A Comprehensive Review of Second Life Batteries Toward Sustainable Mechanisms: Potential, Challenges, and Future Prospects

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***Abstract*— The accelerating market penetration of electric vehicles (EVs) raises important questions for both industry and academia: how to deal with potentially millions of retired batteries (RBs) from EVs and how to extend the potential value of these batteries after they are retired. It is therefore critical to deepen our understanding of the comprehensive performance of RBs in appropriate applications, such as stationary energy storage with less demanding on power capacity. The following literature review evaluates the opportunity of the emerging RB market in detail. Meanwhile, various specifically technical issues and solutions for battery reuse are compiled, including aging knee, life predicting, and inconsistency controlling. Furthermore, the risks and benefits of battery reuse are highlighted referring to transportation electrification and entire industrial chain. Also, current policy shortcomings and uncertainties are outlined, and policy recommendations are provided for relevant participants. Six typical application scenarios are selected, and high-value business models for battery reuse are explored from different techno-economic aspects. Insights from this review indicate that as the entire recycling chain is completed, battery reuse will be essential to the future energy market and will play an important role in the future development of low-carbon energy.**

***Index Terms*— Automotive industry, battery aging, battery recycling, life cycle, low carbon, renewable energy, retired batteries (RBs), second life batteries (SLBs).**

I. Introduction

At PRESENT, climate change is a major global challenge for sustainable development. The most challenging goal in mitigating climate change is to achieve carbon neutrality (with emissions low enough to be safely absorbed by the natural system) by mid-century [1], [2], [3], in which the introduction of electric vehicles (EVs) serves as a critical initiative. EVs have developed rapidly in the last decade and will inevitably replace conventional vehicles in the near future [4]. Li-ion battery (LIB), which features high energy density, long life cycle, low self-discharge, and virtually no memory effect [5], [6], has become the preferred power source for EVs. LIB is not only the most important power component in EVs but also the most expensive, accounting for about half of the vehicle cost. Currently, EV manufacturers generally consider replacing batteries at a state of health (SOH) of 70%–80%, at which the battery can no longer meet the daily driving demands of the EV [7], [8]. It is estimated that the global EV population will reach 245 million in 2030 [9]. In China, retired batteries (RBs) will increase from 0.1 to 7.8 thousand tons during 2012–2018 and then up to 1500–3300 thousand tons in 2040 [10]. Exploring additional utilization opportunities for large RBs has become a critical issue to improve the life cycle revenue of batteries and realize their full potential.

Echelon utilization of batteries is identified as the potential solution. RBs that have been diagnosed, sorted, and regrouped are reused in other less-demanding fields, such as smart grids, low-speed EVs, and energy storage system (ESS) integrated with intermittent renewable energy [11], [12]. Fig. 1 shows the whole life cycle of EV batteries with second life. Some of the RBs with good properties are reused and eventually recycled to extract raw material for battery production. Through reusing batteries, EV manufacturers hope to quickly gain a competitive advantage over conventional vehicle rivals through reducing the high capital cost of batteries. Meanwhile, the whole cycle process can serve as a catalyst for society's transition to a sustainable future under the trend of transportation electrification [13], [14].

The battery in echelon utilization can be referred to as second life battery (SLB). With the process of transformation of transportation electrification, the utilization of SLBs has become a critical subject. Echelon utilization of battery has the potential to promote the development of transportation electrification through providing effective charging service. Battery reuse can transform the challenge of grid-connected charging brought by large scale of EVs into a chance of win–win development. Under the strengthening trend of transportation electrification, main countries are actively expanding new profit growth point in policy formulation, innovation and development, and industrial integration. Battery reuse can broaden partnerships in support of interaction between EVs and the power system, including energy transition and market cultivation, in order to promote the coordination of the upstream and downstream of the industrial chain of transportation electrification. Therefore, echelon utilization is an essential link in building a value ecosystem with mutual benefit and win–win results.

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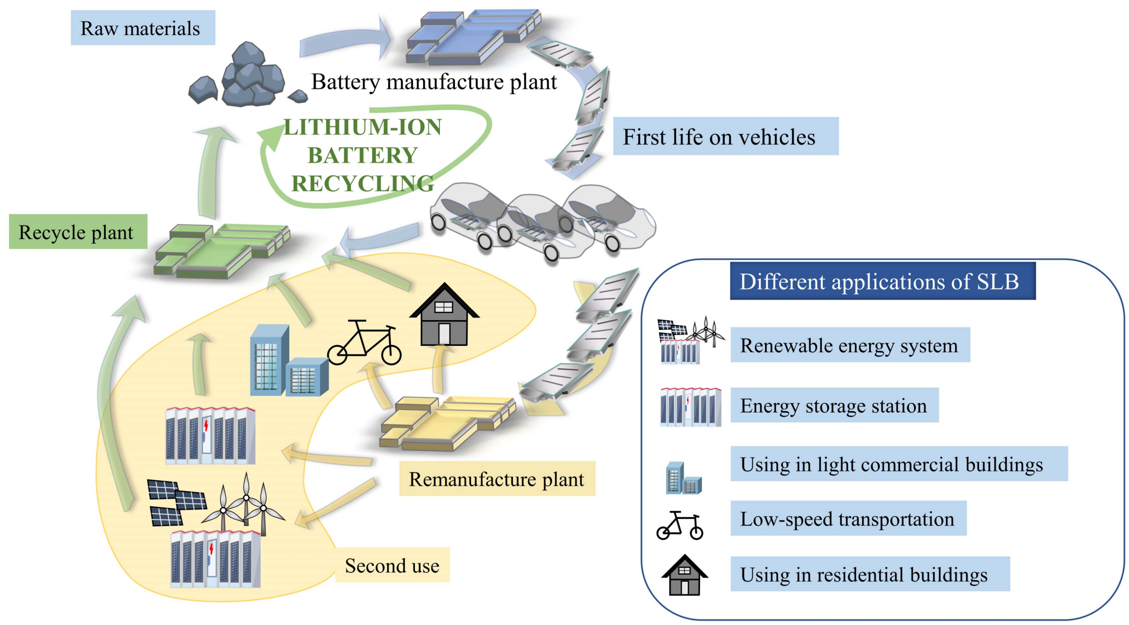

Fig. 1. Process illustration of a battery lifecycle with second life.

However, there are still many critical issues for battery reuse. Aging is the decisive factor for safety and efficiency of battery reuse. The technical state of cells across and within RBs, including capacity, internal resistance, and voltage, is not consistent [15]. Coupled with the sudden acceleration of capacity degradation, namely, aging knee, some key management strategies of SLBs are essential for prolonging its service life [16]. Meanwhile, the risks and benefits of battery reuse toward transportation electrification require a proper evaluation [17]. In addition, it is necessary to further explore the policy issues for the RB development, including the urgency of applying policies, current policy shortcomings and uncertainties, and practical proposals.

Many previous studies have reviewed many technical and economic issues of the echelon utilization of RBs. Shahjalal et al. [18] investigated the main methods for estimating battery aging, including the testing methodology and critical economic analysis. However, the impact of the first life on battery reuse was not considered, and the performance of battery reuse in some specific applications, such as energy arbitrage and residential use, was not fully studied. Hua et al. [19] presented investigations for the main barriers in repurposing RBs, including safety issues and evaluation methods. However, the inconsistency propagation within the battery was not included in this study. The key technologies in echelon utilization were summarized in [20], [21], and [22], including rapid sorting and regrouping methods, and evaluation of residual value. Also, the current status, recycling mode and industrial chain, and policy and standards of echelon utilization and recycling were analyzed comprehensively in these studies. However, the inadequacies of the existing political system on battery reuse were not included, and systematic policy recommendations for the development of SLB were not provided. Apart from this, the future development trend of SLB was not fully studied, and the degradation models for SLB were not summarized [23].

As can be seen from the existing review studies, the unique aging characteristics of RBs and the impact of the first life on battery reuse have not been refined and summarized well. Also, some key technical issues, such as balancing battery management systems (BMS) and repurposing strategies, have not been analyzed well. Meanwhile, most existing studies have not conducted an in-depth review of the echelon utilization of RBs in practical applications and the policy status. Aiming at the problems existing in the existing research, this article comprehensively reviews and summarizes the current status and future development of battery reuse. The main innovative works of this study can be concluded as follows.

1) The current state of research on battery reuse is comprehensively analyzed. The technological solutions for echelon utilization from different publications are summarized in detail. The main aspects of SLB are examined, including aging knee, life predicting, and inconsistency controlling.
2) The opportunity of the emerging SLB market is detailedly evaluated based on production and demand. The risks and benefits of battery reuse toward sustainable development are reviewed from several perspectives, including transportation electrification, safety, economy, and environment.
3) The urgency and necessity for regulatory policies are clarified from the perspective of the SLB industrial chain. Current policy shortcomings and uncertainties are outlined in order to develop targeted and effective management tools. Policy recommendations are provided for SLB participants.
4) Six typical application scenarios are selected at different sizes. The feasible applications using SLB from publications are critically summarized to explore high-value business models from several dimensions of technology and economy.

TABLE I
OVERVIEW OF COUNTRIES/CASES WHERE USED BATTERIES PROJECTS COULD MAKE SENSE [24], [25]

	OEM	Location	System capacity/ power	Battery type	# of batteries	Application
Off-grid	GM	US	50 kWh/25 kW	Li-ion (Volt)	5	Power Supply
	Toyota	US	85 kWh	NiMH (Camry HV)	208	Renewables Integration
	GM	US	\	Li-ion (Volt)	5	Renewables Integration
On Grid	BMW	US	160 kWh/100 kW	Li-ion (Mini-E)	\	Renewables Integration
	Toyota	Japan	4 kWh & 10 kWh	NiMH (Prius)	\	Backup Power, Demand Charge
	Nissan	Japan	400 kWh/600 kW	Li-ion (Leaf)	16	Renewables Integration
	Renault	France	66 kWh	Li-ion (Kangoo ZE)	6	Renewables Integration, Grid Stability
	BMW	Germany	2.8 MWh/2 MW	Li-ion (ActiveE & i3)	100 +	Renewables Integration, Grid Stability
	Mitsubishi & PSA	France	\	Li-ion (Peugeot Ion, C-zero, iMiev)	\	Renewables Integration, Smart Grid
	Daimler Accumotive	Germany	13 MWh	Li-ion (Smart)	\	Renewables Integration, Grid Stability
	Nissan	UK	4.2 kWh	Li-ion (Leaf)	\	Storage: Residential Energy Storage Unit
	Nissan	Netherlands	4 MWh/4 MW	Li-ion (Leaf)	280	Backup Power, Peak Shaving, Grid Stability
	BMW	Germany	12 kWh/50 kW	Li-ion (i3)	8	Fast Charging
	BMW	Spain	50 kW	Li-ion (Zoe)	\	Fast Charging
	Audi	Germany	\	Li-ion	4	Fast, Green Charging, Grid Stability
	Renault	UK	50 kWh/50 kW	Li-ion (Zoe)	\	Fast, Green Charging

The remainder of this article is structured as follows. Section II presents the market prospects for battery reuse. Section III discusses the key technical issues and prospects. Section IV analyzes the major risks and benefits. Section V discusses limitations, and the need and urgency for supportive policies for the development of SLBs. Section VI discusses the application perspective for battery reuse and future development directions. Finally, the conclusion is presented in Section VII.

