditions across technical, operational, and business domains. This study systematically explores these preconditions through a synthesis of academic literature complemented by semi-structured interviews with companies in the EV battery ecosystem. In total, the study identifies seven preconditions for development and seven preconditions for implementation, providing a structured understanding of the requirements across both phases. Findings highlight the necessity of early diagnostics, safe disassembly, robust performance evaluation, and comprehensive system integration strategies. The study concludes with a discussion on the pressing need for harmonized procedures, enhanced monitoring frameworks, and market aligned business models to unlock the potential of SLB solutions within a circular economy.

Keywords: second-life battery, energy storage, battery circularity, battery management, circular economy, circular business models.

1. INTRODUCTION

As the electric vehicle market expands globally, so does the volume of retired lithium-ion batteries reaching the end of their lifecycle. Although these batteries typically exit service when their state of health (SOH) drops to around 80%, they often retain 70–80% of their original capacity [1]. This remaining capacity makes them

highly suitable for repurposing in less demanding applications such as stationary energy storage systems (ESS). The reuse of these batteries not only extends their life but also contributes to sustainable energy transitions by reducing raw material demand, minimizing waste, and supporting renewable energy integration [2]. Nevertheless, tapping into the full potential of second-life batteries is not straightforward [11] [12]. It requires overcoming numerous technical, operational, and business challenges that span from battery disassembly to the development and implementation of second-life batteries (SLBs) in energy storage applications. Understanding these preconditions is crucial, as they form the foundation for designing viable SLB solutions [13], ensuring system reliability, and aligning with evolving regulatory and circular economy goals. Preconditions are key because they translate broad challenges into concrete requirements that must be fulfilled in order to enable safe, cost-effective, and scalable second-life battery solutions. In this paper, preconditions refer to the essential technical, operational, economic, and strategic requirements that must be met to enable the successful development and implementation of second-life battery solutions. This paper aims to identify and describe the essential preconditions that must be met to ensure successful development and implementation of SLB in energy storage solutions. It draws on recent academic frameworks [3] and key developments in battery circularity policy [4] to support the analysis.

2. METHODOLOGY

This study employs an explorative qualitative research approach [14]. It adopts a two-stage methodology combining a structured literature review with qualitative validation through semi-structured interviews. First, a systematic literature review was conducted to identify and analyze the key phases

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involved in the development and implementation of SLB solutions. Academic journal articles and industrial reports were examined to extract common practices, challenges, and frameworks used across SLB case studies. These insights were synthesized to construct a conceptual process model that distinguishes between the development and implementation phases of SLB systems. The resulting framework (Fig 1) maps sequential steps from the end-of-first life through battery assessment, disassembly, regrouping, and business model design, followed by operational deployment, fault handling, and eventual recycling. This figure was developed iteratively based on recurring patterns observed in the literature and refined to ensure clarity across technical, operational, and strategic dimensions.

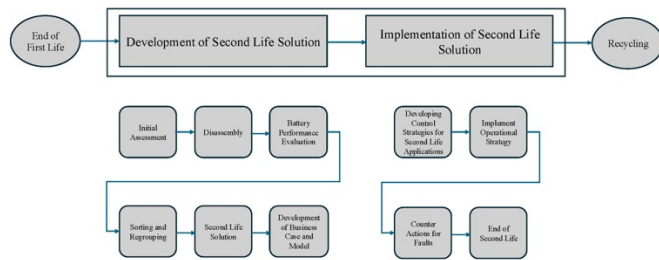


Fig. 1 Development and implementation phases of SLB solutions

In Figure 1, the top-level elements denote phases. First, the Development of Second-Life Solution phase consists of six sub-phases. The initial assessment involves identifying the battery model, chemistry, and reason for retirement in order to evaluate compatibility and forecast remaining useful life [3]. Disassembly follows, requiring safe dismantling at the pack, module, or cell level through standardized protocols [2]. Next, battery performance evaluation includes diagnostic testing of state of health, internal resistance, capacity, and thermal behavior. This is followed by sorting and regrouping, where batteries are arranged into uniform modules according to voltage and capacity. The second-life solution stage addresses system design and integration, including the adaptation of the battery management system and compliance with safety standards. Finally, the development of a business case and model incorporates market analysis, cost–benefit evaluation, warranty frameworks, and policy incentives.

