# Unlocking the Value of Retired EV Batteries: Technologies, Application, and Commercial Models for Second-Life Energy Storage in Power Systems

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ABSTRACT

The large-scale retirement of electric vehicle (EV) batteries presents a dual challenge: managing end-of-life systems while harnessing residual value to enhance power system sustainability. Owing to the relatively modest performance requirements of stationary applications, repurposing retired EV batteries as second-life battery energy storage systems (SL-BESSs) provides a cost-effective means to extend service life and improve resource efficiency. This review systematically evaluates the technical, operational, and institutional foundations required for the effective integration of SL-BESSs into power systems. In this context, echelon utilization is positioned as a pivotal transitional stage toward a circular battery economy. Building on this perspective and moving beyond prior studies that focus on reuse feasibility or single-case assessments, this work synthesizes three core dimensions: battery management algorithm adaptation, scenario-driven deployment compatibility, and scalable commercial model architectures. Key technical obstacles are identified, including cell-level inconsistency, limited operational data, and uncertainty in degradation forecasting. Mitigation strategies are discussed, referencing advances in clustering algorithms, transfer learning, and hybrid physical-data modeling. Deployment suitability is assessed across generation, grid, and end-user segments based on application-specific requirements and evidence from global demonstration projects. A structured classification of commercial models, including Battery-as-a-Product, Battery-as-a-Service, Platform-as-a-Service, and Energy-as-a-Service, is presented and linked to policy frameworks and performance benchmarks. This alignment informs the development of scalable deployment pathways. By integrating perspectives from control engineering, systems integration, and market design, this review provides a robust analytical foundation for advancing second-life battery applications in power systems. Although interest in this area is growing, comprehensive interdisciplinary research and collaboration remain needed.

## 1. Introduction

### 1.1. Motivation

The accelerating shift toward global electrification across key sectors such as transportation, buildings, and industry is central to achieving energy transition and decarbonization goals [1]. This transformation has intensified the demand for scalable and reliable energy storage systems. Among the available technologies, lithium-ion batteries have emerged as the dominant solution due to their high energy density, long cycle life, and decreasing cost, particularly in electric vehicles (EVs) and grid-scale applications [2].

However, this rapid expansion has introduced substantial risks. Lithium-ion batteries rely heavily on critical minerals such as lithium, cobalt, and nickel, whose global supply is finite and geographically concentrated [3]. Nevertheless, the supply of such minerals is inherently limited. As illustrated in Fig. 1, the International Energy Agency (IEA) projects that under stated policies scenario, these resources will become insufficient to meet global demand within the next decade. The Net Zero Emissions by 2050 Scenario represents a normative vision designed to guide the global energy sector toward achieving net-zero $CO_2$ emissions by mid-century [4]. Achieving this ambitious target would accelerate this shortage due to increased deployment of EVs and grid-level batteries. Moreover, Fig. 2 highlights a pronounced geographical imbalance in mineral distribution, exposing the battery supply chain to geopolitical uncertainties. Collectively, these challenges threaten the long-term affordability, sustainability, and resilience of the energy transition.

Meanwhile, a substantial volume of EV batteries is expected to reach the end of their first life in the coming years. As shown in Fig. 3, the Global EV Outlook 2025 [6] indicates that EV sales have surged over the past decade, and most traction batteries retire after five to eight years due to capacity fade and increased internal resistance. According to McKinsey Company, the market potential of second-life lithium-ion batteries may exceed 200 GWh per year by 2030 [7].

The growing volume of retired EV batteries has raised a pressing global challenge regarding their safe, sustainable, and economically viable management. Since retired EV batteries often retain adequate capacity for less demanding stationary applications, both industry and academia have shown increasing interest in their reuse, particularly within power system contexts. This practice, known as echelon utilization, involves repurposing retired EV batteries for

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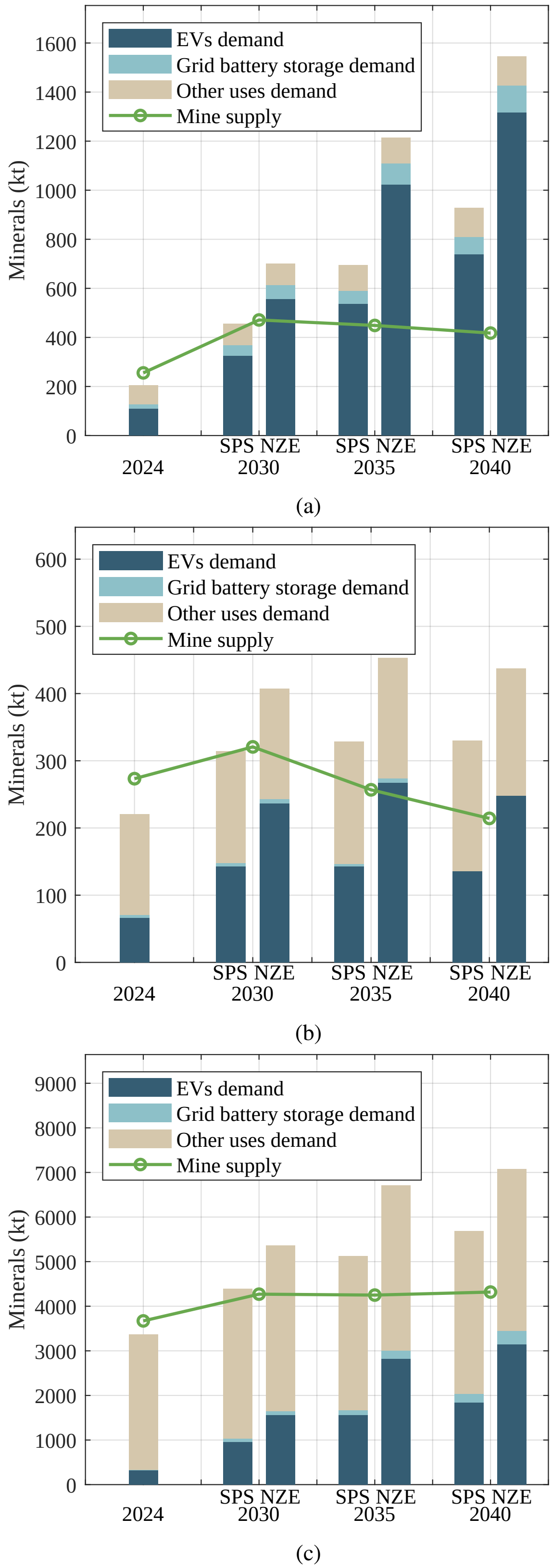


**Fig. 1:** Current and projected supply-demand balance for critical minerals. (a) Lithium. (b) Cobalt. (c) Nickel. *Note.* SPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario [5].

alternative applications. Compared with direct disposal or premature recycling, echelon utilization provides a promising approach to recovering the residual value of retired EV batteries.

The current industry landscape, summarized in Fig. 4, presents both significant opportunities and practical barriers. According to Element Energy, echelon utilization of second-life EV batteries could reduce capital costs of battery energy storage systems (BESSs) by 30%-50%, potentially attracting grid storage developers and promoting the battery circular economy [8]. Additionally, using second-life batteries helps mitigate raw material constraints and reduce battery material costs. Despite these potential win-win benefits, their deployment in power system BESSs remains limited due to technical, regulatory, and economic challenges. Addressing these challenges is essential to unlocking the full value of second-life batteries and ensuring a more sustainable battery lifecycle.

In summary, the twin challenges of mineral scarcity and the accelerating retirement of EV batteries underscore the need for effective second-life strategies. Power systems, in particular, offer a timely and practical platform for integrating second-life batteries. To fully harness this opportunity, the battery industry must overcome key technical hurdles related to state-of-health (SOH) evaluation, classification, and system integration. Close collaboration with grid storage developers is also essential to identify suitable application scenarios and establish commercially viable business models.

## 1.2. Literature review

A growing body of literature has explored the echelon utilization of EV traction batteries in recent years. Several early review articles investigated the feasibility of reusing retired EV batteries and laid out preliminary visions for the development of a circular battery industry. Based on a comprehensive assessment of second-life feasibility, Ref. [9] introduced a revised 3R strategy: redesign, reuse, and recycling. This strategy offers policy and technological guidance for the next stage of battery recovery. Drawing on updated industry reports and technical studies, Ref. [10] analyzed the techno-economic viability of large-scale second-life battery deployment, and emphasized the necessity of establishing a centralized battery-life database for accurate performance evaluation. Extending the scope beyond individual battery units, Ref. [11] introduced a systems-level framework to integrate echelon utilization into the circular supply chain, aiming to enhance the sustainability of the EV battery ecosystem. Collectively, these studies provide a solid foundation for understanding the technical and systemic aspects of second-life battery deployment.

Given that the techno-economic performance of echelon utilization is closely tied to specific application scenarios, several studies have evaluated the suitability of second-life batteries across a range of operational contexts. Ref. [12] categorized second-life battery applications into three

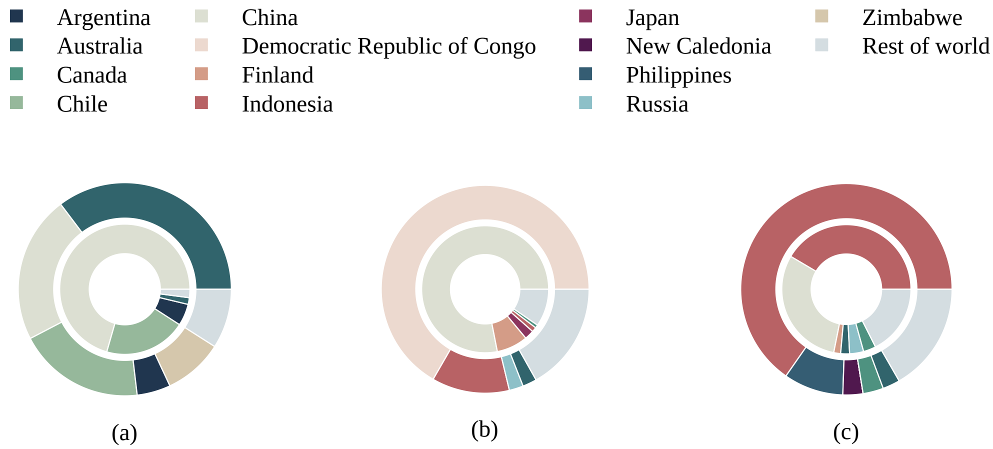


**Fig. 2:** Geographical distribution of critical-mineral mining and processing. (a) Lithium. (b) Cobalt. (c) Nickel. The outer ring depicts the geographical breakdown of critical-mineral mining output, whereas the inner ring depicts that of critical-mineral processing output. Each ring displays solely the leading countries, with "Rest of world" denoting all other areas.