II. Market Prospects for Battery Reuse

The world's passion for greening the transport sector has gradually activated the market for EVs. In recent years, the support from the main countries, such as Europe, China, and USA, has increased the market share of EVs significantly. However, the high cost of batteries has caused more and more industry participants to think about how to solve the problem. Battery reuse is undoubtedly a promising strategy. Some projects for SLB applications have been launched by some automotive companies, such as BJEV in China, Nissan in USA, Renault in U.K., and BMW in Germany [24], [25] (as shown in Table I).

At present, the global EV market is rapidly developing. In 2020, global sales of EVs have increased by 43%, with the European market increasing by 137%. More than 1.3 million electric cars have been sold in China in 2020. China's determination to support e-vehicles has never changed [26]. In 2019, China's Ministry of Industry and Information Technology released the New Energy Vehicle Industry Development Plan (2021–2035), in which the share of EVs in total vehicle sales will reach 20% in 2025 [27]. Similar targets exist in Europe and USA. The rapid development of EVs has brought about the problem that how to deal with large RBs.

Over the past decade, the price of batteries was about U.S. $1000/kWh in 2010 [30], [31], which dropped by nearly 17% per year, and now, it is about U.S. $120–180/kWh. The U.S. $150/kWh price means that EVs will move beyond niche applications and into the large-scale penetration phase [32]. As the early stage of the major burst in the EV market has passed, battery prices have entered a more stable decline stage. It is believed that battery price declines will be closer to 8% per year in the future.

Compared to new batteries, the cost of SLB acquisition, labor, transportation, and so on is not clear. The price of SLB used in the case study is 33.7%–55.2% of new batteries [24]. However, compared to other studies, this ratio is optimistic. Neubauer et al. [33] performed a detailed analysis of the price of SLBs. According to his research, 50%–70% is a relatively reasonable range (without considering the impact of reduced battery reuse costs after large-scale development of SLBs). Based on various publications, this study assumes that the current price of SLBs is 60%–75% of the price of new batteries. Fig. 2 shows the comparison between the current selling price of SLBs and new batteries. Fig. 2 also shows the proportion of each part of the repurposing cost.

Fig. 3 shows the prediction of prices for new batteries and SLBs and the capacity development of the global energy storage market that can be served by batteries (2020–2030). Wu et al. [38] forecast that the Chinese market for RBs will reach 112 000 tons in 2020 and 708 000 tons in 2030. It can

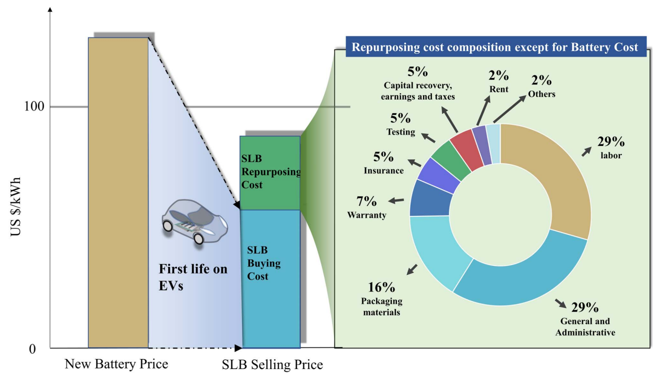

Fig. 2. Selling price comparison between new battery and SLB and the SLB repurposing cost composition except for battery cost (data based on [28] and [29]).

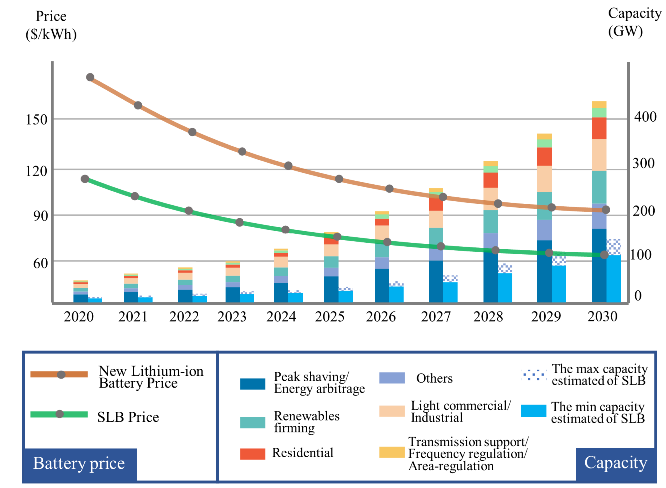

Fig. 3. 2020–2030, new LIB price and SLB price trend; ESS capacity of battery growth in stationary applications (data based on [9], [29], [34], [35], [36], and [37]).

be seen that the RB market is entering an era of broad market. However, although the capacity of RBs is large, the capacity of EV batteries available for reuse is likely to be a small fraction. It is estimated that the world market for SLBs will reach about 120 GWh and not more than 150 GWh in 2030, as shown in Fig. 3. The Indian energy storage market (using renewable energy sources) could exceed 70 GW in 2022 [39]. The growth of the energy storage market is mainly driven by the demand for stationary storage and transportation. The global market is expected to grow to more than 2500 GWh by 2030, with stationary storage (which SLBs mainly serve as) accounting for more than 400 kWh [36]. In all cases, the market for energy storage is large enough for the use of SLBs. As can be seen in Fig. 3, energy arbitrage/peak shaving accounts for the largest share, followed by renewables firming. Capacity for residential demand response is less than that for commercial and industrial. Capacity for frequency regulation and area regulation is relatively small, and the smallest portion is used for supporting transmission regulation.

III. Technical Issues and Prospects

A. Impact of First Life

Performance degradation in power, energy efficiency, and capacity has evolved with the increase in battery cycles. Capacity loss is the main reason for battery retirement [40]. Therefore, capacity-defined SOH, which is the ratio of current capacity to that of fresh battery, is selected in this review.

Nearly 80% of SOH is widely considered as the end of life (EOL) of batteries on EVs. However, the SOH differentiation in RBs should not be ignored. Casals et al. [41] investigated the aging state of RBs to conduct a more accurate determination of EOL of EV batteries. The experimental results showed that the SOH of RBs was scattered in a wide range of 70%–90%. The reasons for this situation can be roughly attributed to the lack of SOH estimation on EV, the diversity of external environmental conditions, and the difficulty in accurately determining the needs of the EV owners for battery capacity. In the current EV market without the intervention of other external forces, such as EV manufacturers, the government, and battery leasing companies, the EV owners are the most important factor in determining when to retire battery. According to the quantitative analysis, 80% of the remaining capacity could still meet the daily needs of 85% U.S. motorists [8]. It was also found that RBs have an average SOH of 71%, not for about 80% [42]. Similarly, the suitability of 70%–80% SOH as a standard criterion for EV battery retirement was also questioned in [43]. Therefore, a fixed SOH standard may be impossible to describe the battery SOH at retirement with different use conditions in first life.

Another effect of the first life may be the interference with the aging process of the second life. After analyzing the techniques of RBs, Quinard et al. [44] concluded that the complete heterogeneity of RBs from one EV to another is caused by complex combinations of aging mechanisms, which can be either mechanical or electrical. Furthermore, Martinez-Laserna et al. [43] adopted nickel manganese cobalt/carbon (NMC/C) SLBs on a residential demand management application and a power smoothing renewable integration application, which aims at evaluating the effect of first life over the reuse performance. Simulation results showed that the decrease in capacity and increase in internal resistance tend to be more pronounced for SLB under more demanding first-life conditions. It is also reported that higher demand in first life may cause the earlier occurrence of aging knee, which is the turning point of two-stage battery degradation behaviors with different rates [45]. Generally speaking, the degradation of LIBs presents a nonlinear behavior on the whole stage. If the nonlinear degradation behavior is approximated by piecewise linear, the battery will initially decade with a relatively stable slow rate, and the battery's degradation rate will have a sudden and rapid increase after passing certain service, the turning point of which is called aging knee or knee point [46], [47]. Aging knee is particularly evident in a multitude of cells with cobalt chemistries, which is batteries with high energy density such as NCM batteries [45], [48].

Rohr et al. [49] believed that battery degradation and uncertainties during first life, such as cell spreading and nonlinear aging, are essential for determining the remaining useful life of SLB. Since first life is so important to determine the second life performance, it is very required to establish a tracking

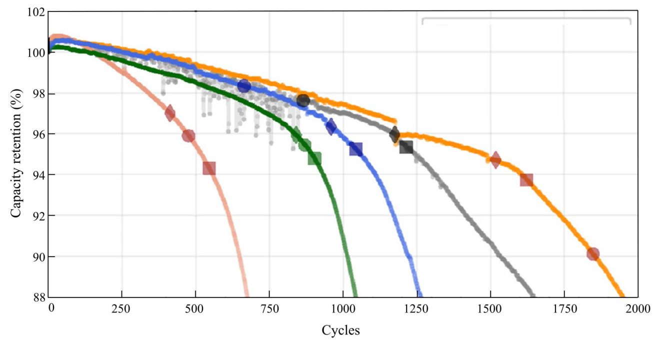

Fig. 4. Comparison of aging knee obtained with Bacon–Watts [52] (in square), maximum curvature [53] (in diamond), and slope-changing ratio methods [54] (in circular) on a sample of cells from the A123 dataset (from left to right: b2c47, b3c3, b1c3, b1c0, and b1c1).

mechanism for the aging history of the first life to distinguish batteries that are more suitable for battery reuse.

B. Aging Knee Uncertainties

It is uncertain whether the high degradation rate after aging knee can enable the battery to provide a utility value for second life. Furthermore, changes in the internal parameters of the battery may even pose higher safety risks. The impact of aging knee on battery reuse is mainly reflected in two aspects: 1) the impact on the feasibility of battery echelon utilization and 2) how to design appropriate strategies to extend battery service and carry out maintenance in a cost-effective way from the perspective of battery management [50].

