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Second Life of Electric Vehicle Batteries: A Review of Reuse in Stationary Energy Systems

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***Abstract*—The electrification of the transportation sector has witnessed a significant surge, with global sales of EVs doubling between 2021 and 2023. The EV batteries are deemed retired after 8-10 years due to the decline in performance. However, they are at 70-80% of their initial capacity at retirement, and there are better options than directly recycling them at this stage. The potential repurposing of EV batteries for stationary energy storage systems (SESSs) presents a promising avenue. While the concept is compelling, its economic and ecological viability requires careful consideration. The second-life battery energy storage system (SLBESS) can be used to increase self-consumption, perform peak shaving, and provide grid support. However, the ever-declining cost of new Lithium-ion batteries (LIBs) poses a potential threat to the SLBESS as they have a fixed repurposing cost. This article provides a systematic review of the latest developments in SLBESSs within both research and industry. The review delves into the applications of SLBESSs in each sector and examines the challenges present to this technology.**

Keywords—Second-Life Batteries, Repurposed Batteries, Retired Batteries, Stationary Energy Stroage System

I. Introduction

According to the International Energy Agency (IEA), the share of electric vehicle (EV)s in global car sales has increased from 9% in 2021 to around 18% in 2023 [1]. In the latest EV outlook by BloombergNEF, it is predicted that almost 39 million EVs will be sold globally in 2030 [2]. On average, an EV has a battery capacity between 45 kWh and 80 kWh [3], which means that by 2030, almost 1.8 TWh – 3.1 TWh of batteries will roll out each year. A Lithium-Ion Battery (LIB) is deemed retired or unsuitable for automotive applications due to reduced capacity and power after 8-10 years of service [4], and its state-of-health (SoH) is around 70%-80% [5], [6].

The life cycle of an EV involves stages such as production, assembly, usage, and recycling for raw material extraction at the end of life (EoL). However, as illustrated in Fig. 1, Börner et al. presented alternative approaches to simple recycling at the end of first life (EoFL) to enhance secondary resource utilization. If a battery shows a high SoH at the EoFL, it can be directly reused in a new EV without any refurbishment. Another possibility is to remanufacture the retired batteries to restore their original specifications. Repurposing the used batteries for a less intensive application can be another option. While the old batteries may no longer meet the operational requirements for electric vehicles, they are well-suited for applications like stationary energy storage system (SESS). Moreover, with the expected demand for battery energy storage system (BESS)s to reach 2.5 TWh by 2030 [7], the utilization of second life battery (SLB) for this purpose becomes more compelling.

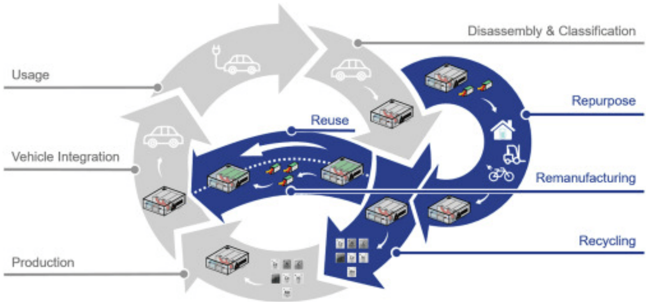

Figure 1: Different pathways at the EoFL for EV batteries [8].

4R Energy Corp., a collaboration between Nissan and Sumitomo Corp., developed a systematic approach for dealing with retired batteries, categorizing them into grades A, B, and C based on their current health. Components from batteries assigned an A grade are directly reused in the production of new EVs. Grade B batteries find application in the manufacturing of large SESS and forklifts. Batteries designated as grade C are utilized for backup power supply purposes. This systematic grading and repurposing approach contributes to extending the useful life of retired batteries and optimizing their utilization in various applications [9].

Using these retired automotive batteries as SLB in SESS can potentially reduce the Levelized Cost of Electricity (LCOE) due to lower cost than new batteries. Additionally, this practice contributes to a decreased carbon footprint since it eliminates the need for new raw material extraction [10]. SLBs find applications in various areas, such as self consumption increase (SCI) of renewables, peak shaving, backup power, grid services, and energy arbitrage. Nevertheless, the transition of batteries from a vehicle to a SESS presents challenges that must be addressed to establish a circular economy for batteries and create a more sustainable future.