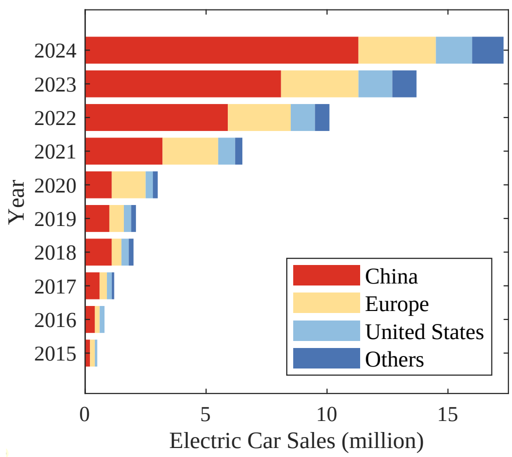


**Fig. 3:** Global electric car sales, 2015-2024 [6].


**Fig. 4:** Schematic illustration of the battery industry landscape, which highlight the importance of echelon utilization of retired EV batteries in power systems.

major types, but lacked a detailed synthesis of scenario-specific technical requirements. Ref. [13] examined operational constraints and design considerations for second-life applications, though the analysis was limited to home-storage and industrial load-leveling systems. To address this gap, Ref. [14] conducted a comparative assessment across six application scenarios and six performance dimensions, highlighting the importance of scenario matching and robust risk management to ensure safe deployment. However, a comprehensive evaluation of the technical compatibility between second-life battery characteristics and power system storage applications remains largely absent in the literature.

In parallel, considerable efforts have been devoted to the transformation process from retired EV batteries to usable second-life units, involving stages such as disassembly, inspection, sorting, and regrouping. One major bottleneck for large-scale echelon utilization is the efficient and accurate sorting of a massive volume of retired batteries. Ref. [15] tackled this issue and proposed several practical solutions. Furthering this line of inquiry, Ref. [16] emphasized that the speed and precision of battery sorting are crucial not only for performance consistency in echelon utilization, but also for enabling a closed-loop lifecycle. Two pivotal methods were introduced: a rapid classification method based on relaxation time distribution and machine learning, and a non-destructive approach leveraging electrochemical impedance spectroscopy (EIS). Ref. [17] offered a comprehensive overview of end-of-life battery evaluation from the perspectives of process integration, enabling technologies, regulatory frameworks, and technical bottlenecks. Importantly, this work discussed regrouping standards based on cell-to-cell variation, which are critical to ensuring both

**Table 1**
Comparison between this work and the existing reviews.

| Reference | Software-based BMS challenges | Application suitability | Commercial models |
|---|---|---|---|
| [9] | × | ✓ | ✓ |
| [10, 11, 15, 16, 18] | ✓ | × | × |
| [12–14] | ✓ | ✓ | × |
| [17] | × | × | ✓ |
| This paper | ✓ | ✓ | ✓ |

✓: The item is considered. × : The item is not considered.

safety and performance. Complementarily, Ref. [18] addressed safety risks by reviewing testing methodologies and proposing quantitative indicators such as the state of safety (SOS) and risk-priority number (RPN) for risk identification and prioritization in echelon applications.

Comparisons between this work and other relevant reviews are illustrated in Table 1. In brief, prior reviews on the echelon utilization of traction batteries have primarily focused on assessing the technical feasibility of sorting and regrouping retired batteries. In contrast, the specific technical challenges involved in managing second-life battery energy storage systems (SL-BESSs) have received limited systematic attention. Likewise, comprehensive analyses of viable commercial models for second-life batteries within power-system contexts are largely absent. These omissions undermine investor confidence and impede the advancement of a circular battery economy.

### 1.3. Contributions

This study addresses key research gaps in the echelon utilization of second-life batteries within power systems by investigating three core dimensions: control algorithm adaptation for battery management systems (BMS), scenario-specific adaptability within power system applications, and reconstruction strategies for battery commercial models. By analyzing recent technical advances and system integration challenges, this work aims to support the practical deployment of retired EV batteries for energy storage in power systems, thereby extending their operational lifespan and enhancing the overall life-cycle value. The major contributions are as follows:

(1) A system-level roadmap for the circular battery economy is proposed. By comparing mainstream end-of-life treatment pathways for EV batteries, this study highlights the strategic importance of echelon utilization in the power system and its role in closing the battery life cycle loop.

(2) The technical challenges and corresponding remedies related to BMS control algorithms for second-life batteries are systematically reviewed. To the best of our knowledge, this is the first work to explicitly define the control-specific issues encountered in grid-integrated applications. The insights presented support the development of tailored BMS designs that enhance the technical viability of second-life battery deployment.

(3) The adaptability of second-life batteries to diverse power system scenarios is evaluated across six key dimensions. Drawing upon recent case studies and pilot implementations, this work assesses their compatibility with generation-, grid-, and demand-side applications, thereby informing scenario-driven deployment strategies.

(4) Potential commercial models for second-life battery utilization are investigated with a focus on operational simplicity and end-user needs. These models are classified according to value-added service offerings from manufacturers, aiming to reduce adoption barriers and support scalable, market-oriented echelon utilization.

The remaining sections of this work are organized as follows. Section 2 presents a roadmap for an ideal battery circular economy. The principal challenges of managing SL-BESSs and promising technological solutions are discussed in Section 3. In Section 4, the suitability of second-life batteries for various power-system applications is examined in detail. Section 5 reviews the barriers posed by the current commercial model and the policies to second-life batteries and explores future commercial models to enhance their economic viability. Section 6 summarizes the main conclusions of this work.

## 2. Battery end-of-life treatments

Traction batteries retired from service due to maintenance, end-of-life, or performance degradation may undergo one of four treatment pathways: disposal, remanufacturing, echelon utilization, or recycling [19].

**Disposal** refers to the direct discarding or landfilling of end-of-life EV batteries [20]. This method not only wastes recoverable materials but also overlooks batteries with remaining usable capacity. More critically, landfilling poses substantial environmental risks. Discarded cells may release toxic pollutants such as hydrofluoric acid (HF) and hydrogen cyanide (HCN) [21]. Lithium-ion batteries, currently dominant in EVs, pose hazards due to lithium plating, which reacts violently with water [22]. These pollutants can contaminate air, soil, and water, threatening both ecosystems and human health.

**Remanufacturing** involves dismantling, testing, and refurbishing retired batteries to restore them for traction applications [23]. In the current industry practice, a SOH of approximately 80% is widely regarded as the threshold marking the first life end of life (FL-EOL) for electric vehicle batteries [24]. Nevertheless, retired batteries display a broad range of SOH values, and some remain sufficiently healthy to continue serving as traction batteries. These batteries are subjected to targeted repairs or component replacement and are subsequently rebuilt to meet their original performance specifications. This process shortens the supply chain and reduces energy consumption compared to full recycling or new manufacturing.

**Echelon utilization** targets batteries no longer fit for EV propulsion due to capacity fade or increased internal resistance but still functional for low-power applications. These include low-speed EVs and stationary energy storage

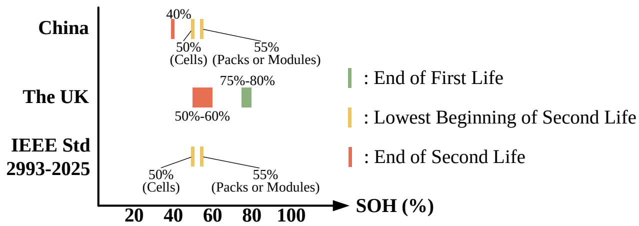


**Fig. 5:** Thresholds of SOH for second-life battery applications in China [26], the UK [27], and IEEE standards [25].

systems. For the latter, IEEE Std 2993-2025 [25] and GB/T 34015.3-2021 [26] specify that repurposed cells must still deliver at least 55% of their factory-rated capacity when discharged at a C/5 rate at room temperature. Retired cells meeting this threshold are sorted by comparable performance, regrouped, and redeployed in less demanding applications. Echelon utilization thus defers recycling and extends the useful life of battery materials.

However, Fig. 5 indicates that uniform criteria for the retirement of second-life batteries are still lacking. To date, recommended retirement thresholds for second-life batteries have been formally proposed only in China [26] and the UK [27], while many studies pragmatically take SOH = 40% [28, 29] or 60% [30–32] as the end of second-life operation. It is generally considered that a second-life battery reaches its final end of life (EoL) once it enters the accelerated degradation phase, in which the available capacity decreases rapidly and severe safety issues may arise. However, uncertainty in the knee point hampers the reliable prediction of the accelerated degradation stage, thereby hindering the establishment of unified criteria that define the end of a battery's second life.

**Recycling** applies to both first- and second-life batteries once they no longer meet required performance or safety standards. This process enables the recovery of valuable raw materials for new battery production. The recycling workflow generally comprises mechanical pretreatment followed by chemical extraction. Current chemical extraction methods include pyrometallurgy, hydrometallurgy, bioleaching, and direct recycling. Pyrometallurgy reduces cathode materials at high temperatures to stable oxides or metals, with molten-salt approaches being widely used. Hydrometallurgy, another dominant method, converts metal compounds into soluble ionic forms using chemical reagents. In contrast, bioleaching and direct recycling, though still largely at the research stage, offer enhanced environmental benefits. Bioleaching uses microbial metabolism to selectively extract metals, while direct recycling refurbishes electrodes through low-impact processes that preserve material structure [33]. Developing commercially viable and scalable processes for these greener methods remains a major research focus.