Fig. 4 shows the aging knee identified in a sample of LIBs in the A123 dataset [51], using methods in [52], [53], and [54]. Large uncertainty in the occurrence of aging knee can be seen in Fig. 4. Since it is considered as a predictor of a more rapid capacity degradation, aging knee tends to be used to define the EOL of the battery on EV in some research [48], [55]. However, the applicability of the definition for EOL based on aging knee is not fully investigated. Significant research indicated that EOL appears within >90% SOH range, which certainly does not mean that the EOL for battery on EVs should be adjusted to 90% SOH. At present, much research focuses on how to accurately predict aging knee under the indicator of SOH. Diao et al. [54] precisely defined the aging knee as the intersection of two tangent lines on the capacity degradation curve, which were located based on the points with the minimum and maximum absolute slope-changing ratio. The occurrence of aging knee is affected by C-rate, temperature, and other operating factors. Zhang et al. [48] used quantile regression integrated with Monte Carlo simulation to establish an aging knee recognition method adapted to various conditions. It is verified that all of the aging knee concentrates in the 90%–95% SOH range at both 25 °C, 35 °C, and 45 °C for NCM battery, which demonstrated that an early assessment for battery failures to avoid safety risks may be particularly indispensable. Similarly, it was shown that the battery does not reach EOL (about 83% SOH) when it reaches aging knee [56]. The aging knee also occurred within the SOH range of first life in [57] and [58]. However, there are also some positive conclusions. Through the accelerated cycle test for the second life of LIBs, Braco et al. [59] concluded that the battery is sufficiently durable during its second use before reaching the aging knee. The SOH in the aging knee, which varies from 45% to 49.5%, showed that about 30% of the original capacity can be used in SLBs.

Another important issue needs to be resolved is that whether the battery cannot promise a qualified performance in second life after reaching aging knee. Based on current publications, batteries with relatively low energy density, especially with circumvents for the risk brought by unstable elements such as cobalt, may be able to provide performance security assurances for echelon utilization. White et al. [60] investigated the performance of seven different SLBs in power system energy arbitrage. The experimental results showed that the design of the thermal management system and chemistry dominates the performance of the RBs. NMC batteries provide the best usable energy capacity (≥94%) and energy efficiency (≥97%), while NCA batteries (with twice the energy density of NMC batteries) provide the lowest usable energy capacity (≥84%) and energy efficiency (≥89%). Lower energy losses and better thermal management could allow batteries to deliver higher performance with less risk of accelerated degradation or thermal runaway in high power. Therefore, a much more detailed examination must be performed for batteries with relatively high energy density.

The standards for the aging knee must be determined based on the changes in capacity, internal resistance, and the propagation of parameter inconsistencies. Diao et al. [45] designed a factorial experiment of accelerated cycle testing with stress factors of temperature and C-rate and developed a capacity degradation model in accordance with the characteristics of two-stage degradation process. A meaningful conclusion drawn was that the appearance of knee point is independent of the discharge C-rate in the range of C/7-2C at 10 °C–45 °C. The explanation provided was that the small electrode particle size ensures the maintenance of nearly a homogeneous distribution at different C-rates, without exceeding the yield point of the material for the induced stress [61]. It indicates that the extension of battery service, especially in second life, is largely feasible through designing suitable strategies.

C. Inconsistency Control

Battery inconsistency mainly reflects in differences of initial performance parameters across and within batteries, such as capacitance, internal resistance, and state of charge (SOC). Battery inconsistency can be traced back to the stage of first life and even production. Variations in manufacturing and assembly are the two main causes of inconsistency for fresh batteries [62], which would continue to propagate as the batteries are continuously used. Even a small error during the manufacturing process, mainly at the level of electrodes, including the thickness, density, and weight fraction of active materials [63], [64], will affect the aging performance of the battery at the next stage [65]. External parameters, such as temperature and depth of discharge (DOD), can lead to further battery parameter inconsistency development during operating.

Some strategies are needed to control the inconsistency during the echelon utilization of battery.

1) Balancing BMS: A balancing BMS may help to suppress the propagation of aging heterogeneity [66]. Abdel-Monem et al. [67] used a passive balancing BMS that can monitor battery voltage, current, and temperature in an ESS consisting of three batteries with different SOCs. The experimental results showed that the BMS can reduce the initial SOC difference from 43% to 5% while limiting the voltage imbalance to below 20 mV. Although the BMS is able to integrate SLBs at different levels (size, capacity, and chemistries), it is not very efficient, given that battery balancing requires thousands of cycles. Liu et al. [68] used the current ripple at the inductance of the multiwinding transformer to share the inductance of the dc–dc converter with the balancing system. The experimental results showed that the efficiency of the proposed system can reach 94.1% at an input power of 28 W for a battery string connected in series at rest. Tong et al. [69] developed a worst SOH estimation scheme to match batteries with different aging states and SOC levels. The worst battery, determined based on its SOH, was allocated the most computing resources in the BMS design. The status of remaining batteries was determined by comparing with the worst battery. The experimental results showed that some insignificant parts, such as the polarization resistance and the open circuit voltage hysteresis, do not need to be estimated using this method. Compared with other extended Kalman filter estimators, the worst difference method was able to provide satisfactory estimation results at a much lower computational cost. Lamoureux et al. [70] used online electrochemical impedance spectroscopy to measure battery impedance, so as to determine the aging degree of battery modules. A controller for the power mixing of battery modules in different SOH was also proposed. The experimental results showed that the proposed controller can slow down the degradation of SLB. The experimental results show that the controller can prolong the service life of SLB by more than 50%.

2) Thermal Management: The accuracy of aging estimation at various temperatures can be different [71]. In general, the thermal reliability of batteries mainly includes two aspects: thermal diffusion and temperature uniformity at high temperatures, and heating and thermal insulation capabilities at low temperatures. Therefore, a complete thermal management system for batteries must have a heating and cooling system [72].

The height of the conduction element has the greatest influence on the maximum temperature and temperature difference of the battery module. An asymmetric design of the battery terminal may also cause uneven resistance of the battery terminal. An inappropriate battery layout may have low cooling efficiency. The short-term thermal gradient of the battery module causes a current deviation within the battery and then gradually leads to problems such as inconsistencies within the battery [73]. SLB obviously performs higher energy efficiency using better thermal management, such as air- and liquid-cooled active heat dissipation methods, compared to passive heat dissipation methods [74].

3) Repurposing Strategies: To deal with the insistency, RBs are often assembled into new battery modules after repurposing. The repurposing process consists of disassembling, testing, screening, and regrouping to the assembly site [75], in which disassembling and testing are often a time-consuming and tedious step. Disassembling consists of at least two steps: the removal of the battery from the vehicle and the disassembly of the battery into its cells, which contains a lot of labor and material costs [76].

Horesh et al. [77] developed a heterogeneous unifying battery reconditioning system, cycling battery modules to unify SOH of cells. Lee and Kum [78] developed a battery cell screening framework, including battery cell modeling, testing, parameter prediction, and a detection algorithm to improve the consistency of SLB without additional labor and cost. Ran et al. [79] proposed a pulse clustering model embedded in an improved bisecting K- MEANS algorithm. This strategy can reduce the detection time for battery performance parameters to a minute level, and an overall accuracy can reach 88%. Zhang et al. [80] developed a screening method based on the improved fuzzy C-means algorithm to extract four important features from the partial charge curve of each cell, including the key point, curve gradient, voltage energy, and volatility. This method can map the relationship between capacity and features, with an accuracy of 90.9%. Its efficiency was about 7.6 times higher than the supervised screening method. Lai et al. [81] used two screening approaches, namely, a neural backpropagation network for large samples and a piecewise linear fitting model for small samples. The experimental results showed that the estimation error of the proposed method was less than 4%, and the efficiency was five times higher than the full boosting and unloading method.

Jiang et al. [82] developed a sorting and grouping method for RBs considering the aging mechanism. Several factors were first extracted using a fuzzy clustering algorithm, including capacity and internal resistance. RBs were sorted according to the power and capacity requirements of application scenarios. The experimental results showed that the proposed method guarantees the effective selection of 80 $LiFePO_4$ RBs compared with single-factor sorting. The incremental capacitance analysis for evaluating the loss of lithium inventory and loss of active material may have a beneficial effect on improving the consistency of aging rate and prolonging the service life of SLB. The forementioned studies for RB repurposing are summarized in Table II.

As mentioned above, the feasibility of SLB depends largely on the first life; in particular aging knee must be considered. Therefore, tracking the first life history is an essential issue for SLB. Rohr et al. [49] developed a management system that records and uploads battery usage data to track the use history of EV batteries online and predict their future evolution (aging performance) in other applications. Baumann et al. [83] developed a cloud-connected system for EV batteries to calculate capacity degradation and resistance growth and obtain the additional value of batteries in various potential second-use scenarios. Thus, these methods can help to reduce large time and economic cost through avoiding inspecting and testing.

Due to the high cost of repurposing, many studies have turned to focus on the direct use of battery modules. Specifically, the converter is controlled to be compatible with

TABLE II
OVERVIEW OF STUDIES INVESTIGATING RBs REPURPOSING STRATEGIES

Authors	Methods	Objective	Reference Indicators
Ran et al. [79]	a pulse clustering model integrated with improved bisecting K-means algorithm	sorting	capacity voltage resistance
Lee et al. [78]	cell modeling cell testing parameter estimation selection	repurposing	capacity voltage resistance capacitance
Zhang et al. [80]	based on the improved fuzzy c-means algorithm	screening	voltage gradient Energy volatility
Lai et al. [81]	back-propagation neural network piecewise linear fitting model	screening and regrouping	voltage capacity
Jiang et al. [82]	Based on proposed fuzzy clustering algorithm	sorting and regrouping	capacity resistance amplitude consistency

different types of RB modules. Mukherjee and Strickland [84] developed a modular converter that can adopt different charging and discharging modes to integrate different types of batteries. The simulation results showed that a tradeoff between efficiency, control complexity, and operating range can be achieved. Similarly, Liu et al. [85], [86] developed a self-adaptive differential power control strategy based on an online battery parameter estimation method. This strategy was used to control the dc sides of the H-bridges in the cascaded H-bridge converter, which can couple with the dynamic changes of battery parameters and operating conditions.

D. Life Evaluation

Aging prediction, which refers to SOH estimation in this article, plays a crucial role in determining the feasibility of SLB in second life. Depending on the characteristics of the method, the battery SOH estimation methods can be broadly divided into experimental method, adaptive filtering method, and data-driven-based method [87]. The main features of different SOH estimation methodologies are shown in Fig. 5.