Section II. discusses the methodology opted to perform the review, and section III. presents an overview of the projects reviewed for this article. Section IV. and V. explain the details about the degradation mechanism and repurposing of the EV batteries. Section VI. encompasses the popular second-life applications, and section VII. discusses the most important challenges faced by the second life battery energy storage system (SLBESS) manufacturers. In the end, section VIII. summarizes the takeaways of the article.

II. Methodology

This article is a systematic review of the SLB projects in the research sector and industry. The literature surveyed includes academic publications retrieved from databases like IEEE, MDPI, and Elsevier. Keywords like 'reused,' 'repurposed,' 'retired,' and 'second-life' were combined with 'EV battery' and 'stationary energy storage system' to find relevant literature. This article focuses on real-life SLB projects, and therefore, papers exclusively based on simulations were excluded from consideration. Additionally, insights were derived from press releases and newsletters of companies such as EV manufacturers, SLBESS manufacturers, and utilities. Moreover, online news articles from sources like [11] and [12] were consulted to learn about the latest industrial developments regarding SLBESSs around the globe. The information from these various sources has been organized into a database, presented in appendix A. and appendix B..

III. Overview of Projects

The projects are categorized into two groups: research projects (appendix A.) and industrial projects (appendix B.). Research projects are either funded by the EU or the local government of the respective country. These initiatives concentrate on optimizing energy utilization and increasing the self-consumption of renewable sources, primarily PV. Project capacities vary from a few kWhs to several hundred kWhs, with the largest project having a 500 kWh SLB capacity in Hannover, Germany.[13].

On the other hand, industrial projects consist of either a product developed by an individual company, available as an off-the-shelf solution in the market, or an SLBESS developed by an industry consortium. These consortia include EV manufacturers, system manufacturers, and/or utility companies. The projects developed by these consortia are all large-scale projects, and the most common application is grid support, primarily frequency control reserves as illustrated in Fig. 2. The largest BESS using SLBs will become operational this year in Texas, US. It has a capacity of 50 MWh and will support the grid from a wind farm [14].

LIB, predominantly of NMC chemistry, emerged as the primary choice for both types of projects. Approximately 80% of the projects featured batteries sourced from Nissan and Renault. Electric vehicle manufacturers such as Audi, Mercedes, and BMW have recently showed a growing interest in SLBESS. Audi, in collaboration with utility companies like RWE and EnBW, has successfully developed SLBESS projects of more than 5 MWh [15], [16].

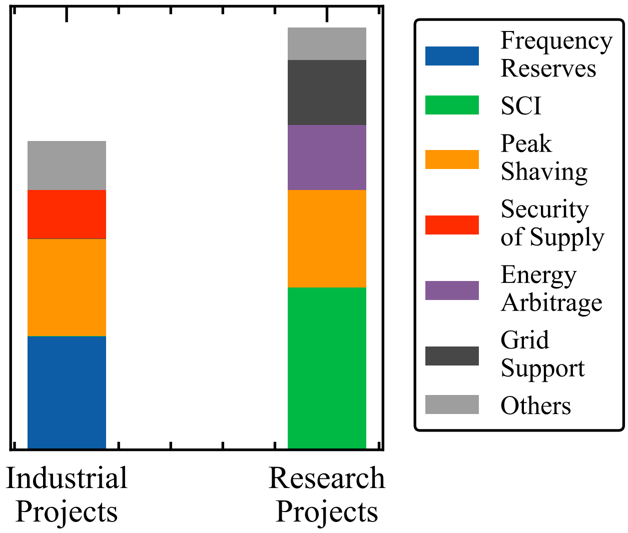

Figure 2: An overview of applications of SLBESS in research sector and industry.