Among the four treatment options, disposal ranks lowest in both environmental and economic value. Nonetheless, an industry report by the CAS Science Team (2025) indicates that only 25% of retired traction batteries in China are collected through formal channels [34]. One contributing factor is that many EV manufacturers regard battery end-of-life handling as a financial liability rather than a source of value. Ref. [35] noted that recycling is often unprofitable, especially for lithium iron phosphate (LFP) batteries, which lack high-value metals such as cobalt and nickel. Ref. [36] further emphasizes that echelon utilization may offer greater economic and environmental benefits than recycling, given the immaturity of current recycling technologies.

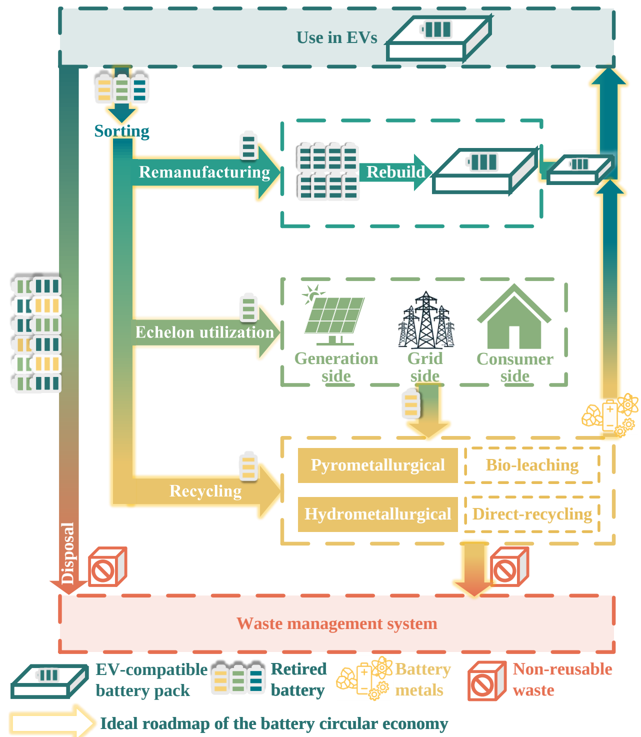


**Fig. 6:** Process illustration of the prevailing end-of-life EV battery treatment options.

Building on the preceding analysis, Fig. 6 presents a roadmap for an ideal battery circular economy. Following dismantling and diagnostic evaluation, retired EV traction batteries are classified according to their SOH. Batteries that meet traction-grade requirements are remanufactured and reintroduced into EV service. Those suitable for less demanding applications are redeployed through echelon utilization. The remaining batteries, which fall below reuse thresholds, are directed to recycling for material recovery. This tiered approach minimizes environmental impact by reducing landfill and hazardous waste, while deferring recycling to allow time for environmentally friendly technologies to mature and scale.

In parallel, the rapid expansion of photovoltaic and wind power is creating a substantial demand for stationary energy storage. Unlike EVs, power system applications impose less stringent energy density requirements but are highly cost-sensitive. These characteristics render the power system a particularly suitable domain for the echelon utilization of retired EV batteries.

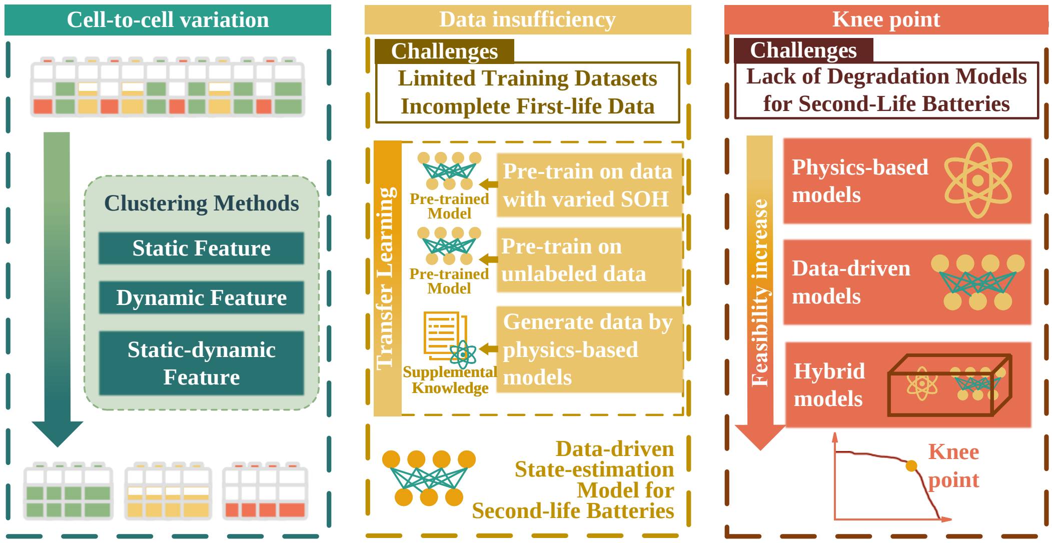


**Fig. 7:** Schematic representation of key technical challenges in software-based battery management for SL-BESSs.

## 3. Software-based battery management technologies

Despite the advantages of reduced capital costs and eased resource constraints, the integration of second-life batteries into power systems necessitates specific adaptations to software-based battery management technologies. As illustrated in Fig. 7, three key challenges confront the design and implementation of battery management algorithms in SL-BESSs: cell-to-cell variation, data insufficiency, and degradation knee point prediction.

**Cell-to-cell variation** refers to the pronounced heterogeneity in both internal characteristics and observable performance among cells within a second-life battery pack. Minor manufacturing deviations among cells are progressively amplified during long-term cycling, which in turn aggravates performance divergence [37]. Meanwhile, cell-to-cell variation stems from the diverse operational profiles and environmental exposures encountered by individual cells during their first life [17, 38]. Although IEEE Std 2993-2025 [25] specifies cell-level consistency requirements for SL-BESSs based on static indicators, inconsistencies at the module and pack levels, as well as the dynamic inconsistency of batteries, still need to be addressed by advanced battery management technologies.

**Data insufficiency** constitutes a fundamental limitation in the management of second-life batteries, particularly when compared with first-life systems. While numerous open-access datasets exist for new lithium-ion cells, such as those from Panasonic [39] and the Oxford Battery Degradation Project [40], publicly available data specific to second-life batteries remain scarce. This lack of data hampers the development of accurate state estimation algorithms and long-term degradation models for SL-BESSs. The issue is further compounded by the frequent unavailability or incompleteness of first-life operational records, often due to data privacy restrictions or the absence of standardized recording protocols.

**The degradation knee point** refers to the inflection region on a battery's capacity fade curve where the rate of degradation accelerates markedly [41]. This phenomenon is generally attributed to complex internal transitions within the cell, which are largely unobservable through external sensing. Experimental investigations, such as that by Braco et al. [42], have implicated lithium plating as a key contributing factor. Building on this, Ref. [43] provides a broader classification of potential mechanisms, identifying six principal categories: additive depletion, electrode saturation, lithium plating, mechanical deformation, percolation-limited connectivity, and resistance growth. Despite these efforts, the development of a universal and predictive model for knee point behavior remains elusive, posing a significant barrier to accurate long-term performance forecasting in second-life battery applications.

To further examine these technical bottlenecks, the following subsections elaborate on each challenge in turn: cell-to-cell variation, data insufficiency, and knee point prediction.

### 3.1. Cell-to-cell variation

According to the Cannikin law, the capability of a battery pack is limited by its worst-performing cell, which means that cell-to-cell variation directly affects the system reliability. If cell heterogeneity is ignored, the pack may suffer overcharging or over-discharging, which could induce thermal runaway and ultimately fire hazards [44]. Consequently, clustering-based cell classification is crucial for efficiently managing the large cell population in large-scale SL-BESSs and for prolonging the second-life duration of batteries.

With respect to feature selection, clustering methods for second-life batteries fall into three categories: static feature sorting, dynamic feature sorting, and static-dynamic fusion feature sorting [45].

Static features capture a battery's performance under nonworking conditions, such as SOH, state of charge (SOC) and open circuit voltage (OCV). Ref. [46] clustered the cells solely by SOC to identify those requiring balancing, thereby efficiently mitigating SOC inconsistency. Farakhor et al. [47] applied a K-means clustering algorithm to group cells by SOC, temperature, and internal resistance. Subsequently, a representative electro-thermal model was built for each cluster to capture its aggregated dynamics, thereby reducing the computational burden of large-scale BESSs. The advantage of static feature clustering methods is that they provide fast and straightforward classification of second-life batteries. Consequently, static features have emerged as a dominant option to mitigate internal inconsistency within heterogeneous BESSs in current research. However, they ensure only static consistency and may fail to maintain it during operation.

Conversely, dynamic feature sorting methods rely on inputs such as voltage curves and EIS. These features enable a detailed characterization of cell dynamics. As an illustrative example, EIS provides information about multiple internal parameters and processes inside the battery. Lai et al. [48] used a backpropagation neural network (BPNN) to infer battery capacity directly from EIS data, which supports rapid sorting of cells for second-life applications. Nevertheless, Nevertheless, accurate EIS measurements are costly and require lengthy testing procedures, so they are generally unsuitable for on-board implementation. To overcome this limitation, Locorotondo et al. [49] realized fast EIS measurement using pseudo-random binary sequence (PRBS) excitation and applied the measured spectra for cell clustering, enabling on-board clustering and accurate real-time diagnosis of cells with different health conditions. However, the applicability of this approach to large-scale SL-BESSs with vast numbers of cells remains to be fully assessed. Compared with EIS, voltage profiles are significantly easier to acquire than EIS measurements. A rapid screening scheme built on LightGBM is introduced in [50], relying solely on partial charge/discharge curves to cut testing time without sacrificing accuracy. To enhance classification reliability, Liu et al. [51] developed an enhanced fusion-clustering algorithm that takes voltage curves as input. Based on adjustable parameters and cluster numbers, it can accommodate multiple scenarios featuring different capacity distributions. However, centrally classifying all cells in large-scale SL-BESSs based on dynamic characteristics incurs substantial computational overhead, rendering the direct application of dynamic feature sorting methods infeasible.