1) Experimental Methods: External experiments are usually used to analyze the aging behavior of the battery, which can be divided into direct measurement and indirect analysis method. The direct method enables to evaluate the battery SOH by directly measuring some performance parameters such as internal resistance and capacity, mainly including Ah-counting method [89], ohmic impedance measurement [90], and cycle counting method. The Ah-counting method obtains SOH by accumulating the total charge capacity put into or the total discharge capacity released from the battery in the cycles between fully discharged and fully charged state [89]. The battery is considered to be fully discharged when reaching the cutoff voltage and to be fully charged when the charging current drops to zero. Ohmic impedance measurement evaluates the SOH through measuring ohmic impedance, which calculates the ratio of the voltage variation to the current variation. Ohmic impedance is relatively easier to be measured compared to the capacity, and however, the effect of the sampling interval is

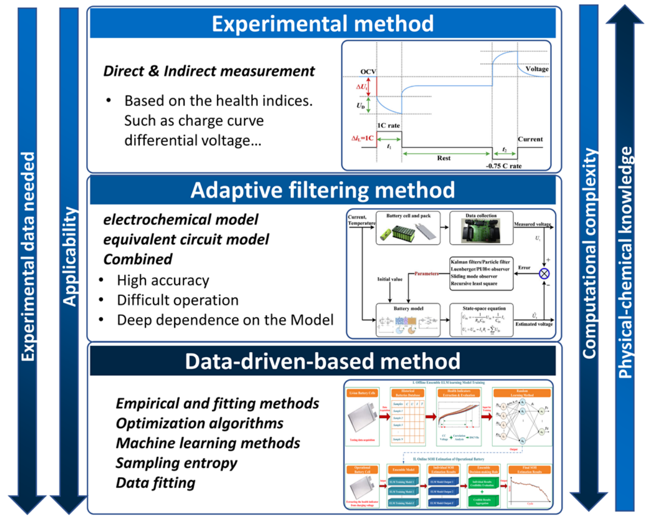

Fig. 5. Battery SOH predictions methodologies at a glance (the upper two figures are from [87] and the lowest figure is from [88]).

also more evident [90]. Ohmic impedance is related to battery capacity to some extent, but the ohmic impedance changes may only be obvious near EOL. The cycle counting method counts the total cycle number, and the SOH is obtained through comparison with the total available cycle numbers of battery. This method is unreliable because the total cycle numbers cannot be accurately predicted [91].

In the indirect method, the SOH of battery is calculated by analyzing some designed process parameters, which can reflect the aging process of the battery in some health indicators, such as capacity and ohmic impedance. Commonly used indirect methods include the charge curve method, incremental capacitance analysis and differential voltage analysis, ultrasonic inspection, and other health index methods [87]. The charging curve method plots the various parameters' changes such as voltage and current, which directly reflect the internal characteristics of the battery. Incremental capacitance analysis and differential voltage analysis analyze the degradation process and aging mechanisms of battery through incremental capacitance and differential voltage curve, which can be obtained by the constant-current charging/discharging [92]. Ultrasonic inspection monitors the battery health indicators through ultrasonic sensing and data processing combined techniques [93]. Ahmadi et al. [94] integrated Ah processing as a uniform measure of time, charge–discharge cycles, standard battery capacity, DOD, and C-rate of charge and discharge into the battery degradation model, with the premise that the battery exhibits three different types of capacity decay mechanism throughout its life cycle. The simulation results showed that battery degradation in second life is not particularly obvious due to the low current demand and a small SOC cycle interval. After the battery passed the first two faster decay stages and exceeded 80% SOH, the capacity in the second life maintained a linear decay at a lower rate before reaching 65% SOH, and the life span exceeded more than ten years.

2) Adaptive Filtering Methods: The electrochemical model and the equivalent circuit model perform the description of battery charging/discharging behavior based on internal

TABLE III
SUMMARIZATION OF SOME BATTERY SEMIEMPIRICAL MODELS

Model	Aquation	Explanation
Cycle life degradation	$Q_{loss} = 0.0032\exp(-\frac{15162-1516C\_rate}{R\cdot T_{bat}})(A_h)^{0.824}$ [99]	A_h: Ah-throughput T_{bat}: the absolute temperature (K) *R*: gas constant (J/(mol·K)) *C_rate*: the discharge rate Q_{loss}: the normalized battery capacity loss
	$RC = a\cdot\exp(-c\cdot(TDC/1000)) + b$ [100]	a, b and c: fitted parameters *TDC*: the total discharge capacity *RC*: the remaining capacity. Q_{loss}: the normalized battery capacity loss
	$Q_{loss} = B\cdot\exp(\frac{-E_a}{R\cdot T_{bat}})(A_h)^z$ [105]	E_a: the activation energy (J/mol) *R*: gas constant (J/(mol·K)) T_{bat}: the absolute temperature (K) *B*: pre-exponential factor
Calendar life degradation	$Q_{loss} = 14876t^{0.5}\cdot\exp(-24.5/RT)$ [106]	*t*: days *R*: gas constant (J/(mol·K)) T_{bat}: the absolute temperature (K)

reaction and transfer mechanism. Adaptive filtering methods combined the electrochemical model or equivalent circuit model with control and feedback, which have high accuracy and robustness [87]. Adaptive filtering methods commonly evaluate the SOH of the battery by identifying health-related parameters through advanced filtering and state estimation methods. However, the accuracy of adaptive filtering methods highly relies on the model accuracy. At the same time, in order to meet the requirements of accuracy and efficiency in online applications, it is necessary to debug the parameter calibration algorithm repeatedly.

Temperature, charge and discharge C-rate, mean SOC, cycle times, and DOD are the main factors that impact battery degradation [95]. Casals et al. [95] developed a parameterized battery equivalent electrochemical model considering the various factors, which uses the aging reference value of Ah. This model was used in [96] and [97] to estimate the economics of reusing batteries. Similarly, Lamoureux et al. [70] developed a battery degradation model based on a two-stage equivalent circuit model considering different SOC and temperatures.

3) Data-Driven-Based Methods: Data-driven methods rely on large historical experimental data to obtain a black-box model for predicting SOH. The obtained model describes the dynamic aging behavior of battery starting from external characteristics, without depending on awareness of the internal electrochemical process of LIBs. The commonly used data-driven methods include empirical methods, optimization algorithms, machine learning methods, sampling entropy, and data fitting [87].

Empirical methods use more macro physical empirical model and employ a data-driven method to update the parameters of the model to realize the accurate prediction of the SOH [98]. Empirical methods predict battery aging using some simple fit models such as polynomial, exponential, and logarithm functions, with small computational effort [16]. However, only one certain function cannot perform strong robustness. Song et al. [99] used a dynamic degradation model that considers time, temperature, charge/discharge C-rate, and battery charge/discharge cycle interval, which is a semiempirical model that improves the fixed and standard charge/discharge interval. The least-squares method has been used to calculate the proposed model parameters, which is shown in Table III. There are also some estimation models summarized in Table II. Liu et al. [100] developed an SOH estimator for NCM batteries using backpropagation neural networks to train the relationship between multiple health indicators and the battery lifetime, as shown in Table III. Notably, the model proposed in [100] applies to the battery in 50%–100% SOH. Machine learning is recently applied to the data-driven field to obtain mapping relationships between the battery SOH and features of the sample. A model-based empirical method exists for a long time and is a more general term to explore the internal evolutionary process of data based on observation or experience. The empirical method is not formal with too many human manipulation factors. Methods based on machine learning are a recent data-driven term that is higher objective and higher automated, less manipulable, and more formal than empirical methods.

Generally speaking, data-driven method is a computationally efficient method and can achieve offline/online system-level estimation [101]. However, the accuracy of the model is closely related to the size of training data. The accuracy and generalization capabilities remarkably decreased when the scale of data is not sufficient and the conditions contained are not adequate.

E. Typical Applications as Stationary Storage

From the perspective of the whole power system, as shown in Fig. 6, the applications of stationary storage can be divided

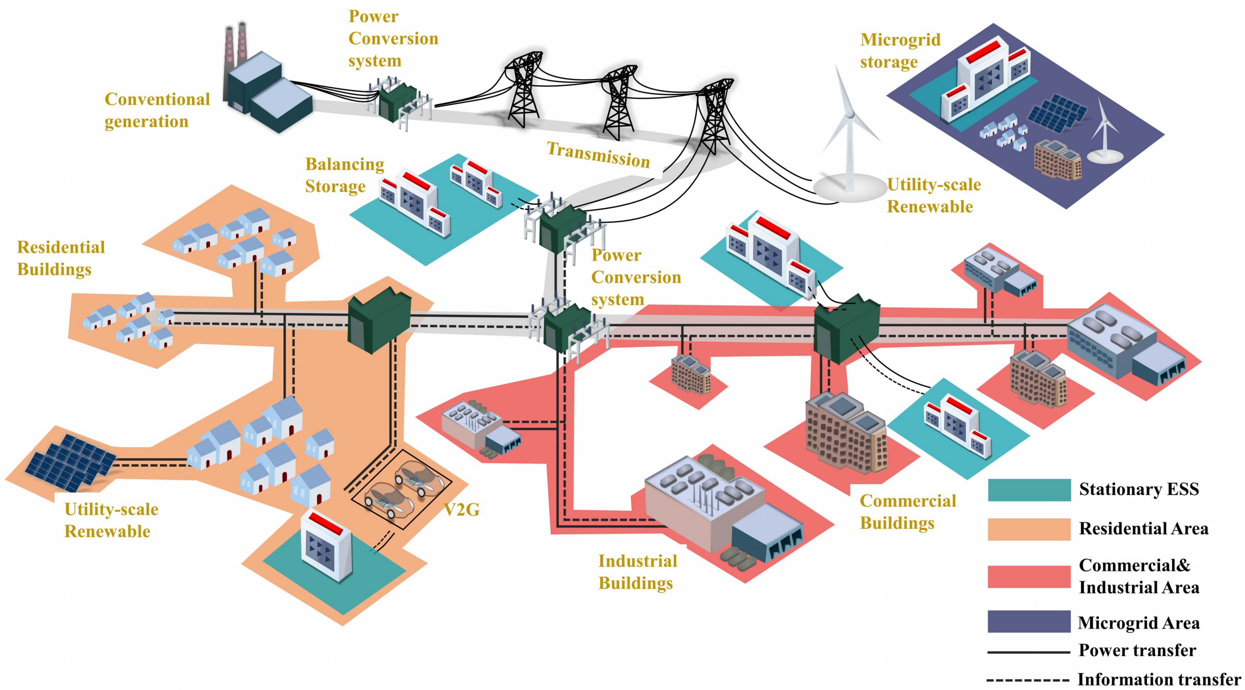

Fig. 6. Different applications of stationary ESS in the entire power system.

into three types: on the power generation side, on the transmission and distribution side, and on the consumer side [102]. They have different energy and power requirements. High-energy demand applications, such as energy time shift, usually require a longer discharge time but not a high response time. In contrast, high-power demand applications, such as system frequency modulation, usually require a fast response time but not a long discharge time. Management strategies in application, including sizing, operating, and controlling, are important for the performance of SLB. Table IV summarizes the publications on the integration of SLBs in stationary applications.

Wieland et al. [103] adopted SLB as stationary centralized and decentralized battery storage in five scenarios ranging from short term to mid-term, which covers small scale (up to 30 kWh) to large scale (up to MWh). The simulation results showed that SLB performs poorly in energy arbitrage under a second EOL criterion of 64% SOH. However, this result is acceptable, considering that new batteries only lasted one year until 80% SOH. Casals et al. [96] used an equivalent electrical battery aging model to simulate SLB capacity degradation in four scenarios, in which 40% SOH is set as the second EOL. The simulation results showed that the SLB lifetime could be over 30 years for fast charging EV stations, almost 12 years for self-consumption and transmission delay, and even a remarkable six years for area regulation. Li et al. [104] investigated the feasibility of reusing battery in charging stations coupled with photovoltaic (PV). The simulation results indicated that the performance of SLB is greatly influenced by some operation parameters such as DOD. Also, a 29.4% cost reduction in the long-term operation with the RBs can be achieved through the optimization of using conditions.