IV. Battery Degradation

As time progresses, the batteries start to lose capacity, and the internal resistance increases [4]. Battery aging is a combination of cyclic and calendric aging. Calendric aging is a function of time, temperature, and state-of-charge (SoC), whereas cyclic additionally depends on depth-of-discharge (DoD), and C-rate as well. Thus, a battery from a colder region will exhibit different degradation behavior than a battery whose first life was spent in a hotter region. Furthermore, different LIB chemistries show different aging behavior. For instance, an LFP battery has a better cyclic lifetime than any other LIB [17]. These considerations should be considered when assembling a SLBESS.

Moreover, it can be observed from Fig. 3 that the battery degradation is linear up to a certain point known as the knee point, and afterward, the battery degrades non-linearly. Depending on the requirements of the second-life application, the knee point can occur earlier or later in the second life of the battery, resulting in varied lifetimes, as illustrated by Casals et al. in [18]. The study simulated five different applications for SLB, revealing a significant difference from 1.7 years for EV fast charging to 29 years when used as an uninterruptible power supply (UPS).

Accurate SoH and remaining useful life (RUL) estimation is essential for the success of a SLBESS project. Various methods exist for SoH estimation, such as electrochemical impedance spectroscopy (EIS), Coulomb counting, and data-driven algorithms [19]. Similarly, for RUL estimation, the literature offers model-based methods, data-driven approaches, and hybrid methods. A trade-off must be considered between accuracy and computational effort when opting for a suitable model [20]. In 2022, JT Energy Systems inaugurated Saxony's largest battery energy storage facility in Freiberg. The project utilized LIB from the electric forklifts and retired EVs, and has a peak power of 25 MW. Data-driven models were used

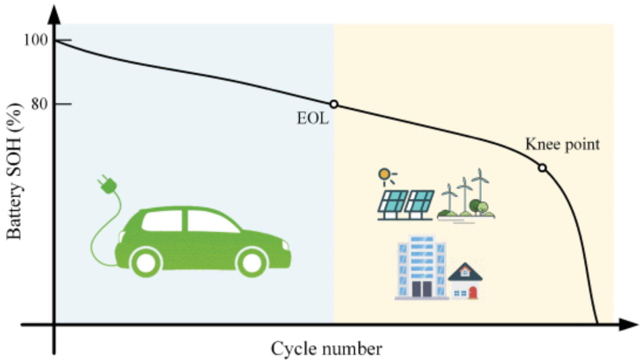

Figure 3: Battery degradation behavior over a lifetime. [4]

for the classification, based on SoH, and RUL calculations [21].

V. Battery Repurposing

For an efficient SLBESS, strategic repurposing decisions are crucial. A significant consideration is the extent of disassembly; dismantling the battery down to the cell level enables the manufacturer to recombine cells with similar characteristics, such as SoH, thereby extending the SLBESS's lifetime. However, it comes with an associated cost increase, as demonstrated by Rallo et al. in [22]. The cost of repurposing was 32 €/kWh, 60 €/kWh, and 76 €/kWh for pack-level, module-level, and cell-level repurposing, respectively.

According to the reviewed data, the majority of the existing large-scale SLB projects are based on pack-level repurposing to avoid high investment costs. SLBESS manufacturers are actively exploring methods to minimize these costs. An American company, B2U, has developed an EV Pack Storage (EPS) system that monitors individual packs. This system facilitates the seamless connection and disconnection of packs, ensuring that the weakest battery pack does not constrain the performance of the SLBESS [23]. Likewise, Jaguar Land Rover (JLR) collaborated with Wykes Engineering to seamlessly integrate retired batteries into SLBESS. This integration is cost-effective, as there is no need for additional repurposing expenses; the batteries can be extracted directly from the vehicles and placed into the SESS racks without additional modifications [24].

Toyota Central R&D Labs, Inc. has developed an innovative storage system called Sweep energy storage system (ESS). It is designed to maximize the utilization of retired EV batteries, accommodating significant variations in performance and capacity attributed to aging and diverse chemistries. The sweep ESS is a device that controls charge and discharge energy. It achieves this by rapidly switching electricity flow on and off (bypassing) through series-connected batteries in microseconds. Moreover, the sweep function has the capability of direct AC output from the batteries by reusing the onboard inverters, eliminating the need for an additional power conditioner (PCS). This not only contributes to cost reduction but also mitigates power loss associated with the conversion from AC to DC by PCS, thereby enhancing overall energy efficiency. [25]

VI. Applications

While SLBESS can be used for various applications, this section discusses those commonly adopted by researchers and implemented in industrial settings.