To combine the strengths of the two preceding classification schemes, static-dynamic fusion feature sorting methods have attracted extensive attention. Yin et al. [52] proposed a two-stage sorting method for retired batteries. In the first stage, second-life cells are preliminarily grouped by discharge capacity and temperature rise to eliminate anomalies and determine the prospective cluster count K. In the second stage, dynamic features extracted from voltage curves are supplied to a K-means++ algorithm, enabling efficient and comprehensive classification of large retired-battery populations. Pan et al. [53] proposed a multi-stage sorting strategy for retired batteries that clusters both static and dynamic features. To identify discriminative and interpretable static features, this method employs Pearson-correlation analysis to select low-correlation static variables that reveal the cells' internal state. Static-dynamic fusion feature sorting approaches generally partition the classification process into two distinct stages. Initially, static feature-based classification enables rapid grouping of cells. In the second stage, each group utilizes distributed computing resources to perform more refined classification based on dynamic characteristics. Looking ahead, clustering methods that combine static and dynamic features could deliver efficient, accurate cell classification for large-scale SL-BESSs. This capability would strengthen consistency management across the entire system.

### 3.2. Data insufficiency

Data insufficiency remains a critical barrier to effective energy management in SL-BESSs, especially for data-driven methods used in battery state estimation. Inaccurate SOC and SOH estimation can increase the risk of over-charging or over-discharging, which may trigger fire hazards. Cheng et al. [54] proposed an optimal dispatch approach for second-life batteries with online SoH estimation based on Gaussian process regression (GPR). However, the proposed method is unable to estimate SOH at the early stage of second-life operation. Similarly, the long short-term memory (LSTM)-based SOC estimation approach for second-life batteries in [55] suffers diminished effectiveness because data insufficiency may induce overfitting [56].

The integration of transfer learning offers notable potential for battery state estimation in the presence of data insufficiency for second-life cells because of the ability to reuse or transfer knowledge from previously learned tasks [57]. Shu et al. [58] proposed a long-term SOH prediction model by coupling a transfer-learning strategy with a LSTM network. On the basis of the pre-trained model based on the first 40 % of cycling data, this framework can rapidly yields a new SOH prediction model by fine-tuning the partial parameters based on a new data set, which eliminates the problem of information loss caused by the data insufficiency. To address the issue of data scarcity, Ref. [59] proposed a deep generative transfer learning framework for building the battery SOH estimation model adaptable to different degradation modes. This framework outperforms state-of-the-art machine learning methods and equivalent circuit model-based methods across all data availability conditions. Due to battery degradation reduces nominal capacity and alters internal electrochemical reactions, the SOC estimation models trained on open-source datasets for new cells perform poorly on second-life batteries. Liu et al. [60] explored LSTM-based SOC estimation schemes augmented with transfer learning to accommodate batteries at various health states. By fine-tuning the parameters of the fully

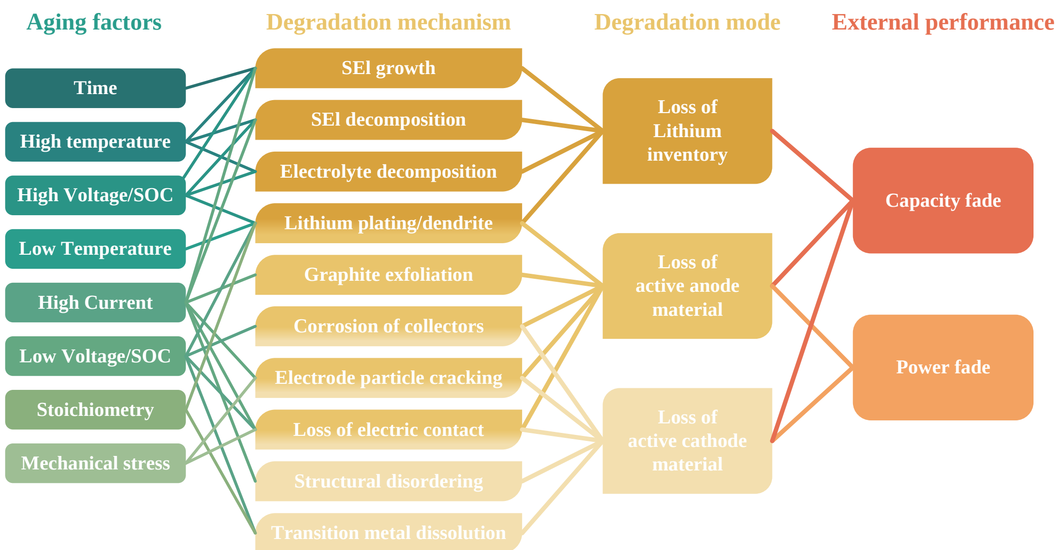


**Fig. 8:** The potential aging factors and mechanisms for lithium-ion batteries, adapted from [18].

connected layer, the transfer-learning algorithm enables precise SOC estimation at SOH of 96.3%, 89.5%, and 87.3%, thereby enhancing the model robustness under degradation. Furthermore, incorporating self-supervised learning into the transfer-learning pre-training stage could unlock the full value of unlabeled data, thereby easing the data-scarcity bottleneck in SOH estimation in the future [61].

It is noteworthy that a particular implementation of transfer learning has attracted wide attention for addressing data insufficiency [62]. In this architecture, the data-driven model is trained on both the limited experimental data and the extensive datasets generated by physics-based models. It migrates the supplemental knowledge of physics-based models into practical SOH estimation for second-life batteries [63]. Zhu et al. [64] combined simulation data produced by the porous electrode theory-based degradation models with real-world data to build a precise SOH estimation for second-life batteries, which is challenging owing to the incompleteness of first-life data. Mitigating data insufficiency enables the BMS to leverage more accurate battery information for power allocation, which improves SL-BESS reliability and prolongs the batteries' second-life operation.

## 3.3. Knee point

Once the battery capacity declines beyond the knee point, the rate of degradation accelerates sharply, increasing the likelihood of failure. Accordingly, accurate knee point identification is crucial for estimating the RUL of second-life batteries and for extending their second-life duration. Reliable RUL prediction depends on robust degradation modeling, which can be broadly classified into physics-based models, data-driven models, and hybrid modeling approaches [62].

Physics-based models embed known aging mechanisms into electrochemical formulations such as the pseudo-two-dimensional (P2D), single-particle (SPM), and enhanced SPM (ESPM) models [65], providing strong interpretability. However, the partial differential equations (PDEs) underpinning these models are computationally intensive and often unsolvable by conventional solvers in real-time applications [66], thereby limiting their practical deployment. It is even worse that an effective generic physical model for knee points has yet to be established. As illustrated in Fig. 8, multiple degradation mechanisms, including solid electrolyte interphase growth, lithium plating, and structural deformation, contribute to capacity fade [67], with dominant mechanisms varying across different degradation stages [68]. However, the unclear physical underpinnings of the knee point significantly hinder the construction of mechanistic models.

In contrast, data-driven models estimate battery degradation and RUL based on observed historical data, without relying on prior electrochemical knowledge. A common approach is the semi-empirical model, which fits degradation curves using power-law formulations derived from extensive cycle testing [69]. However, the absence of large-scale testing matrices for second-life batteries limits the generalizability of such models. For instance, while Ref. [70] suggests adjusting the power-law exponent to account for prior usage, the effectiveness of such adaptation remains unverified. More recent approaches employ machine learning methods. Ref. [71] proposed a Gaussian process regression model that adaptively weighs input variables based on their relevance to degradation behavior. Yet, the model remains constrained to controlled laboratory settings. To enhance real-world applicability, Sohn et al. [72] introduced a two-stage convolutional neural network (CNN) that extracts temporal features from historical and real-time cycling data to identify cells approaching the knee point and forecast the remaining number of cycles before critical degradation.

**Table 2**
Hybrid modeling approaches to overcome the limitations of physics-based and data-driven battery models.

| Modeling approach | Limitations | Description of the method to address the limitations | Reference |
|---|---|---|---|
| Physics-based model | High computational burden | Help with solving PEDs. | [78] |
| | Unknown dominant degradation mechanisms | Distinguish the degradation mechanisms. | [79] |
| Data-driven model | High data demand and limited interpretability | Integrate physical insight into data-driven frameworks. | [74–77] |

Although data-driven approaches have demonstrated impressive performance, models that do not incorporate explicit aging mechanisms may diverge from actual cell degradation behavior due to limited interpretability [73]. Hybrid modeling approaches that integrate physical insight into data-driven frameworks offer a promising alternative. For instance, Ref. [74] proposed a hybrid method that combines Bayesian inference with linear regression to accurately identify knee point in conventional and accelerated aging lithium-ion batteries online. There are also some hybrid approaches that works to lessen the amount of data required. By embedding physically meaningful parameters derived from degradation mechanism models [75], the model maintains high accuracy even under incomplete data conditions. In a related work, Ref. [76] incorporated support vector regression (SVR) with mechanism-derived features to improve operational precision. More recently, Jia et al. [77] introduced a physics-guided machine learning framework for knee point prediction, which integrates electrode-level physical constraints during model training. By embedding domain-specific knowledge into the learning process, this approach enhances interpretability while maintaining predictive robustness on small datasets.

In addition, hybrid modeling approaches have the potential to overcome two major limitations of physics-based methods: high computational burden and unknown dominant degradation mechanisms. Physics-informed neural network (PINN) offers a promising framework for PDEs by leveraging deep learning models trained via automatic differentiation [78]. Similarly, Ref. [79] employed the PINN framework to extract mechanistic insights into failure evolution by integrating physical laws into data-driven models, indicating the potential of hybrid modeling approaches to deepen future understanding of the governing degradation mechanisms behind knee-point behavior.