Second, the Implementation of Second-Life Solution phase comprises four sub-phases. The first is the development of control strategies, which encompass real-time monitoring, predictive maintenance, and energy balancing. The second is the operational strategy, involving staff training, system integration, and adherence to service-level agreements. The third concerns counter actions for faults, which require contingency procedures, rapid response mechanisms, and predictive diagnostics. The final sub-phase is the end of second life, where systems are decommissioned responsibly and directed to recycling pathways. Development begins with assessing battery suitability through reliable diagnostics and state-of-health data, followed by safe disassembly, performance evaluation, and sorting into compatible modules. These modules are integrated into tailored system designs with required adaptations and compliance checks, and the phase concludes with establishing a viable business case supported by market and policy considerations. Implementation then focuses on control strategies, real-time monitoring, predictive maintenance, and operational protocols, alongside staff training, system integration, and fault management through contingency measures and predictive diagnostics. Finally, end-of-life decommissioning is carried out via recycling and closed-loop recovery to minimize environmental impact and support circular economy principles.

To validate and refine this framework, semi-structured interviews were conducted with stakeholders across the SLB value chain, including manufacturers, system integrators, smart charging providers, transport operators, and municipal actors (Companies A–E). These interviews confirmed the relevance of the phases and sub-phases and identified specific preconditions at each stage.

Table 1 presents the profile of the interviewed companies (Company A–E), outlining their current offerings and respective ecosystem actor roles, thereby providing an overview of the diversity of stakeholders engaged in the EV battery ecosystem and operating across different segments of the SLB value chain.

Company code	Current offerings	Ecosystem actor category
A	Bus operations, public transport services	EV operator and battery 1st life user
B	Energy optimization, battery storage solutions	System integrator; Energy service provider

C	Rail and mobility services	EV operator and battery 1st life user
D	Municipal energy and sustainability projects	Municipality
E	City bus transport services	EV operator and battery 1st life user

Table.1 Profile of interviewed companies

3. RESULTS

The results of this study, derived from a combination of literature review and semi-structured interviews, reveal a set of interdependent preconditions critical to the successful development and implementation of SLB solutions. Our literature analysis show that technically, it is essential to have robust early-stage diagnostics that accurately predict the second-use potential of retired EV batteries. Without precise SOH estimation, batteries may either be wrongly discarded or integrated into systems where they underperform. Safe and standardized disassembly processes must also be in place, especially given the diversity in battery types, chemistries, and embedded battery management systems (BMS) among manufacturers. Advanced diagnostic testing procedures are equally important, as they ensure that only high-performing cells or modules are reused, thus improving both safety and longevity. From an operational standpoint, deploying SLBs in real-world storage systems demands sophisticated control systems that allow for real-time monitoring and autonomous fault handling. Predictive maintenance frameworks, powered by historical usage data and AI-based algorithms, have proven to be valuable tools for minimizing downtime and maximizing battery utility [5]. Economically, successful SLB projects must minimize logistics and refurbishment costs through optimized battery collection, testing, and repackaging workflows. They also require flexible business models that include service-level agreements, usage-based leasing options, and performance-based guarantees to build customer confidence and market acceptance. Finally, alignment with international standards and policies is essential. Inconsistent reuse criteria and unclear ownership models can hinder adoption, particularly among regulatory frameworks. This set of insights is derived from the literature analysis.

The results from the semi-structured interviews complement the literature review findings by providing practical, industry-specific perspectives on the preconditions necessary for the development and

implementation of second-life battery energy storage systems (SLBESS).

3.1 Preconditions for Development

In total, the analysis identified seven distinct preconditions for the development phase. The interviews revealed a coherent set of technical, operational, and economic preconditions that must be satisfied before a SLBESS can progress from conceptual design to large-scale deployment. One of the most prominent technical aspects highlighted by multiple respondents was the **need for accurate and comprehensive early diagnostics of used batteries**. Companies consistently stressed that a robust understanding of battery state-of-health, remaining useful life, and cell-level performance variability is critical for reducing the risks associated with mismatched modules and unplanned system failures. Without such detailed diagnostic capabilities, there is an increased likelihood of performance degradation occurring prematurely, which could undermine both customer trust and investor confidence. Company A, for instance, noted that in the absence of reliable diagnostic tools, the long-term operational stability of repurposed systems becomes questionable, making it difficult to guarantee warranty conditions or secure contracts for larger projects.