A. *Self-Consumption Increase*

Self-consumption measures how much of the energy generated by renewables is utilized directly or indirectly through storage by the consumer. The motivation behind increasing self-consumption lies in the disparity between the buying and selling electricity prices for a prosumer [26]. In Germany, over the last decade, the feed-in tariff for solar PV has declined, while the electricity price has nearly doubled from 25 cents to 46 cents per kWh [27]. This incentivizes prosumers to maximize the use of installed PV systems without relying extensively on the grid.

From 2015-2018, a project called Energy Local Advanced Storage System (ELSA) was carried out in 6 different European locations. One of these locations was Kempten, Germany, which is a residential district with multiple apartment buildings. The primary goal at this location was to use SLBs and develop an intelligent energy management system (EMS) that can increase the degree of self-consumption of the energy generated by solar PV. Six buildings were included in the demonstrator project. The buildings had a combined PV generation of 37.1 kWp. The SLBESS had an initial capacity of 66 kWh, which was later upgraded to 95 kWh. The system had a maximum charging power of 18 kW and a maximum discharging power of 72 kW. ELSA Residential EMS (EREMS) was developed to control the battery system autonomously based on the load profile of the buildings and PV generation. Out of an average mismatch of 60 kWh per day, the SLBESS provided the inhabitants of the district, on average, an extra 40 kWh each day by intelligently charging and discharging the batteries. Furthermore, the SLBESS reduced the additional load of 3.4 kW on the grid daily [28]. The storage system was the only controllable device at this location. The results can be improved further by increasing the number of controllable devices such as heat pumps. Adding more houses and/or commercial buildings will also make the overall system more efficient, as explained by Tang et al. in [29].

B. *Peak Shaving*

Peak shaving involves reducing or leveling peak loads. Utility companies impose an additional fee on commercial and industrial consumers based on their peak power demand, often amounting to as much as 50% of the total electric bills [4]. This strategy is implemented to incentivize companies to reduce their load on the grid. SLBESS can be used for peak shaving by these companies. However, the economic viability must be assessed thoroughly, as Fallah et al. in

[30] emphasized the sensitivity of benefit-to-cost ratios (BCR) and return on investment (ROI) to various use cases due to differing battery lifetimes. This also highlights the importance of accurately assessing the RUL of SLB to determine the feasibility of the project, as recommended by Rallo et al. in [31]. Peak shaving using SLBESS was equally popular among both types of projects reviewed.

The Ampere Building in Paris, France, was another site tested under the ELSA project. The building originally had 22 kWh of SLBs installed, which was later upgraded to 88 kWh. The maximum charging and discharging power was 80 kW. Additionally, PV panels of 60 kWp were installed on the roof of the building. Unlike Kempten, this site was also equipped with additional controllable loads. One of the primary objectives at this location was to flatten the power consumption of the building load. A maximum peak power reduction of 7.9% was observed over a three-day window, with an average peak power reduction of 7.0% [28].

In 2018, a 3MW/2.8MWh SLBESS incorporating retired Nissan LEAF batteries was installed at the Johan Cruijff Arena in Amsterdam, Netherlands. One of the objectives of this industrial project was to reduce peak loads during concerts. [32]

C. Frequency Containment Reserve

SLBESS are ideal for applications demanding rapid response [4]. A notable application is the provision of frequency containment reserve, which is essential for maintaining grid stability. The grid frequency, 50 Hz for most countries, requires constant regulation to ensure safe grid operation [33]. SLBESS can be useful for managing frequency fluctuations caused by the imbalance between supply and demand.