In summary, the complex and often latent mechanisms underlying the knee point pose substantial challenges for both mechanistic and purely data-driven approaches. As shown in Table 2, hybrid modeling approaches leverage the complementary strengths of physics-based reasoning and data-driven generalization. These approaches are emerging as a promising pathway toward accurate knee-point prediction and RUL estimation in SL-BESSs.

## 4. Second-life battery applications in the power system

Although the cost advantages and demand compatibility of second-life batteries are widely recognized, a significant gap remains in aligning these batteries with the specific requirements of various power system applications. While numerous demonstration projects have been implemented globally, systematic assessments of scenario suitability are still insufficient, particularly in terms of performance tolerance, economic viability, and operational risk. To provide context, Table 3 summarizes representative pilot projects, followed by a multi-dimensional analysis of the compatibility of second-life batteries across different segments of the power system.

### 4.1. Generation side

Given the inherent intermittency, volatility, and randomness of solar and wind resources, BESSs are predominantly integrated with photovoltaic plants and wind farms on the generation side. Their integration enhances plant performance and reduces operational costs.

Specifically, the intermittent nature of renewable energy sources necessitates the use of BESSs for flexible energy management to meet the ramp rate compliance (RRC) required by the grid. However, the high cost of new batteries remains a significant barrier to large-scale deployment. To mitigate this economic burden, Ref. [105] proposes replacing new batteries with second-life batteries and optimally sizing SL-BESSs to maintain ramp rates within permissible ranges. This study also incorporates scenarios with large recorded energy demands to justify the use of larger SL-BESS capacities and validates feasibility using real photovoltaic generation data from a Spanish plant. Similarly, Ref. [106] demonstrates the cost-effectiveness of SL-BESSs in mitigating ramp-rate violations. Acknowledging the potential stress caused by frequent charging and discharging, the authors developed an innovative control method known as the moving average ramp rate controller (MARRC) algorithm, which minimizes unnecessary battery operation. Drawing on a real-world smoothing profile from a PV system in Ethiopia, the study shows that second-life batteries seldom operate at C-rates exceeding 1 and undergo relatively constant degradation while supporting renewable energy integration.

**Table 3**
Representative pilot projects involving second-life batteries in power system applications.

| Leading entity | Application | Size | Location |
|---|---|---|---|
| Element Energy and Nextera Energy Resources | Integration with renewable energy | 53 MWh | USA [80] |
| BMW and Vattenfall | Integration with renewable energy | 12 MWh | Netherlands [81] |
| B2U | Integration with renewable energy | 10 MWh | USA [82] |
| B2U | Integration with renewable energy | 1.5 MW/12.5 MWh | USA [82] |
| B2U | Integration with renewable energy | 3 MW/28 MWh | USA [83] |
| Alfen | Integration with renewable energy | 3 MW | Holland [84] |
| BMW and Vattenfall | Integration with renewable energy | 33 MWh | UK [85] |
| BAK POWER BATTERY and CSG ENERGY | Frequency regulation<br>Peak shaving | 2 MW/7.2 MWh | China [86] |
| Alfen and Vattenfall | Frequency regulation<br>Peak shaving | 5 MW/20 MWh | Sweden [87] |
| Daimler, The Mobility House, GETEC and REMONDIS | Frequency regulation | 13 MWh (Second-life batteries accounted for 90% of the share.) | Germany [88] |
| BMW, Bosch and Vattenfall | Frequency regulation | 2 MW/2.8 MWh | Germany [89] |
| Audi and RWE | Frequency regulation | 4.5 MWh | Germany [90] |
| Connected Energy | Frequency regulation | 1.2 MW/0.72 MWh | Belgium [91] |
| FCA and ENGIE EPS | EV charging station<br>Frequency regulation | 25 MW (Second-life batteries account for an unknown share.) | Italy [92] |
| NISSAN | Backup power | 4 MW/1.7 MWh | Spain [93] |
| The Office of Environmental Programs at City of Phoenix | Commercial and industrial energy storage | Total 0.08 MWh (Second-life batteries are deployed in five separate locations in Phoenix.) | USA [94] |
| Aeroporti di Roma | Commercial and industrial energy storage | 2.5 MW/10 MWh | Italy [95] |
| Johan Cruijff ArenA, Enel X and Fraunhofer ISE | Commercial and industrial energy storage | 3 MW | Holland [96] |
| NISSAN | Commercial and industrial energy storage | - | Japan [97] |
| NISSAN | Energy storage for buildings | - | South Africa [93] |
| NISSAN | Energy storage for buildings | 1.5 MWh | USA [93] |
| NISSAN | Energy storage for buildings | 0.0042 MWh | Europe [98] |
| General Motors and ABB | Energy storage for buildings | 0.025 MW/0.05 MWh | USA [99] |
| EnerDel and ITOCHU | Energy storage for buildings | - | Japan [100] |
| Powervault and Renault | Energy storage for buildings | - | UK [101] |
| Connected Energy | Energy storage for buildings<br>EV charging station | 0.3 MW/0.36 MWh | UK [102] |
| Galp and TES | Energy storage for buildings<br>EV charging station | 0.18 MW/0.368 MWh | Spain [103] |
| BMW and HUAYOU | EV charging station | - | China [104] |

Because project disclosures are non-uniform, the size data of certain SL-BESS installations are incomplete.

In addition, second-life batteries can serve as power output compensators, mitigating renewable generation forecast errors to better meet dispatch requirements. In [107], an evaluation framework is developed to assess the potential of SL-BESSs in reducing dispatch costs by absorbing forecast errors in load and wind generation. With the advancement of forecasting technologies, the magnitude of prediction errors has been significantly reduced, thereby lowering the need for second-life batteries to operate at high C-rates to enhance planning accuracy.

At present, alleviating transmission congestion is a top priority for generator-side storage applications. This task, however, requires SL-BESSs capable of sustained energy discharge over extended durations. To reduce energy curtailment, surplus energy during congestion periods must be stored and later released when system constraints are relieved [108]. Since such congestion events can last for several hours, this scenario imposes stringent requirements on discharge duration and system capacity, thereby necessitating large-scale SL-BESS deployments. As shown in Table 3, despite operational challenges related to the management of large fleets of second-life battery cells, major stakeholders are actively advancing pilot projects that explore the integration of SL-BESSs into renewable energy systems. This momentum is largely driven by the fact that generator-side storage demands large energy capacities, while imposing only moderate requirements on conversion efficiency and energy density.

## 4.2. Grid side

### *4.2.1. Frequency regulation*

As the penetration of photovoltaic and wind turbine units increases, system inertia is gradually declining, leading to a significant rise in the rate of frequency change over short time intervals. Grid-scale BESSs play a vital role in mitigating the temporal variability introduced by intermittent renewable generation sources [109]. Although Robson et al. [110] suggest that replacing new batteries with second-life batteries can improve net profits in frequency regulation markets, their analysis overlooks the impact of rapid charge-discharge cycles on the SOH of second-life batteries.

Table 3 indicates that high C-rate capability is usually essential, since frequency-regulation storage must supply or absorb considerable power in sub-second intervals. However, this mode of operation may lead to lithium plating, which is a major factor contributing to the onset of the knee point in second-life batteries, as discussed in Section 3. In this context, White et al. [111] conducted a comprehensive assessment of six retired EV battery types for frequency regulation applications, providing practical guidance on selecting suitable candidates for second-life BESS deployment. Their experimental results show that batteries with higher energy conversion efficiency can significantly reduce operating costs by lowering the energy required to maintain a stable SOC.

Finally, revenue in frequency regulation markets typically consists of both capacity and performance compensation. As outlined in Section 3.2, second-life batteries still face challenges in achieving rapid and accurate SOC estimation. This limitation not only degrades performance but also undermines their competitiveness in frequency regulation services.

### *4.2.2. Peak shaving*

In peak shaving scenarios, energy storage systems generate profit by shifting energy consumption from low-demand periods (valleys) to high-demand periods (peaks). The profitability of such operations depends primarily on the cost of energy storage and the differential between peak and off-peak electricity prices. Due to their lower capital cost, second-life batteries present a promising solution for this application, particularly under the premise of delivering environmental benefits [112], and are especially attractive when deployed by grid operators [113].

Rahil et al. [114] tested a second-life battery pack comprising 84 series-connected cells under peak shaving duty cycles. Their results confirmed the battery pack's compatibility with peak shaving operations, largely due to the long resting periods between charging and discharging, which allow the system to return to electrochemical and thermal equilibrium and thereby improve performance. Although second-life batteries have demonstrated encouraging laboratory performance in peak shaving applications [115], practical implementations typically require large storage capacities to support sustained charge/discharge operations [14].

At present, the availability of SL-BESSs at sufficient scale for practical peak shaving remains limited. For example, RWE is currently constructing a 600 MW/1.2 GWh battery storage facility in Germany dedicated to peak shaving services [116]. In contrast, the 53 MWh SL-BESS operated by NextEra Energy Resources remains the largest second-life battery installation known to date [80]. This stark difference in scale raises concerns about the competitiveness of SL-BESSs in large-scale peak shaving applications.

### *4.2.3. Backup power*

Unexpected power outages and scheduled maintenance activities often interrupt power generation due to equipment failures or aging in power plants. Moreover, black start procedures require an external power source to reinitiate operations following a complete shutdown, underscoring the importance of reliable backup energy reserves to support plant continuity and grid resilience [117]. The secure operation of modern power grids depends on the availability of substantial backup energy capacity.

Because backup energy systems are infrequently used, they generally exhibit extended payback periods and can accommodate relatively lower energy conversion efficiencies. These characteristics align well with the technical and economic profile of second-life batteries, which offer reduced capital costs and fast response times. Consequently, SL-BESSs are considered a promising solution for backup applications.