Lacey et al. [107] utilized SLB for grid support, including peak shaving and update deferral. The simulation results showed that SLB could provide promising cost competitiveness and voltage support. The 1232.5-kWh battery is configured to deliver 493-kWh energy over a 4-h period. Hart et al. [108] developed a simple equivalent circuit to simulate the aging behavior of NMC and $LiFePO_4$ at different temperatures. Due to heterogeneity, a power management algorithm was developed to match two EV packs connected in parallel. The experimental results showed that satisfactory long-term performance in microgrids can be achieved by adopting a suitable control strategy in the mixed SLBs scheme.

SLB is also used to support the integration of intermittent renewable energy. Shokrzadeh and Bibeau [109] developed a model to predict the energy growth caused by the increasing market share of plug-in EVs in Canada by 2050 and investigated whether SLB used to integrate wind energy can meet the load demand. The simulations yielded a positive result and confirmed that SLB has the potential to significantly improve the share of renewable energy with minimal impact on the grid. Deng et al. [110] integrated an echelon battery system into a centralized EV charging station with PV power sources. A positive result was obtained. Kootstra et al. [111] used SLB to stabilize PV power generation. The simulation results showed that battery reuse was not a worthwhile choice for stakeholders, while SLB was able to meet system requirements.

Gladwin et al. [112] analyzed the SLB performance in three scenarios in conjunction with grid power or PV generation for residential energy demand. The simulation results showed that the most beneficial scenario is to use the battery in conjunction with PV, where the battery could achieve a 14-year payback period with a potential cost savings of 75%. Similarly, Tong et al. [69] studied the performance of an integrated PV and SLB energy system in a house, and a BMS was developed

TABLE IV
OVERVIEW OF PUBLICATIONS ABOUT INTEGRATION SLBs ON STATIONARY APPLICATIONS

Authors	Applications	Profitable applications	Description
André Assunção, et al. [122] (2016, Portugal)	Residential demand management coupled with PV	Residential load following (payback <10yrs)	SLB served as a cost-effective solution compared to new batteries
Catherine Heymans, et al. [123] (2014, Canada)	Residential demand management (peak shaving)	Residential demand management	There is a need for the government to offer incentives for adopting this green technology.
Vilayanur V. Viswanathan, et. Al. [7] (2011, US)	Power reliability	Power reliability	The impact of different EOL and reward levels on the economic feasibility is analyzed
Gillian Lacey, et al. [107] (2013, UK)	Peak shaving Power reliability	NA	SOH and allowable DOD are important factors in determining the required battery capacity.
Shahab Shokrzadeh, et al. [109] (2012, Canada)	Renewable firming	NA	By 2050 the integration of wind and SLB can meet the load imposed by the PEVs' charging.
Shi Jie Tong, et al. [113] (2013, US)	Off-grid ESS	Off-grid ESS (50% of cost less than the system using new batteries)	SLBs can achieve similar performance to systems compare to new LIBs at a lower cost.
Wei Wu, et al. [124] (2020, China)	Industrial Grid support	Industrial Grid support (profit margins vary with SLB purchase price)	$116/kWh profit and a lifetime of 4.5 years (from 80% to 50% SOH) without considering the acquisition cost of SLBs.
Reinhard Madlener, et al. [125] (2017, Germany)	Residential demand management	Residential demand management	€107/kWh for the breakeven SLB price.
Uttam Kumar Debnath, et al. [11] (2016, Australia)	Smart Grid	generation side asset management	Using SLBs is more economic feasibility.
Lluc Canals Casals, et al.[126] (2019, Spain)	Residential demand management Frequency regulation	Frequency regulation	Reusing battery in stationary applications is necessary. And EV manufacturers should consider eco-design to facilitate battery life management.
H. Rallo, et al. [97] (2020, Spain)	Energy arbitrage Peak shaving	Energy arbitrage Peak shaving	Energy arbitrage produces higher savings than peak shaving.
Lluc Canals Casals, et al. [96] (2019, Spain)	Autonomous use self-consumption area regulation transmission deferral.	NA	SLB lifespan largely depends on its use.
Chris White, et al. [74] (2020, Canada)	Frequency regulation	NA	Thermal management design and Frequency regulation power magnitude influenced battery thermal response mostly.
Andoni Saez-de-Ibarra, et al. [114] (2015, Spain)	Residential demand management coupled with PV	Residential demand management	Sizing process is also important for maximizing the economic benefits of using SLB.
Maria Anna Cusenza, et al. [127] (2019, Italy)	Building demand management coupled with PV	NA	Improving the design of the LIBs-PV system in terms of resource efficiency and control of chemical toxicity is critical for environmental sustainability in both first and second life.
Ziyou Song, et al. [99] (2019, USA)	Renewable energy firming (wind)	No profitable	Reusing LIBs in the studied wind farms is not worthwhile.
Shijie Tong, et al. [69] (2017, USA)	Residential demand management coupled with PV Peak shaving	NA	With the retrofitted design and technology, SLB regained competitive performance, except for the imbalance at a high SOC and lower cycle efficiency compared to new batteries.

to avoid high charging and discharging conditions. The experimental results showed that a system with a 10-kWh battery pack and a 2.16-kW PV system could reliably solve the energy problem of a single house. Furthermore, Tong et al. [113] investigated the feasibility of an off-grid EV charging system integrated with PV and SLB under the weather conditions of a real city. The simulation results showed that a system with a 2.16-kW PV system and a 13.9-kWh battery pack is able to provide 194 days of full power for a year under a daily energy demand of 10 kWh.

Kootstra et al. [111] used SLBs to store excess solar energy to reduce subsequent power export from the grid in a PV system near Davis, CA, USA. The sizing optimization of battery and PV system was investigated integrating with three energy management strategies, and economics was set as the most important factor in determining the optimal sizing. The simulation results show that the total peak demand in the power grid can be reduced by more than 70%, or even by 80%, for a battery with a size of about 10 kWh and a PV system with a capacity between 1.5 and 3 kW. Compared with the new batteries, the cost of SLB is lower, so it is necessary to increase the size of battery, not the size of the photovoltaic array, in order to reduce the dependence on net-metering tariffs. Saez-de-Ibarra et al. [114] summarized the characteristic analysis for residential applications of SLBs as a two-step methodology, first calculating the optimal size of the storage system and second testing the application profiles of the batteries. The optimal capacity of SLB was determined after optimizing several parameters (including PV size, power value, and characteristic parameters of the storage). An economically positive result was obtained under the size optimization. Saez-de-Ibarra et al. [115] also used a similar strategy to determine optimal sizing in grid integration of renewables combined with SLBs. The optimal sizing process was divided into two main steps: calculating the optimal size of the battery in the first step and calculating the global optimal size considering the optimal values in the second step. The Casaquemada PV system with a nominal power of 1.9 MW on the Solucar platform was studied to evaluate the adaptability of the sizing method in the real case. The final optimal size of the SLB was 235.2 kWh. However, the major drawback of the study is that the authors did not provide further insight into the battery degradation process. Consequently, the system could not be evaluated based on the SLB aging performance.

The feasibility of SLB in microgrid has also been demonstrated. Lacap et al. [42] investigated the design, construction, and operation of a commercial-scale microgrid using a second life Nissan Leaf battery as energy storage for two buildings with a total area of 1550 m^2 and an average power demand of 85 kW. The analysis results showed that an average reduction of 60% in maximum peak demand and 39% in peak energy consumption with 164.5 kW of PV and 262 kWh of energy storage can be achieved in the microgrid. Qualitatively, no major capacity drop of SLB was observed during the first year of operation. However, the capacity drop during second life was not calculated.

These applications can be roughly classified into two types: one closely related to utilities and the other to commercial and residential end users. Utility operations require large energy storage (MWh) and power (MW), far in excess of the needs of vehicle applications. Meanwhile, a larger configuration often means more opportunities for safety problems. In contrast, the commercial and residential end-use applications, which are on the same scale as the vehicle applications, appear to be well-suited for secondary use because there is little need to reconfigure the batteries [116]. Calendar and cycle life degradation compliance is the primary technological barrier to the use of SLBs.

IV. Major Risks and Benefits of Battery Reuse

A. Potential Risks

The current battery information on EV, such as year, capacity, and manufacturer, is generally interconnected and incomplete [117]. Coupled with the electrochemical changes inside batteries, some risks are of great possibilities for SLB to be posed in some fields including safety and environment, which indicates that echelon utilization is still an immature scheme in the short term.

1) Risks for Safety: Battery safety is an absolute condition for battery reuse, which is primarily determined by the electrochemical system stability [118]. Safety accidents are generally accompanied by continuous heat and gas generation, which is resulted by the battery internal disturbances, including excessive side reactions such as lithium plating. The deposition of metallic lithium around the graphite anode of battery during charging, namely, lithium plating, may lead to thermal runaway. Fortunately, however, some research results have preliminarily proven that massive lithium plating is not always preventing the battery from achieving adequate longevity in second life [119]. Furthermore, suitable operational environments on C-rate and temperature are effective for controlling the lithium plating [120]. For example, thermal runaway problems can be easily caused by the poor battery consistency, the limited charging and discharging C-rate, and the large C-rate [121]. Therefore, existing external practical strategies, such as optimal thermal management systems, efficient balance systems at cell level, and appropriate charging/discharging strategies, are helpful for safety management in battery reuse [118].

At present, however, a clear picture of safety features and management, and mature and standardized methods for the safety assessment of SLBs is still lacking. There are no effective screening and inspection measures yet, which is the biggest pain point in the industry chain of echelon utilization. The tiny changes inside battery cells are difficult to examine in detail [128]. If the cells are disassembled and inspected one by one, it is very difficult and costly [129]. Meanwhile, the way of using the whole package is not yet mature, which cannot guarantee that there are no security risks. Moreover, considering the faster degradation rate and the cost of dismantling, inspecting, repurposing, and maintaining, the echelon utilization may have no obvious economic advantage over the new battery [130].

2) Risks for Environment: Environmental pollution is also a potential risk factor. Due to the lack of a sound traceability system and an effective supervision mechanism, LIB manufacturers aiming at immediate benefits would not take the initiative to recycle the batteries they sell. Under this context, echelon utilization may bring catastrophic environmental pollution. The mainstream of RBs is metal materials, such as aluminum, copper, nickel, steel, lithium, manganese, and cobalt, which account for about 50% of the total mass [131]. High-value material recycling and other material safe handling to promote sustainable development of resources is also an important issue for battery reuse [132]. Meanwhile, there may be the quality problem of battery material recycling caused by battery reuse. The possibility of quality problems will increase the demand for metal resources needed for the battery, which is contrary to the original intent of reusing batteries for material sustainable development [25].