In 2020, a 5 MW/20 MWh SLBESS was connected to a 10 kV grid in Uppsala, Sweden, specifically to provide frequency containment reserve (FCR). The requirements for providing FCR services included a 50% system ramp-up within 5 seconds and reaching 100% within 30 seconds. The SLBESS demonstrated promising results by maintaining the voltage variations within the acceptable limit of 1%. [34]

D. Microgrid

SLBESS is well-suited for use in microgrids. Microgrids consist of distributed generators and have the capability to operate both integrated with the main grid and as standalone systems. All the projects mentioned in appendix A. are based on creating a smart grid that utilizes some controllable loads such as heat pumps, electric water heaters, and EV charging stations to maximize the utilization of energy produced by the renewable energy sources (RES) connected to the grid and support the main grid.

Moment Energy, a Canadian manufacturer of SLBESS, implemented a 96 kWh system at the God's Pocket resort last year. The SLBESS, named the Flora system, serves as the primary energy source at this off-grid resort, resulting in a remarkable 75% reduction in the run-time of the diesel generator. [35]

In 2018 Portugal's Porto Santo became the world's first island to completely ban fossil fuels by creating a smart grid. The Island has a SLBESS of 132 kWh made from 11 Renault discarded batteries. Additionally, it has a 2 MW solar power plant, 340 kW mini-PV installations, 2 wind turbines of a total of 1.11 MW, an electric car fleet of around 22 vehicles, and two desalination plants with 600 and 1000 kW. It uses intelligent charging and vehicle-to-grid (V2G) technology to optimize the Island's RES utilization and plans to use the two desalination plants as a source of flexibility in the future. [36], [37]

E. Demand Response

The increased number of variable renewable energy (VRE) sources has created operational challenges like negative electricity prices, grid congestion, and curtailment, as explained by Holttinen et al. in [38]. The increasing presence of solar PV in the distribution grid has given rise to the 'duck curve' phenomenon [39]. This curve manifests as high solar PV generation during the daytime, causing a drop in net demand, and peaks in the evening when solar PV output abruptly diminishes. A SLBESS can be used as an energy buffer to address this issue.

Furthermore, demand response can be provided using SLBESS. Demand response refers to maintaining a balance between supply and demand by incentivizing consumers to shift their energy consumption to periods when the grid is overloaded. SLBESS can be used as a flexibility option by the grid operators. The ELSA project in Paris successfully enhanced flexibility by increasing demand by 3.8%, falling slightly short of the targeted 4.4% increase. This outcome underscores the significance of appropriately sizing the SLBESS to meet specific project objectives.

F. Energy Arbitrage

Energy arbitrage involves purchasing energy when prices are lower and using it during periods of higher energy prices. The ELSA project in Paris achieved a 0.4% energy shift from peak hours to off-peak hours, whereas the project in the UK showed a shift of 0.4%. Although intriguing, energy arbitrage and demand response, explained above in application E., are not commonly employed applications for SLBESS.

VII. Challenges

This section encapsulates some of the significant challenges currently confronted by SLBESS manufacturers. While certain challenges may be mitigated through effective policies, others remain open questions, potentially posing a threat to the future viability of this technology.

A. Conflict of Interest

The EV battery is optimized for high energy density and fast charging capabilities, with less emphasis on cycle life, given that private EVs do not undergo full cycles regularly. In contrast, home and industrial storage systems are designed for nearly one full cycle daily [8],[40]. Consequently, when repurposed for stationary storage applications, retired EV batteries experience accelerated degradation, resulting in reduced battery lifetime.

Mathews et al. in [41] illustrated that by decreasing the DoD from 80% (95% - 15%) to 50% (65% - 15%), the battery's lifetime significantly increases from 8.4 years to 16.1 years, nearly doubling its operational lifespan. Based on this study, these batteries are more suitable for applications like backup power or UPS. Commercial EVs, such as electric buses and trucks, share a similar interest. However, the retirement of these commercial vehicles is expected to occur in a few years. A 500 kWh SLBESS research project is underway in Hannover, Germany, utilizing Mercedes-Benz eCitaro batteries [13]. However, the batteries come from test vehicles; hence, the results might differ when real retired commercial EV batteries are used.