Although dedicated second-life BESS installations for backup use are still limited, their technical feasibility and economic potential have been demonstrated. For instance, Kostenko et al. [118] validated the cost-effectiveness of SL-BESSs in such applications. In addition, Debnath et al. [119] proposed a backup energy system that aggregates electric vehicles and second-life batteries to supply energy during scheduled outages. They developed a load scheduling model that confirmed the economic viability of this approach while enhancing overall grid reliability.

## 4.3. Demand side

The integration of second-life batteries with local loads can significantly lower electricity expenditures and reduce dependence on the grid. Typically, behind-the-meter energy storage systems are geographically distributed, impose less stringent constraints on continuous discharge time and energy density. These characteristics make second-life batteries highly promising for demand-side deployment.

### *4.3.1. Microgrid*

With the increasing deployment of distributed energy resources, microgrids have emerged as a practical solution for addressing localized supply-demand imbalances. Stationary ESSs play a crucial role in balancing local loads, improving energy flow efficiency, and enhancing microgrid reliability. Owing to their cost advantages, second-life batteries represent a promising and economically viable option for energy storage within microgrids [120].

Bai et al. [121] conducted an economic evaluation of second-life battery deployment in an isolated microgrid, employing a reliability-oriented iterative design framework to determine the optimal microgrid configuration. Their results indicate that second-life batteries outperform new batteries in terms of cost-effectiveness, particularly under conditions of stringent reliability requirements and low electricity tariffs. However, microgrids often serve remote or isolated regions with harsh conditions such as high C-rates, low temperatures, and high humidity. These factors accelerate battery degradation. Therefore, at the planning stage, the influence of the microgrid environment on SL-BESS maintenance complexity should be carefully evaluated, in order to avoid situations where the plant fails to recover its investment due to premature battery failures [122].

Furthermore, transportation costs for deploying and maintaining SL-BESSs in remote areas are non-negligible and must be evaluated alongside battery aging characteristics inherited from first-life usage. In this context, Alharbi et al. [123] developed a microgrid planning model incorporating a degradation mechanism of retired EV batteries, aiming to balance capital investment with long-term maintenance and replacement costs.

### *4.3.2. Commercial and industrial energy storage*

Stationary energy storage systems are increasingly deployed in commercial and industrial (C&I) parks to improve supply reliability and reduce electricity expenses. On the basis of the Italian scenario, Berzi et al. [124] simulated a model integrating a second-life EV battery with PV generation and a mobile network base station. Their results reveal that the SL-BESS can guarantee at least three hours of backup for the mobile network station while exploiting its energy-shifting capability to reduce system operating costs and carbon emissions. Currently, a large number of second-life battery projects are integrated with C&I parks. For example, in the PIONEER project, an SL-BESS stores excess daytime electricity generated by a 30 MW photovoltaic plant and discharges it during peak hours to meet the energy demand of Leonardo da Vinci Airport [95].

Given the sensitivity of C&I users to capital investment, second-life batteries represent a promising solution for cost-effective storage deployment. Unlike remote microgrids, C&I systems generally operate under more controlled environmental conditions, avoiding high C-rates, elevated temperatures, or high humidity. These conditions mitigate the risk of accelerated degradation in SL-BESSs. However, the relatively low energy density and high internal resistance of second-life batteries may result in increased land use and operating costs. Therefore, optimal SL-BESS deployment in C&I contexts requires a comprehensive cost-performance trade-off analysis.

### *4.3.3. Energy storage in buildings*

Building-integrated energy storage systems serve to reduce electricity expenses and improve supply reliability. The characteristics of residential energy storage are similar to those of commercial and industrial parks, though typically on a smaller scale. As a result, second-life batteries reduce upfront investment barriers, offering an affordable pathway for building electrification, which benefits both residents and the grid [125].

Nissan has been active in this area, having launched several pilot projects across Europe, the Americas, and Africa. For example, in the xStorage Home project, Nissan developed a compact residential SL-BESS that enables households to capture and store renewable energy [98].

### *4.3.4. EV charging station*

The stochastic behavior of EV users places increasing stress on the power grid, a challenge that grows with EV adoption. Energy storage systems deployed at EV charging stations are typically modest in scale, with limited demands for energy density or environmental robustness. This makes SL-BESSs suitable for serving as energy buffers, smoothing power fluctuations during peak charging periods and mitigating sudden impacts on the grid [126].

A comparative study in Ref. [127] assessed grid-only and SL-BESS-supported fast-charging configurations across five cities, demonstrating the ability of SL-BESSs to reduce both levelized electricity costs and global warming potential. Several pilot projects have explored this application. For example, the Volkswagen Group repurposes end-of-life EV batteries for use in fast-charging stations, extending battery service life [128].

However, potential high C-rate operations during peak intervals may significantly accelerate battery degradation. In addition, the increased internal resistance in second-life batteries reduces energy conversion efficiency. These factors warrant ongoing monitoring of pilot projects to assess the long-term viability and profitability of SL-BESSs in EV charging applications.

### 4.4. Comprehensive evaluation

Different energy storage applications impose distinct performance requirements on BESSs. Moreover, pronounced gaps in management complexity, degradation dynamics, and external performance distinguish second-life batteries from new units. Appropriately matching second-life batteries with suitable application scenarios constitutes a key strategy for extending their second-life operation [30, 31]. Accordingly, this section categorizes the requirements into six key dimensions: system size, battery power level, environmental tolerance, energy density, energy conversion efficiency, and battery reliability.

System size determines the energy that an SL-BESS can supply, and is therefore pivotal for time-shift applications, such as integration with renewable energy and peak shaving. This dimension is evaluated chiefly with reference to the sizes of second-life battery pilot projects listed in Table 3. Due to their inherently lower energy density compared to new batteries, second-life batteries typically require larger installations to meet extended discharge needs, thereby increasing the burden on the BMS. This challenge is exacerbated by significant cell-to-cell variations commonly observed in SL-BESSs.

The battery Power level demanded by an application governs the frequency of high-C-rate operation, which raises the likelihood of encountering the knee point in second-life batteries and potentially leads to premature failure. This requirement is evaluated mainly through qualitative analysis and by consulting the power-to-energy ratios of pilot projects listed in Table 3.

Battery reliability requirements reveal an application's priority. They indicate whether the project cares more about limiting performance degradation or about lowering upfront capital cost. Given that batteries typically account for more than half of the total BESS capital expenditure [129], developers must strike a balance between reliability and economics. Cost-sensitive applications, such as integration with renewable energy, may prefer second-life batteries for their lower upfront costs. In contrast, performance-critical applications, such as frequency regulation or EV fast charging, often prioritize reliability and are more tolerant of higher capital costs.

Energy density, expressed in $Wh \cdot kg^{-1}$ or $Wh \cdot L^{-1}$ [130, 131], reflects the amount of energy a battery stores per unit of mass or volume. The assessment of energy-density requirements for an SL-BESS centres on land cost, which varies with site location and overall system size.

Energy conversion efficiency measures the ratio of retrievable output energy to the energy input during charging. The elevated internal resistance in second-life batteries generally leads to reduced energy efficiency, which directly affects the economic performance of SL-BESSs.Consequently, applications that demand a high battery Power level and frequent dispatch place particular emphasis on the energy conversion efficiency of the energy storage system.

Environmental tolerance refers to the system's ability to operate under challenging environmental conditions, such as high humidity or low ambient temperatures. These factors are known to accelerate battery aging, yet empirical data specific to second-life batteries under such conditions remain limited. Therefore, environmental compatibility, largely governed by site location, constitutes a crucial consideration when assessing SL-BESS suitability.

Based on the qualitative analyses presented in Sections 4.1 to 4.3, Fig. 9 summarizes the six-dimensional requirement profiles for various application scenarios. Each requirement is categorized as "High", "Medium", or "Low". The higher the requirement level of a given application, the greater the technical and economic challenges for implementing SL-BESSs. For comparison, panel (i) in Fig. 9 includes the BESS requirements for EVs, which are consistently high across all six dimensions. Applications whose demands are less stringent are expected to incorporate second-life batteries sooner. By contrast, applications that impose high demands in these six dimensions are likely to defer adoption until the economic performance of pilot projects is demonstrated.

## 5. Commercial models, policies, and standards for second-life batteries

The feasibility of echelon utilization depends not only on technological advancements but also on the establishment of sustainable commercial models that support industrial development and large-scale deployment. The long-term profitability of SL-BESSs is determined by both strategic and operational capabilities [132]. Strategic capability is primarily associated with the scheduling of charging and discharging across the system, while operational capability involves the real-time monitoring and management of internal battery conditions, as discussed in detail in Section 3.

Based on the delineation of responsibilities between strategic planning and operational execution, the existing and prospective commercial models for second-life batteries can be classified into four distinct types: Battery-as-a-Product (BaaP), Battery-as-a-Service (BaaS), Platform-as-a-Service (PaaS), and Energy-as-a-Service (EaaS). Among them, field deployments of the latter two remain unreported. These models differ in ownership structure, value creation mechanisms, and risk allocation. Table 4 presents a comparative analysis of these four models across key operational and business dimensions. Fig. 10 further illustrates the relationship structures among manufacturers, service providers, and end users under each model.