Cusenza et al. [127] investigated the potential biological negative effects of reusing RBs in the storage system of buildings. The simulation results showed that battery reuse can strength some negative impacts, including abiotic depletion

TABLE V
MARKET CHARACTERISTICS FOR REPURPOSED LIBS [94], [136]

Application	Number of packs	Market size	Delivery level	Power level	Tran. time	Freq.	$ Saved in a year per kW
Renewables firming	200s	<100	1 MWh	10 MW	3-5h	15 days/ month	1000-1500
Peak shaving/ Energy arbitrage	100s	100-1000	1 MWh	1 MW	3-5h	Daily	120-250
Area-regulation	100s	<100	1 MWh	10 MW	Cycled continuously	Continuous	1000
Transmission support	1000s	<10	1-10 MWh	100 MW	5s	1/month	50-150
Residential	1-10	>3000,000	5-10 kWh	1-10 kW	3-5h	Daily	50-120
Light commercial	5-20	>150,000	75-100 kWh	25-200 kW	3-10h	Daily	80-200

potential, human toxicity cancer and noncancer effect, and freshwater eutrophication potential. The negative environment impacts were mainly due to the fact that part of the electricity generated by PV power plants was used for the production and recycling of EV batteries. It may be necessary to improve the battery's resource efficiency, chemical toxicity control, and production. Some risks for environment in research are summarized in Table VI.

B. Potential Benefits

1) Benefits for Transportation Electrification: As the market share of EV gradually increases, their huge electricity demand may have a negative impact on the current power system. Renewable power generation is considered the most economical and environmentally friendly solution for this issue. Shokrzadeh and Bibeau [109] developed a model to predict the market share of plug-in EVs in Canada by 2050 and investigated the feasibility of reusing LIBs integrated wind energy to support the load demand of EVs. The effective power generation cost of an intermittent source, the capital cost of generating dissipated power, and the required storage cost per kW were summed up to formulate the total capital cost of generating a continuous unit of electricity. The simulation results showed that wind generation supported by SLB can satisfy the load demand of plug-in EVs. The results also supported the integration of SLBs with renewable energy sources to minimize the demand on environmental resources. The cost reduction from battery reuse could enable higher market penetration of EVs.

Battery reuse may not reduce the initial cost of EVs. Neubauer and Pesaran [55] developed an equation to express the relationship between the battery health and reuse costs and the willingness of customers to pay for an equivalent new batter, which is described as follows:

$$S = \max\left(K_u K_h C_n - C_{\text{rp}}, C_{\text{rc}}\right) \quad (1)$$

where S is the salvage value, K_h is the health factor, K_u is the used discount factor, C_n is the cost of a new battery, C_{rp} is the cost of reuse, and C_{rc} is the recycling revenue. The cost of battery reuse in on-grid energy storage was analyzed in detail, with the assumption that the future salvage value of SLBs will be proportional to the cost of an equivalent new battery. The simulation results showed that SLB could become a common part of the future life cycle of EV batteries and be beneficial for cost-effective energy storage. However, SLB is not expected to have a significant impact on current EV prices. The decline in battery prices is the most important factor leading to negative outcomes, as the nearly ten-year life cycle can cause the price of new batteries to differ many times over. This gap is difficult to offset by the benefits of battery reuse.

Gu et al. [133] studied the closed-loop supply chain for recycling and reuse of EV batteries with three periods consisting of battery manufacturers and remanufacturers. In period 1, all batteries are produced from raw materials. In period 2, high-value batteries are reused, and low-value batteries are recycled. In period 3, batteries are recycled. An optimal pricing strategy between manufacturers and remanufacturers was developed based on the return yield, sorting rate, and recycling rate. The simulation results showed that reusing batteries can help reduce the consumption of raw materials. It is worth noting that if the cost of SLBs were higher than the cost of recycling, then recycling would be an economically advantageous option [134]. It was reported that the current cost of battery recycling is relatively high and the recycling rate is low (less than 2%) [33], [135]. Therefore, incorporating the reuse process into the battery life cycle has the potential to offset the high cost of recycling and increase the recycling rate of batteries.

2) Benefits for Economy: Economic benefits are generally considered to be achieved through maximizing the residual use value of the battery. Viswanathan and Kintner-Meyer [7] investigated the commercial value of reusing batteries in the power system with an 8% annual cost decay rate set to calculate battery costs. The simulation results showed that the value of battery reuse highly depended on battery ownership options, including EV or battery manufacturers, leasing by utilities, and EV owners. Volatility of SLB market usage was also discussed under three different market prices to examine the impact of SLB market conditions. The simulation results showed that battery reuse can be more profitable than direct recycling even under relatively negative market conditions.

Jiang et al. [10] developed a numerical model to analyze the opportunities and challenges of battery reuse and recycling in China. The simulation results show that reusing battery as energy storage can create an economic benefit of U.S. $147.8 billion by 2040, while it is estimated to be U.S. $76.9 billion for directly recovering valuable materials of RBs.

TABLE VI
OVERVIEW OF STUDIES INVESTIGATING ENVIRONMENTAL BENEFITS AND RISKS OF ECHELON UTILIZATION

Authors	SLB application	Impact indicators and variation	Comparison object
Sathre et al. [141]	Renewable firming	GHG emissions (14%↓)	Local Power Supply system
Ahmadi et al. [142]	Peak shaving alternative	GHG emissions (56%↓)	Natural gas
Wilson et al. [143]	Residential Load Management	GHG emissions (15%↓) Terrestrial Acidification Potential (23%↓) Surplus Ore Potential (44%↓) Fossil Resource Scarcity Potential (10%↓) Water Consumption (17%↓)	Fresh battery
Richa et al. [144]	No-indicate	Cumulative energy demand (13-46%↓) Global warming potential (12-46%↓)	Lead-acid battery
Tao et al. [145]	No-indicate	GHG emissions (8-17%↓) Cumulative energy demand (2-6%↓)	Direct recycling
Wilson et al. [143]	Residential Load Management	Human Toxicity Potential: cancer (6%↑) Freshwater Eutrophication Potential (16%↑) Freshwater Ecotoxicity Potential (7%↑)	Fresh battery
Cusenza et al. [127]	Residential Load Management (93kWh installed capacity)	Human toxicity cancer (14%↑) Human toxicity non-cancer (30%↑) Freshwater ecotoxicity (6.7%↑)	9kWh installed capacity SLB

The application of SLBs is considered to be diverse and can be divided into small applications (such as residential) and large applications (such as supporting the power grid) [107], [136], [137]. According to [94] and [136], the different market characteristics are summarized in Table V. Different markets, covering different ranges from kWh to MWh, have different application requirements and usage characteristics of SLBs.

Wolfs [138] evaluated the economics of using SLB to support power supply, which included a medium-scale centralized system and a small-scale highly decentralized system integrated with the grid. The simulation results showed that the use of SLBs in these applications was not economical considering the declining new battery prices and the potential degradation mechanism. However, this trend was not evident on the medium scale. Therefore, the flattening of the grid load may not be beneficial to the deployment of SLBs.

Residential load shifting and peak shaving are seen as important revenue sources of revenue for SLB. Madlener and Kirmas [125] developed a simulation model for an integrated residential PV system to calculate PV power generation, battery demand, load profile, and cash flow generated. The rates of increase (per year) in electricity prices were divided into three different levels: 2%, 4%, and 6%. The simulation results showed that a higher electricity price increase can lower the breakeven battery price. The impact of battery cost on profitability can be ignored when the annual electricity price increase reaches 6%. Therefore, the profitability of SLB is inextricably linked to an appropriate grid-optimized operating strategy. Similarly, the simulation results showed that SLB is profitable in residential PV systems and renewable energy power plant integration by sizing optimization [114].

Pagliaro and Meneguzzo [139] concluded that reusing is a necessity for EV manufacturers based on the market in China. Wu et al. [124] studied the profitability of using SLBs in China. The simulation results showed that SLB can achieve a lifetime of 4–5 years and a potential value of U.S. $116/kWh with an SOH usage of 50%–80%. However, the validity of this result is highly dependent on the degradation rate of the battery.

The experimental results showed that the price of the SLB with the proposed reconditioning system in [77] under the baseline scenario is U.S. $6 higher than with a simple reuse process (sorting battery modules to produce battery packs with similar SOHs). A U.S. $4 price lower than a simple reuse process could be achieved if the repair cycles, labor time, warranty, purchase price, and so on are reduced. A sensitivity analysis of network revenues was conducted for four types of energy storage: with reconditioning with grid services, with reconditioning by energy shifting, with a simple reuse process, and with new batteries. The result of the analysis is shown in Fig. 7, where the height of each color block represents the degree of influence of a change in this parameter on the profitability of the system. The higher the height, the greater the influence. In all scenarios, DOD is the most sensitive variable. Other sensitive factors are also intuitively shown in Fig. 7.

Steckel et al. [140] developed a model to estimate the levelized cost of stationary energy storage for SLB. The simulation results showed that the cost of SLB is at $234–278/MWh for a 15-year project period, which is more expensive than the harmonized results for a new battery of U.S. $211/MWh. However, results are highly sensitive to discount rate assumptions, DOD, and module reuse costs.

3) Benefits for Environment: Echelon utilization may further bring some environmental benefits. Table VI summarizes the publications about the environmental research of SLB. Sathre et al. [141] developed a parametric battery life cycle system model to evaluate the greenhouse gas (GHG) footprint of SLB applications. The simulation results showed that if 5% of California's total electricity consumption fueled by natural gas was replaced by SLBs, about 7 million metric tons of CO_2e per year in 2050 would be reduced. However, the carbon reductions from SLBs will change if the electricity supply structure in other regions is different than in California. For example, if clean energy (e.g., hydroelectricity) occupies a

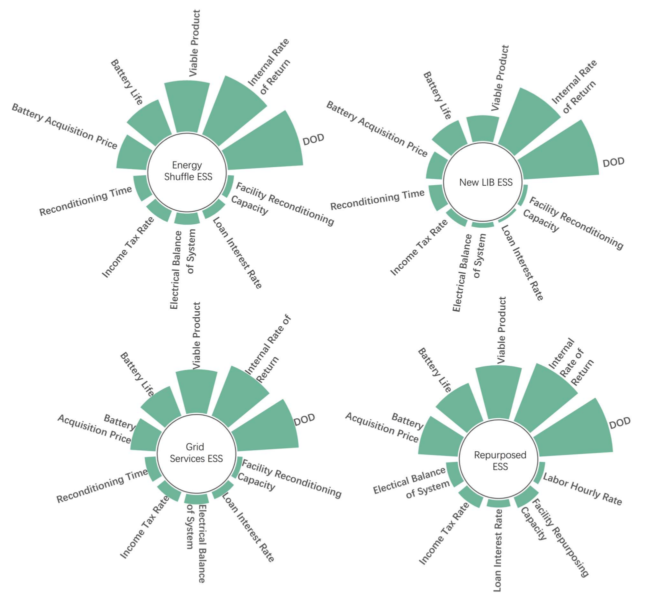

Fig. 7. Sensitivity analysis of different factor inputs in revenue of four ESSs.

large part of a region's electricity supply structure, the carbon reduction effect of SLBs would not be as great. Similarly, Ahmadi et al. [142] evaluated the environmental feasibility of SLB considering battery degradation. The simulation results showed that echelon utilization for peak power generation can achieve a reduction of 56% CO_2 emissions compared with natural gas-fired in the entire life cycle.