B. *Alternative Second-Life Applications*

The standard criteria for EV battery retirement include reaching 70%-80% SoH or when the internal resistance of the battery is approximately 200% of its initial value [40]. This corresponds to a service life of around 8-10 years. Batteries from old EV models released between 2010-2015 are now reaching the retirement age. Those EV batteries had a range of approximately 100-200 km [8]. Back then, second-hand EVs were less attractive due to their limited range. However, with modern EVs having ranges between 400-600 km, the second-hand car market might be a better option than stationary applications as no or little additional refurbishment is required [8].

From a commercial standpoint, old E-buses need not be retired; they can be used for shorter and/or less intensive routes, extending their lifespan. Additionally, private EV owners can utilize the old batteries as replacement batteries. Currently, most EV owners are away during the daytime when the tariff is low due to high RES share; however, a simple EMS can be developed that charges the replacement battery while the user is away. All these alternative options will challenge the feasibility of SLBESS.

C. *Missing First Life Data*

As discussed in section IV., the estimation of SoH and RUL is vital for assessing the economic feasibility of an SLBESS project. The operational conditions highly influence the battery's aging process during its first life. Data-driven methods are preferred for predicting RUL due to their superior accuracy compared to model-based methods and their lower complexity than hybrid models [20]. However, these models heavily rely on training data, which is currently unavailable. Inaccurate RUL estimation decreases the manufacturer's confidence in the SLBESS, thereby creating warranty-related issues for the system — which is something undesirable from customers' perspective.

The implementation of a battery passport in 2027 aims to address a portion of this issue. Li et al. proposed the concept of a digital battery twin in [42], which could potentially alleviate the challenge of missing data. However, the willingness of EV users to share sensitive data, such as daily SoC patterns, remains uncertain, considering the potential privacy concerns it might cause [8].

D. *Economical and Ecological Uncertainity*

The economic feasibility of a SLBESS project depends on the chosen application. Each application, characterized by distinct operational conditions, exhibits varying lifespans. Casal et al. conducted simulations within the SUNBATT project [43], revealing diverse lifetimes for different applications. Retired batteries employed for fast EV charging demonstrated a remarkable 30-year lifespan, while area regulation had a useful life of 6 years. Self-consumption and transmission deferral both indicated a 12-year second life expectancy.

Similarly, the ecological benefits are also uncertain. A study comparing ESS developed from new LFP batteries optimized for stationary applications with those utilizing reused batteries from an EV found the former to have a lower CO_2 footprint [44]. This can be attributed to variations in battery lifetimes, with the dedicated battery estimated to last nearly double the number of years compared to the retired batteries.

VIII. Conclusion

The electrification of the transportation sector is on the rise to reduce the carbon footprint of this sector. The share of EV sales in the global car market has doubled in a span of two years from 2021 – 2023. Generally, an EV battery cannot meet the harsh automotive requirements after 8-10 years of service. However, it still possesses around 70-80% of the initial battery capacity therefore, recycling it at the EoFL would not be the best option.

One possibility is repurposing the battery into a SESS as the requirements are normally less demanding. A SLBESS can be used to deal with the inherent fluctuations of the VRE sources. Moreover, it can be used to perform peak shaving, grid balancing, and it also find utility in the microgrids. Currently, the industry is focused on developing large-scale storage systems for grid support, whereas the research sector is looking into the possibilities of integrating it into smart microgrids.

Although the idea of using retired EV batteries sounds promising, it is only sometimes economically and ecologically favorable. Therefore, an in-depth economic feasibility study and life cycle analysis should be performed for each project. Furthermore, the decreasing cost of new LIB will challenge the feasibility of SLBESS as it has a fixed repurposing cost. Many OEMs are working in collaboration with SLBESS manufacturers to develop solutions that minimize these repurposing costs. Nevertheless, how it will compete with alternative second-life options in the future is yet to be determined.

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Appendix

A. Research Projects

MSPE EES Seminar SLBESS Research Projects

B. Industrial Projects

MSPE EES Seminar SLBESS Industrial Projects