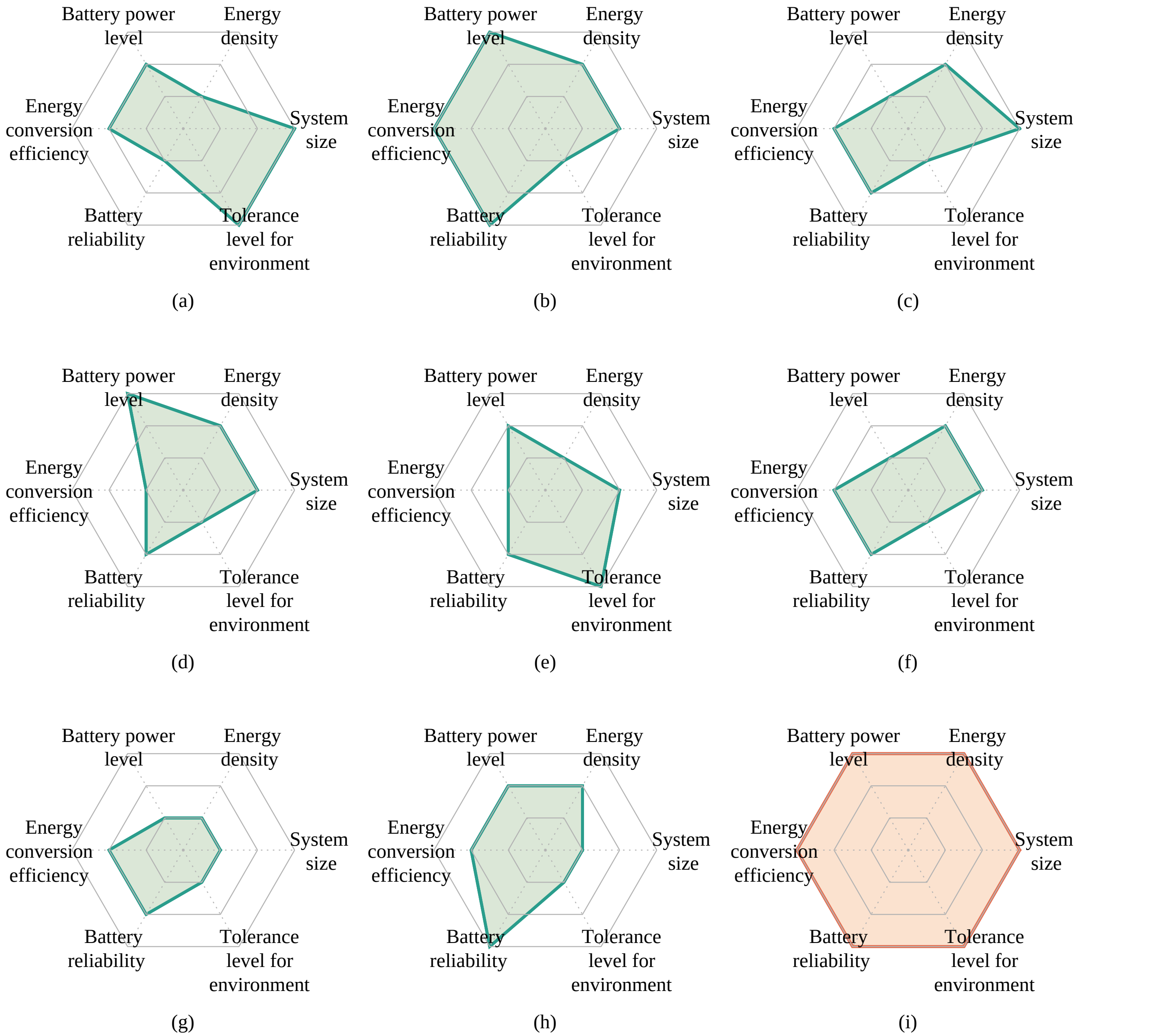


**Fig. 9:** Qualitative multi-dimensional suitability evaluation of SL-BESSs across power system applications. (a) Integration with renewable energy. (b) Frequency regulation. (c) Peak shaving. (d) Backup power. (e) Microgrid. (f) Commercial and industrial energy storage. (g) Energy storage in buildings. (h) EV charging station. (i) EVs.

## 5.1. Battery-as-a-Product

BaaP is the traditional framework for assigning responsibilities within energy-storage facilities [133]. In the BaaP model, users retain battery ownership and assume all operational and planning duties, while the second-life battery provider limits its role to storage system construction and warranty support. Users are required to cover the full capital cost of SL-BESS construction and bear all subsequent operation and maintenance (O&M) expenses. Ownership of the SL-BESS, along with essential first-life battery data, is transferred in full from the manufacturer to the user. Although this model grants users significant discretion over the SL-BESS, it imposes a high technical barrier, and the potentially elevated O&M costs may deter many users from adopting second-life batteries.

Even with minimal post-sale involvement, manufacturers are responsible for ensuring secure and unaltered transfer of first-life battery data. Accordingly, manufacturers are inclined to disclose only the traceability information mandated by prevailing standards or regulations. Currently, there exist jurisdictions that have established battery traceability systems through which users can access essential battery data. For instance, the EU plans to implement a battery passport scheme to promote a circular economy for batteries. However, it remains contested whether the restricted data offered by battery traceability platforms can uphold the

**Table 4**
Comparison of different commercial models for second-life batteries.

| Commercial model | Ownership | Battery maintainer | Strategy maker | User initial investment | Required user expertise | User-borne O&M cost | Manufacturer's discretion over SL-BESS | Risk of first-life data leakage |
|---|---|---|---|---|---|---|---|---|
| BaaS | User | User | User | ○○○ | ○○○○ | ○○○○ | ○ | ○○○○ |
| BaaS | User | Manufacturer | User | ○○○○ | ○○○ | ○ | ○○ | ○ |
| PaaS | Manufacturer | Manufacturer | User | ○○ | ○○ | ○ | ○○ | ○ |
| EaaS | Manufacturer | Manufacturer | Manufacturer | ○ | ○ | ○ | ○○○○ | ○ |

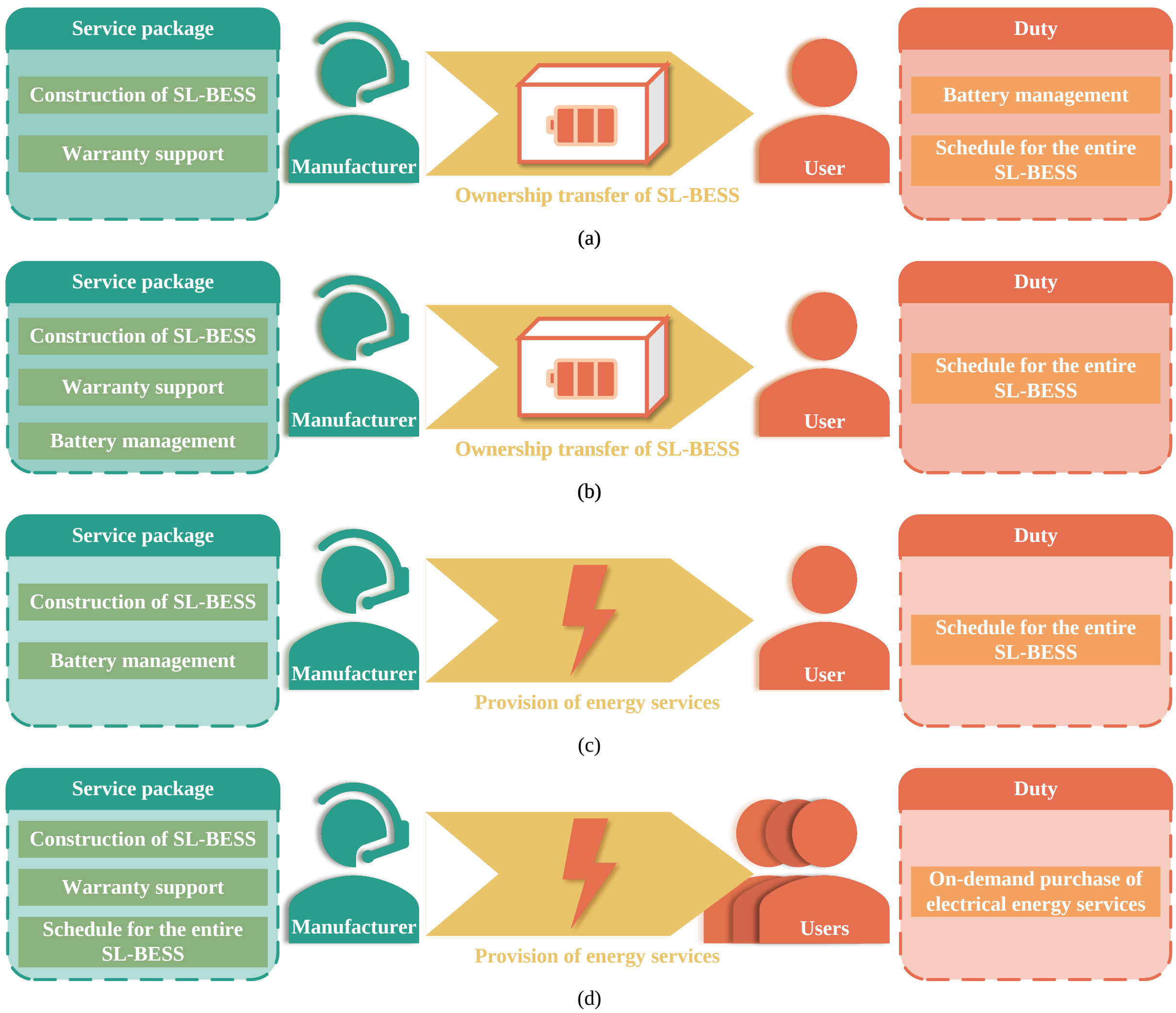


**Fig. 10:** Schematic illustration of three commercial models for second-Life batteries. (a) BaaP. (b) BaaS. (c) PaaS. (d) EaaS.

minimum performance guarantees required for second-life batteries [17].

In addition, owing to reliability concerns, manufacturers tend to offer conservatively shorter warranty periods. As an illustration, the xStorage Home system from Nissan Motor Corporation carries a five-year warranty for second-life batteries, which is only half the term granted to new batteries in the same project [98]. A shorter warranty period necessitates more frequent system replacements, further discouraging potential users from investing in second-life battery systems.

Therefore, under this conventional model, second-life batteries may struggle to gain traction among grid users due to technical barriers and reduced warranty period. More critically, concerns over data security could dissuade EV owners from participating in echelon utilization. To enhance the market competitiveness of second-life batteries, advanced commercial models must be introduced into the industry.