Wilson et al. [143] developed a physical allocation method for RBs based on remaining capacity, module retention rate, and lifetime. The simulation results showed that if SLBs have a minimum service life of six years, a smaller impact compared to new batteries in all selected environmental categories can be achieved.

Richa et al. [144] developed a life cycle access model to analyze the environmental potential of reusing batteries in stationary storage. The simulation results showed that the use of SLBs can reduce cumulative net energy demand and global warming potential by 15% under conservative estimates, compared to an equivalent-functionality lead-acid battery. Tao et al. [145] investigated the energy and environmental sustainability of reusing and recycling batteries. The simulation results showed that because of less material and energy required for both production and recycling, recycling with echelon utilization can reduce carbon footprint and energy consumption by 8%–17% and 2%–6%, respectively, compared to direct recycling of LIBs.

V. Policy Implications and Suggestions

A. Policies for SLB: Necessary and Urgent

There is a clear need to promote policies that provide safer, more efficient, and equitable disposal methods for both reuse and recycling of RBs. Efforts should be made to remove barriers to creating a sustainable and recyclable battery life system through collection, logistics, data sharing, standardization, and basic investments to avoid the occurrence of events similar to the global flow of electronic waste. However, it has been shown that the lack of uniform global and regional policy is one of the critical barriers to developing the market for SLBs [146].

After analyzing the feasibility and cost savings of using SLBs for residential peak load shifting, Heymans et al. [123] advocated the use of official incentives to improve the economic efficiency of battery reuse and illustrated the benefits of government subsidies using Ontario as an example. The main purpose of government subsidies is to reduce or exempt additional costs associated with the use of SLB, including the cost of ancillary equipment, installation, maintenance, and safe operation, in order to increase occupant enthusiasm. If the provincial government eliminates the auxiliary fees and reduces energy prices by 75% for households using SLBs (about 1 in 20 homeowners), it can shift about 1 GWh of electricity demand to off-peak hours, despite increasing administrative costs by more than U.S. $100 million, significantly reducing the risk of blackouts. Approved incentives include capital cost incentives, tax incentives, and energy cost incentives. Fallah et al. [147] developed a model to estimate EV penetration in Ireland based on government policy and customer preferences. The simulation results showed that the annual capacity of SLBs could increase from tens of MWh in 2035 to almost 1.7 GWh in 2050 with minor and moderate changes in environmental regulations.

Nowadays, electrification of the transportation sector is being promoted worldwide, and major EV manufacturers have actively responded to this trend. The development of EVs inextricably linked to policy incentives, such as financial subsidies, the development of charging infrastructure, and the existence of production facilities [148]. However, the incentive policy for new batteries may not be effective in encouraging the use of RBs. This could be explained by the result that tariff support reduces the cost of using new batteries [24]. Meanwhile, the development of SLBs also relates to specific applications, especially stationary energy storage. Telaretti and Dusonchet [34] studied the development of the stationary storage market in the U.S. and related policies. The results showed that policies for the development of the electrochemical storage industry were still in its early stages. Also, it is necessary to develop an optimization framework to model the design strategies for the deployment of SLBs, which can further favor analyzing the relationship between the incentive policy for new batteries and the use of RBs.

B. Current Policy Limitations

As the power battery gradually enters the large-scale retirement phase, policies for RBs must gradually move from an initial design phase to an effective implementation phase with responsive and corrective actions. However, there are two major shortcomings in the design, implementation, and response of policies for RBs that should be recognized.

The first shortcoming is the failure of policy coordination caused by deviations in the alignment of policy incentives, incomplete policy objects, and the premature introduction of policy instruments. For example, there is a spatial mismatch between the supply and demand of renewable energy storage

TABLE VII
VALUE OF SOME SLB APPLICATIONS OF PRESENT AND FUTURE IN SOME COUNTRIES/CASES

Authors	Year of Publication	Applications	At present	Future
K. Gur et al. [124]	2018	Residential PV + SLB	Require large subsidies	Make sense in Germany, France
		Residential SLB only	Make sense in Italy, Spain	Make sense in Germany, Spain, Italy, Sweden
		Commercial	Require large subsidies	Require large subsidies
		Industrial	Positive for Frequency Response Service prices > 20€/MWh	Positive for Frequency Response Service prices > 10€/MWh
Lei Zhang et al. [150]	2020	Grid support	Require more flexible policies, not just subsidies in China	Significant value

capacity between the eastern coastal regions and the western inland areas of China, which may hinder the second use of RBs [10]. Therefore, national coordination may be required for the rational design of collection, dismantling, and reuse facilities for the sustainable management of residual materials.

The second weakness is the influence of moral hazard. When the policy uses subsidies to promote the development of high-quality enterprises, there are also some unreasonable incentives to gain benefits. Some negative consequences, such as adverse selection and inefficient policies, are possible because of "government failure" in the process of RBs. It seems that future policies should use more market mechanisms to guide the use of subsidies and the effective development of the RB industry. In addition to these two main shortcomings, there are still some obvious uncertainties in the technical and economic aspects of RB applications. These uncertainties also hinder the deployment of policies. It could be concluded that the external factors contribute to the uncertainty in four aspects: 1) uncertainty in price, cost, and value; 2) uncertainty regarding societal expectations; 3) uncertainty related to the reuse business case; and 4) uncertainty and challenges for LIB recycling [149].

C. Suggestions

Currently, battery reuse is still at an early stage of development, and certain measures are needed to cope with the increasing number of RBs. After analyzing the Chinese SLB market, Wu et al. [124] made the following suggestions to the government.

1) The standardization of batteries can further promote the standardization of manufacturing and recycling. If the residual capacity, size, and coding rules of batteries are standardized, most of the barriers to battery reuse will be removed.
2) A transparent battery quality tracking and evaluation mechanism should be introduced so that information, such as battery quality deterioration, can effectively guide the further circulation of batteries.
3) It is suggested to improve the disposal of waste batteries through battery recycling regulations.
4) To develop SLB energy storage business models in some cities to study the viability of battery reuse in practice.

Gur et al. [25] presented a comprehensive study of SLB use in the European Union (the results are presented in Table VII) considering the factor of battery price decline. The author's policy recommendations for the European market are similar to those of [124]. However, contrary to some discussions in the literature mentioned above, Gur et al. [25] also insisted on the priority of RB reuse, which is based on the perspective of sustainable development of critical resources (raw materials such as lithium and cobalt). Furthermore, battery reuse would not only benefit the environment but also create additional jobs. Therefore, it is beneficial to increase support for innovative basic research on the application implementation of SLBs. Use government procurement and appropriate tax and exemption policies to provide greater support for the cascade battery industry.

Build national coordination for the rational layout of the collection, disassembly, and remanufacture facilities for RBs. Collecting is the first step for the battery to begin its second life. However, the mechanism of collection and reuse is still unclear and the recycling rate is still unsatisfactory. Building codes and standards are the critical steps to achieve the goal of a high rate of batteries entering the recycling and reuse loop. The liability issue for collection and subsequent reuse or recycling should be clarified and pricing for SLBs should be standardized. In addition, policy mechanisms, such as the interface between labels and responsible sourcing, should be standardized to remove barriers to battery reuse.

Increase the share of renewable energy use, enforce reasonable energy efficiency standards, and create tradable green certificates. At present, SLB manufacturing and battery recycling are obviously technology- and labor-intensive industries. As a result, they are more likely to lead to positive competitiveness and distributional conflicts, including firm productivity, job creation, and private investment. Public funding for

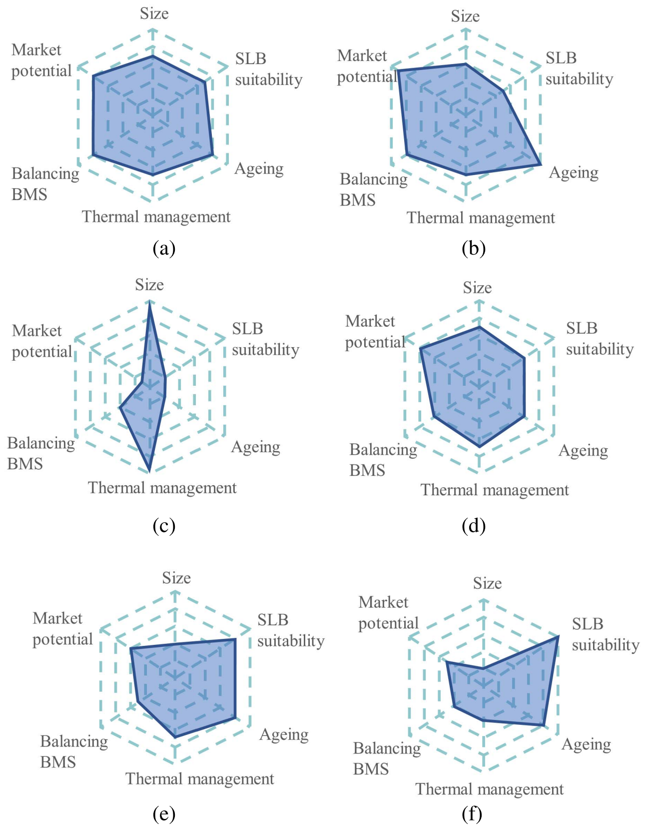

Fig. 8. Comparison of six typical application scenarios in different factors. (a) Renewables firming. (b) Peak shaving/energy arbitrage. (c) Transmission support. (d) Area regulation. (e) Light commercial/industrial. (f) Residential.

research and development and tax policies can play a key role in promoting equitable development and providing the necessary guidance for battery reproduction and recycling. Meanwhile, renewable energy commitments can be designed to ensure environmental sustainability and further progress toward carbon neutrality. It is beneficial to increase the share of renewable energy by reducing CO_2 taxes on renewable fuels in proportion to their greenhouse gas reduction.

VI. Application Perspective and Future Outlook

As discussed in Section III, the technical aspects of echelon utilization should focus on battery aging, size, balancing BMS, and thermal management. Different energy storage scenarios have specific requirements for the batteries, so the above factors also need to be considered differently. In addition to these technical factors, each scenario differs in terms of market potential and suitability for SLB deployment. In this study, six typical scenarios were selected to explore all possibilities for SLB deployment. Fig. 8 shows the evaluation of the different scenarios in six dimensions.