Closely linked to early diagnostics is the **requirement for standardized testing and sorting procedures**. Respondents described how current practices often vary between organizations, resulting in fragmented and inconsistent assessment methods. Harmonized protocols covering capacity measurement, impedance analysis, and thermal performance evaluation were seen as essential for enabling interoperability between suppliers, refurbishers, and system integrators. Without these standards, each SLBESS project risks becoming an isolated case with bespoke testing requirements, leading to inefficiencies, increased costs, and extended development timelines. The absence of common testing frameworks also complicates multi-actor collaboration, as regulatory compliance criteria may differ between regions.

Economic preconditions emerged as equally significant to technical readiness. **Securing a reliable and consistent supply of end-of-first-life batteries** was considered a fundamental precondition, typically requiring strategic procurement agreements with original equipment manufacturers, fleet operators, or recycling facilities. Respondents pointed out that while obtaining used batteries at competitive prices is vital,

this factor alone does not guarantee commercial viability. As noted by Company B and Company D, acquisition costs must be carefully weighed against the expenses of transportation, disassembly, testing, refurbishment, certification, and eventual integration into storage systems. This makes **detailed cost modelling** indispensable, not only for determining the break-even point but also for assessing the long-term profitability and scalability of SLBESS projects.

Operational requirements further reinforce the complexity of the development phase. Companies emphasized the **necessity for specialized facilities equipped for disassembly, module regrouping, and component handling**. Such infrastructure must meet stringent safety and compliance requirements, given the hazards associated with high-voltage systems and potentially unstable cells. Moreover, these operations **demand skilled technicians** capable of applying advanced diagnostic techniques, performing precision assembly, and ensuring that refurbished systems meet industry performance and safety benchmarks. Several interviewees underlined that training and retaining such specialized staff is itself a significant challenge, particularly in regions where battery repurposing is still an emerging industry.

Finally, **strategic alignment with broader sustainability and decarbonization objectives** was identified as a key precondition for investment in SLBESS development. Projects that clearly demonstrate their contribution to circular economy principles, carbon footprint reduction, and responsible resource management are more likely to receive regulatory support, attract private investment, and gain public acceptance. In this way, sustainability serves not only as a guiding principle but also as a commercial enabler, influencing decisions from the earliest design stages through to the development of end-of-life recycling pathways. Several companies suggested that embedding sustainability considerations into every stage of the development process ranging from material sourcing to operational lifecycle planning can create competitive advantages while ensuring regulatory compliance in rapidly evolving policy environments.

3.2 Preconditions for Implementation

For the implementation phase, the analysis identified seven key preconditions that ensure the reliable and sustainable deployment of SLBESS in real-world contexts. The interviews highlighted a distinct but complementary set of preconditions that must be addressed once a SLBESS moves beyond the

development stage and into operational deployment. While the development phase is primarily concerned with technical readiness and economic feasibility, the implementation phase focuses on ensuring that these systems can function reliably and sustainably in real-world conditions over extended periods.

A recurring theme in the interviews was the **importance of establishing robust operational monitoring and control systems**. Multiple companies emphasized the role of continuous, real-time state-of-health tracking and fault detection as essential for minimizing downtime and mitigating safety risks. The ability to predict failures before they occur, through advanced data analytics and condition-based maintenance strategies, was seen as a core capability for maintaining high system availability. Several respondents linked this precondition directly to customer confidence, noting that without such monitoring infrastructure, the perceived reliability of second-life systems remains a barrier to market adoption. Company C, for example, described how predictive maintenance algorithms could significantly reduce operational costs by preventing cascading failures within battery modules and extending overall system life.

The interviews also revealed the **necessity for well-defined operational protocols and safety standards**. These include detailed handling procedures for high-voltage components, BMS configuration guidelines, and standardized approaches for thermal management to avoid overheating during peak loads. Implementation teams must be equipped not only with the technical tools to manage these requirements but also with clear documentation and training pathways that can be replicated across multiple sites. In this respect, **knowledge transfer** between engineering teams, operators, and maintenance staff emerged as a critical precondition for successful scaling.

Economic and contractual frameworks also play a decisive role during the implementation. Several respondents pointed out that implementation success depends on having service-level agreements that clearly define performance expectations, maintenance responsibilities, and liability allocation between suppliers, operators, and end-users. Without such agreements, disputes over warranty claims or performance degradation can create delays, damage business relationships, and even lead to early project termination. Additionally, respondents underlined that long-term operational viability often hinges on flexible business models that can adapt to changing electricity

prices, regulatory incentives, and evolving market demands.

Another key precondition discussed was the **integration of SLBESS into existing energy infrastructure**. This involves not only technical interoperability ensuring that the system can communicate effectively with grid management software, renewable generation assets, or other storage systems but also regulatory compliance with grid connection standards, safety certifications, and environmental guidelines. Company E shared that the lack of harmonized connection codes between regions often leads to costly re-engineering efforts, highlighting the need for early engagement with regulatory bodies during the planning stage.