## 5.2. Battery-as-a-Service

Under the BaaS model, manufacturers are not only responsible for constructing the SL-BESS but also for providing ongoing O&M services. Delegating technically demanding O&M tasks and sensitive first-life data handling to manufacturers, the BaaS model mitigates data-security risks for EV owners and lowers the knowledge barrier for users of second-life batteries. Additionally, the manufacturer's battery expertise ensures more reliable system operation.

Currently, the manufacturers that provide continuous O&M services are Element Energy [80] and B2U Storage Solutions[82] . They have delivered the largest and second-largest second-life grid-battery installations in the USA, respectively. Element Energy has formalized a collaboration with LG, which supplied the batteries for the initial Chevy Bolt models. LG is slated to supply O&M support for the SL-BESS. Backing from LG is expected to alleviate potential customers' concerns, which have long hindered manufacturers from unlocking the second-life battery market. In the other case, B2U Storage Solutions, through its proprietary EV Park Storage (EPS) software, supplies continuous management and optimization that enable second-life batteries from different EV manufacturers to charge and discharge efficiently. By adopting a BaaS model, Element Energy and B2U Storage Solutions lower users' knowledge barriers and have secured a significant share of the second-life battery market.

However, due to the broader scope of services provided by manufacturers, the BaaS model imposes the highest initial investment cost on users among the four commercial models discussed in this section. Consequently, a pricing framework that aligns cost recuperation with customer affordability is essential for manufacturers to foster the diffusion of the BaaS approach. In the future, by deploying edge-cloud collaboration architectures such as the Internet of Batteries (IOB) [134], manufacturers are expected to cut on-site service costs through remote O&M, thereby improving the economic viability of BaaS.

## 5.3. Platform-as-a-Service

In line with the BaaS model, manufacturers undertake O&M responsibility in the PaaS model. The key distinction lies in the ownership structure. Under PaaS, the SL-BESS is owned by the manufacturer, not the user. This commercial model transforms battery sales into a subscription-based service, where manufacturers provide a second-life battery storage platform for users to schedule charge and discharge operations. The contract obliges the manufacturer to guarantee the SL-BESS performance for a defined term to support user scheduling.

The PaaS model focuses on full life-cycle management of second-life batteries. Rather than simply selling batteries, manufacturers provide comprehensive services covering assessment, installation, maintenance, and replacement. In this model, users create value by scheduling charge-discharge operations, while state monitoring and maintenance are delegated to the manufacturer. The PaaS model shifts second-life failure risk from users to manufacturers, because batteries become part of a service rather than a one-off commodity. Therefore, despite the reduced operational discretion granted to users, the PaaS model features low upfront costs, minimal technical barriers, and limited O&M duties. In the future, these factors are likely to enhance user acceptance and support manufacturers in penetrating the second-life battery market during its formative phase.

## 5.4. Energy-as-a-Service

In the EaaS model, charging and discharging schedules are determined by the manufacturers, while users merely purchase storage services on demand. One SL-BESS can simultaneously provide service to multiple users. The manufacturers optimize SL-BESS utilization by aligning diverse user requirements, which reduces storage idle time and improves returns. Meanwhile, the EaaS model lowers the entry barrier for users by offering flexible subscription plans, enabling exploitation of distributed, small-scale loads on the customer side. This prospective scheme holds considerable promise as a future commercial model for users with low storage utilization frequencies.

## 5.5. Policies and standards

Although second-life batteries hold vast application potential, supportive policies and well-defined standards are still required to steer the nascent market.

Policymakers can create favorable conditions for second-life battery deployment by introducing regulatory frameworks that specifically accommodate repurposing technologies. While countries such as Japan [135] and the United States [136] have implemented battery recycling policies, these frameworks require adaptation to address the unique characteristics of battery repurposing. In 2020, the EU launched the Circular Economy Action Plan, which includes proposed regulations aimed at enabling the reuse of EV batteries in second-life applications. Similarly, China's Guidance on Accelerating the Promotion and Application of New Energy Vehicles (2014) [137] first encouraged the establishment of a comprehensive power battery recycling system. This initiative was further strengthened in the Energy-Saving and New-Energy Vehicle Industry Development Plan (2021–2035) [138].

Regulatory frameworks also help overcome key technical challenges associated with end-of-life EV batteries. One prominent issue is data scarcity, which hampers BMS optimization in SL-BESSs. By mandating battery traceability and data disclosure, regulations improve data accessibility across the battery lifecycle. The EU's Battery Passport and China's Traceability Information System are two representative policy tools designed to enhance data transparency for second-life applications. The Battery Passport, initiated by the Global Battery Alliance in 2019 [139], aims to provide comprehensive sustainability and lifecycle data based on the concept of a "sustainable and responsible battery". It has been officially endorsed by several countries and is scheduled to become mandatory in the EU by 2026 [140].

**Table 5**
Comparison of EU and China battery-traceability frameworks.

| Category | Battery passport (EU) | Traceability information system (China) |
|---|---|---|
| Coding standard | Regulation (EU) 2023/1542 | GB/T 34014-2017 |
| Battery-information scope | Full life-cycle carbon-footprint required | Carbon-footprint data not included |
| Data-storage method | Decentralized | Centralized on the national platform |

In parallel, China's Interim Management Method of Power Battery Recycling for New Energy Vehicles [141] mandates joint data management responsibilities between battery and EV manufacturers. Under this regulation, battery manufacturers must encode traction batteries in accordance with national standard GB/T 34014-2017 [142], and EV manufacturers are required to upload relevant information to the traceability platform. By 2025, China plans to establish full digital traceability across production, distribution, dismantling, and repurposing processes [143], thereby enhancing data availability for echelon utilization.

However, as shown in Table 5, the lack of legal interoperability between the EU's Battery Passport and China's traceability platform remains a major barrier to the formation of a unified global market for second-life batteries. Additionally, Weng et al. [144] argued that a battery passport should record the SOH with an error below 5% at no fewer than three distinct time points to effectively support echelon utilization.

It is critical to clarify the liability for end-of-life EV-battery recycling in the second-life battery market. The Directive 2008/98/EC [145] establishes a general legal framework for waste management. Although it does not explicitly target EV batteries, it embeds the principle of extended producer responsibility. Hence, disposal duties fall on battery manufacturers or EV manufacturers rather than users, as likewise affirmed in the Directive 2006/66/EC [146] on batteries. However, the exact assignment of responsibility for waste batteries is still disputed. In the USA, battery retailers must take back spent batteries at no cost, but the statute is not tailored to EV batteries [17]. China, by contrast, specified in 2021 that EV manufacturers are responsible for the recycling and reuse of traction batteries [147].

The standardization of second-life batteries hinges on universal industry standards, which can bolster confidence among end-users and prevent market domination by industry giants. Underwriters Laboratories issued UL 1974 in 2018 [24]. It guides the repurposing manufacturers in classifying and grading EV packs, modules, and cells, which is the critical prerequisite for commercializing second-life batteries. For the lithium-ion batteries with data traceability, IEC 63330-1:2024 [148] sets basic requirements and the test procedure for assessing the performance and safety of used batteries and systems, and it outlines general requirements for applying repurposed batteries. In addition, IEC 63338:2024 [149] offers baseline guidance on second-life battery applications, covering environmental impacts and safety risks. In China, the GB/T 34015 series [26, 150–152] was introduced to guide the repurposing of retired EV batteries. These standards span removing requirements, echelon using requirements, labels for echelon-used battery products and battery design guide for echelon utilization. The Society of Automotive Engineers (SAE) International is also drafting SAE J2997 to normalize the classification of batteries intended for diverse, safe second-life applications [153].

To date, standards for second-life batteries are still scarce, and a globally accepted framework for the battery value chain is absent. These deficiencies impede the widespread echelon utilization. Therefore, it is imperative that governments, manufacturers, and end-users collaborate to establish a unified industry standard for the echelon utilization of retired traction batteries, in order to realize the full potential of second-life batteries and promote the long-term development of a circular battery economy.

## 6. Conclusions

The large-scale retirement of EV batteries presents both a sustainability challenge and an opportunity to enhance energy system flexibility. This review explores the integration of SL-BESSs into power systems from technical, commercialization-related, and institutional perspectives.

Echelon utilization offers a cost-effective solution that extends battery lifespan and supports the circular battery economy. Compared to direct recycling, SL-BESSs are particularly well-suited for generation- and demand-side applications where performance thresholds are moderate, and capital cost sensitivity is high.

Technically, key challenges include cell heterogeneity, limited operational data, and degradation knee-point uncertainty. Advances in clustering, transfer learning, and physics-informed models offer promising paths to more reliable state estimation and control. Economically, service-based models (BaaS, PaaS, EaaS) outperform traditional ownership (BaaP) by improving performance guarantees and reducing user risk, thereby accelerating adoption. Institutionally, fragmented standards and unclear liability hinder large-scale deployment. International coordination on traceability, safety, and extended producer responsibility is urgently needed.

In summary, second-life batteries represent a viable yet underutilized asset for the power-system energy transition. Their further success depends on coordinated innovation across technology, markets, and governance. To facilitate the widespread adoption of second-life batteries, future efforts should prioritize the following key research directions:

(i) Advanced battery management technologies. Development of adaptive and advanced control algorithms tailored to the unique characteristics of second-life batteries will significantly enhance operational safety and efficiency. Moreover, adoption of emerging edge-cloud collaboration architectures may allow manufacturers to manufacturers reduce on-site service costs through remote O&M, which will strengthen the market competitiveness of second-life batteries.

(ii) Systematic tracking of pilot projects and quantitative profitability analysis. Future research should continuously collect real-world data on the operational status and revenue of ongoing and forthcoming SL-BESS pilot projects. These data are critical to evaluating the service life of second-life batteries under varied operating scenarios and to quantifying the ROI and breakeven points associated with different commercial models. The insights provide valuable guidance to storage investors in power systems and may encourage them to deploy second-life batteries.

(iii) A harmonized policy framework. A harmonized policy framework is crucial for lowering international trade barriers, ensuring data interoperability and mutual recognition of standards, ultimately accelerating progress toward a global circular battery economy.

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