A. Application Perspective

1) Renewables Firming: Most renewable energy sources, such as wind and solar energy, have intermittent characteristics. Therefore, the renewable energy system must be equipped with reliable ESS to support the reliable use of renewable energy. Due to better response and higher energy storage density compared to other ESSs, SLBs are still the better choice to support renewable energy. As environmental and economic issues, such as carbon neutrality gradually, play an important role in global social development, renewable power generation has a wide range of applications. The low cost of renewable energy offsets the economic considerations of SLB to some extent. Due to the large size (MW) and high frequency of use, the SLB as energy storage for energy arbitrage needs to pay more attention to the aging problem, and the balancing BMS and thermal management also need to be used to suppress the propagation of parameter inconsistency and improve safety and efficiency.

2) Peak Shaving/Energy Arbitrage: Energy arbitrage is a typical application of energy storage. It stores electricity primarily when there is sufficient and cheap electricity and releases the stored electricity when electricity is scarce and electricity prices are high. This application often requires up to 10 MW of electricity. Also, it has the ability to discharge most of the battery energy within a few hours. Also, the frequency of use is very high, most of the year it is used. At present, the energy arbitrage market is gradually growing, and the usage characteristics are suitable for SLBs with lower power density. Since the main purpose of the application is to make profits, aging is an important issue. Similar to peak shaving, aging, thermal management, and balancing BMS are also important issues in this application. However, the viability of SLB application in a large configuration needs further discussion. The suitability of energy arbitrage for SLB is relatively worse than that of renewables firming.

3) Area Regulation: Load tracking is a utility service that dynamically adapts to achieve real-time equilibrium in response to slowly and continuously changing loads. Load tracking places higher demands on discharge response time, extending into the minute range. The battery has a faster response time and can provide load-tracking services for applications such as regional regulation (frequency regulation of island grid systems). Since it is difficult to predict power generation and consumption for these types of applications on the power generation side, dynamic adjustment of the two often requires a larger size (which can reach MW). Although the battery is continuously charged and discharged, the time required for one cycle can be several days or even longer. Therefore, BMS for aging and balancing is relatively less demanding than that for renewables. Thermal management is similarly important in this application as it is for renewables and peak shaving due to the similar sizing configuration.

4) Transmission Support: SLBs are used to provide intermittent active and reactive power pulses to transmission lines in the power grid several times a month. Because of the enormous power of the transmission lines, the power configuration of SLB must be large enough to support megawatt-scale charging and discharging operations on the order of several seconds. Although the power requirements are relatively large (approximately 100 MW), the frequency of battery use in this scenario is very low and the single-use event lasts only a very short time, so a large-capacity battery is not required. Because of the low frequency of use, the calendar life for aging is mainly focused on and the balancing BMS is relatively demanding. There is a small market potential for transmission support, and because of the limited calendar life, SLB is not suitable for this application either. Thermal management is an issue that needs special focus due to its size.

5) Light Commercial/Industrial: Light commercial/industrial load management is an ancillary service of distributed generation systems. SLBs are capable of providing services that ensure the normal operation of various power generation methods (renewables, grid, and so on). It is relatively easy to achieve significant economic benefits with small size. The size of battery in this application is only in the kWh range. Despite the small size, the frequency of use is high, and the device may be turned on once a day. Therefore, attention to aging is very high, and balancing BMS and thermal management must be considered to ensure that the system can be in good operating condition. Due to a little sizing, there is less demanding on thermal management system under this scenario.

6) Residential: The characteristics of residential load management are similar to those of light commercial, but the size is much smaller and only a small capacity may be needed ($<$10 kWh). Reducing the size leads to weakening for the attention on inconsistent parameters and thermal management. Achieving economic benefits is still the main goal of this application. Therefore, it is also necessary to pay special attention to the aging of the battery. As for the family, thermal safety must also be fully guaranteed. Since the size of the battery is smaller than that used in EVs, the thermal management of SLB is a less difficult issue.

B. SLB and Transportation Electrification

It may be difficult to directly obtain the usage of SLBs in electrified transportation. However, the question about SLB is proposed by the promotion of transportation electrification.

A more effective way to deal with SLBs is required by developing transportation electrification. Maximizing the utility and the value of the vehicle batteries through echelon utilization serves as a valuable effort for the automotive industry to either reduce the selling price of EVs or maximize the profitability of the accelerating electrification of transportation. Meanwhile, SLBs can participate in cleaner transportation-fueling infrastructure, which is undeniably the foundation for accelerating transportation electrification. These essential infrastructures, including widespread charging stations, as well as a fortified and cleaner power grid, are the key to making our electrified future as green as possible. As renewable energy penetration increases, the need for such balancing services is expected to increase. There is still sufficient power and energy capacity left in the SLBs to support various grid ancillary services such as balancing and EV charging support.

The echelon utilization of RBs can offset part of negative impact brought by the transportation electrification. Although being considering more eco-friendly compared with their gas-burning counterparts, EVs still come with environmental costs. Batteries contain valuable minerals such as cobalt and lithium, which are primarily extracted and processed globally. Labor and vital resources, such as water in local communities, can be seriously abused, which contributes to global carbon emissions. Therefore, battery reuse helps to reduce the demand for new batteries in some fields, thus reducing greenhouse gas emissions in developed countries and urban centers, which is an opportunity to create an even greener automotive future.

C. Challenges and Future Prospects

Based on the summary of current research, SLB is undoubtedly a promising application. However, there are still some important issues that need to be further discussed. First, better risk management is needed to ensure the safe use of SLB. In addition, the current shortcomings of SLB are mainly focused on the shorter lifetime and the altered aging mechanism leading to accelerated degradation in the second lifetime. Aging prediction in the second life stage is more challenging than in the first-life stage. In addition, it is necessary to develop a more efficient balancing management strategy to avoid the negative impacts of inconsistency on battery lifetime and performance. In addition to determining the applicability of the scenario, there is also the issue of how to create an effective business plan for echelon use. Specifically, the future development trends related to SLB can be expected in the following three sections, including the business models, cost and standards, and management techniques.

1) Innovation of Business Models: Although some successful explorations have been achieved in some applications of battery reuse, such as energy arbitrage, charging stations, and low-speed EVs, the business model is still immature [151]. Taking the projects listed in Table I as examples, most of the current cascade utilization is in the startup phase and experimental application stage. The actual market volume downstream of the industrial chain is limited and lacks high operation efficiency and large scale of use [152].

The current application scope of RBs is not large enough. At the same time, due to some technical problems to be solved such as inconsistency, the application of SLB will be dominated by light commercialization and residential demand management in the short term. In the long term, it will gradually expand to larger scale applications, such as renewable energy stabilization and area regulation, as the technology matures and scale increases, but avoiding application in some scenarios, similar to transmission support. It is urgent to vigorously promote the business model innovation of battery reuse. In addition to supporting echelon utilization of batteries to realize large-scale and commercial applications in the fields of backup power, energy storage, and low-speed power, application scenarios should also be expanded, such as in the fields of smart cities and the Internet of Things. Meanwhile, the battery-swap-based model could be developed to support model innovations such as the separation of vehicle and battery, leasing, and battery outsourcing [153]. The advantage of battery replacement is that it can achieve rapid energy replenishment, battery upgrade, battery health detection, rapid recycling of battery packs, and flexible battery replacement on user demand. In this way, the management of battery retirement and reuse can be better implemented.

2) Advance in Cost and Standards: At present, the price difference between new batteries and SLBs is not obvious;

the total amount of SLBs has not yet enough to achieve the expected economies of scale. No matter how the supply and demand of market changes, lower cost is the premise for realizing value of echelon utilization [154]. Only SLBs with adequate performance at a lower cost can guarantee good economic benefits in some applications and a smooth industry chain [155].

Lower cost requires not only competitive procurement costs but also low maintenance costs. This makes high demands for the entire industry chain of echelon utilization. The effective control of the process and material costs in dismantling, testing, grouping, grouping, and battery management is an essential element for forging cost advantages compared to new batteries. Battery and vehicle manufacturers should take the initiative to unify standards in the research and development and design stages to realize the competitiveness of SLB. The generalization of battery pack structure design and assembly process can also facilitate low-cost automated disassembly, sorting, inspection, and reorganization for echelon utilization.

3) Development of Key Techniques: Battery databases may be created based on extensive historical data on EVs to directly map the dynamic aging of the battery. As a result, after being retired from EVs, they can be directly classified into different classes according to the characteristics of the batteries without the steps of screening and testing. Also, each type of battery is adaptable to the specific application.

Active balancing strategies can be widely used to improve the balancing efficiency and effectively suppress the propagation of parameter inconsistencies. In addition, SLB can be used in conjunction with other energy storage devices such as new batteries or supercapacitors to reduce the use of batteries during high demand, reduce DOD, and increase service life.

VII. Conclusion

This review gives an overview of the current and future status of SLBs in applications. Great attention must be paid to the aging mechanism of SLBs, especially for aging knee, which is the point at which the battery's aging properties change dramatically. Battery aging is significantly accelerated after the aged knee, but whether this indicates that the battery should be completely retired is uncertain. The parameter inconsistency of SLBs is obviously seen when compared to the fresh battery, which may cause fast degradation and introduce safety risks. It is necessary to use suitable approaches such as balancing BMS to suppress parameter inconsistency. SLB application scenarios are numerous and may be split into large- and small-scale categories. Large-scale energy storage is mostly utilized in conjunction with the whole power system, whereas small-scale energy storage is primarily used in residential or light-commercial areas. Small-scale applications are more suited for battery reuse because fewer repurposing works is required.

Current supply and demand for SLB provide a good basis for the potential industrial chain. However, the lower cost of new batteries has continued to squeeze the SLB profit margins, posing a challenge for SLB applications. Current SLB price maintains 50%–70% of the new battery price, which still exists some room for profit. Safety issues in battery reuse have not been fully investigated. In addition, battery reuse may help to compensate for the large cost of extracting raw materials, which may increase the current low recycling rate. The majority of the research is optimistic about the economic feasibility of reusing battery in various applications. Finally, the influence of policies and external incentives on battery reuse requires more investigation. Policies have a vital role in favoring the development of reusing batteries.

Although numerous researchers have studied SLBs from various perspectives, it is still difficult to provide a definitive answer to the question of whether and which commercial model should be selected. Currently, there are some projects of reusing batteries, but more testing in practice is still desperately required. Some vehicle manufacturers have introduced novel battery operating schemes such as leasing, which could be beneficial for SLB adoption.

Overall, battery reuse is an issue that could become an essential part of future greening of energy supply in conjunction with increasing electrification of the transport sector and sustainable transformation. This work aims to provide a foundation for future SLB research based on the methods and concepts discussed in the literature that can help inspire the application of SLBs.

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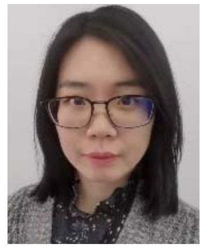

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