Finally, **sustainability considerations** continue to shape implementation strategies, albeit with a focus distinct from the development phase. Whereas development aligns with sustainability in conceptual and procurement decisions, implementation operationalizes these goals through lifecycle management practices, end-of-second-life planning, and closed-loop recycling partnerships. This includes having predefined take-back or recycling schemes in place before system deployment, ensuring that the environmental benefits of SLBESS are preserved throughout their operational lifetime. Several interviewees suggested that **incorporating traceability mechanisms** such as digital battery passports could not only support sustainability reporting but also facilitate compliance with emerging EU and international regulatory frameworks. Table 2 summarizes the preconditions identified in this study across both the development and implementation phases of second-life battery solutions, based on insights from interviews.

Preconditions in development phase	Preconditions in implementation phase
<ul style="list-style-type: none"> -Need for accurate and comprehensive early diagnostics of used batteries. -Requirement for standardized testing and sorting procedures. -Securing a reliable and consistent supply of end-of-first-life batteries. -Detailed cost modelling. -Necessity for specialized facilities equipped for disassembly, module regrouping, and component handling. -Demand for skilled technicians. -Strategic alignment with broader sustainability and decarbonization objectives. 	<ul style="list-style-type: none"> -Importance of establishing robust operational monitoring and control systems - Necessity for well-defined operational protocols and safety standards - Knowledge transfer - Economic and contractual frameworks - Integration of SLBESS into existing energy infrastructure -Sustainability considerations - Incorporating traceability mechanisms

Table.2 Identified preconditions for development and implementation of second-life battery solutions

4. DISCUSSION AND CONCLUDING REMARK

Overall, the findings demonstrate that the identified preconditions are closely aligned with the sequential phases of development and implementation presented in Fig. 1. Importantly, all phases proposed in the conceptual framework were confirmed and approved by the participants during the interviews, reinforcing both their theoretical validity and practical relevance.

This study shows that the feasibility of SLB is not only a matter of technology readiness but the outcome of interlinked technical, operational, economic, and policy preconditions. While prior research has pointed to challenges such as the absence of standardized testing, difficulties in state-of-health estimation, and uncertainties in reuse frameworks [4,5,7], our empirical results confirm these issues and demonstrate how they manifest in practice. For example, interviewees consistently emphasized the importance of early diagnostics, standardized disassembly, performance evaluation, regrouping, operational monitoring, predictive maintenance, and structured end-of-life planning as critical preconditions.

At the same time, this study extends the literature by identifying preconditions that are less well covered in existing theory. Specifically, the interviews highlighted the importance of systematic knowledge transfer between engineering, operational, and maintenance staff, as well as the growing relevance of digital traceability mechanisms such as battery passports for lifecycle transparency [6,10]. These findings suggest that, beyond technical and economic considerations, organizational and digital enablers are increasingly central to enabling large-scale SLB deployment.

The economic dimension also aligns with earlier studies stressing that technical feasibility alone is insufficient. Long-term viability requires scalable business models, cost optimization, and clear contractual frameworks that distribute value fairly among stakeholders [9]. Our findings reinforce this perspective by showing that companies remain hesitant to invest unless reliable revenue streams and risk-sharing mechanisms are in place.

Taken together, this study contributes to the existing literature on SLB preconditions [4,7,9] by both validating prior theoretical frameworks and refining them with new empirical insights. It shows that SLB deployment must be understood as a lifecycle process, where interdependent preconditions across development and implementation phases must be systematically addressed to build a sustainable and competitive SLB ecosystem.

From a practical perspective, the study provides guidance for companies seeking to adopt second-life battery solutions by outlining clear preconditions that can serve as checkpoints across development and implementation. Firms can use these insights to structure diagnostic procedures, standardize disassembly and testing, design robust operational strategies, and build viable business models aligned with policy requirements.

However, the research is limited by its qualitative scope, relying on a small set of interviews and literature, which may not capture the full diversity of industrial practices or regulatory settings. Future research should expand to larger, cross-country datasets, integrate quantitative performance and cost assessments, and explore digital traceability tools such as battery passports to operationalize preconditions at scale [15]. Building on this work, the identified preconditions can also serve as a foundation for defining suitable and viable circular business models for second-life batteries in energy storage solutions, which will be the focus of the next stage of this research.

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