Jurnal Kejuruteraan 37(5) 2025: 2487-2503
https://doi.org/10.17576/jkukm-2025-37(5)-35

A Comprehensive Review on the Current Status, Application and Challenges of Second-life Batteries for Energy Storage System

Md Ayatus Saif[a], Mohamed Ansari Mohamed Nainar[a*], Tze Mei Kuan[b], Man Kit Chong[b] & Mohammad Yeganeh Ghotbi[b]

[a]*Department of Mechanical Engineering, College of Engineering,*
Universiti Tenaga Nasional, 43000 Kajang, Selangor Darul Ehsan, Malaysia.

[b]*Institute of Power Engineering,*
Universiti Tenaga Nasional, 43000 Kajang, Selangor Darul Ehsan, Malaysia.

[*]*Corresponding author: ansari@uniten.edu.my*

Received 22 August 2024, Received in revised form 26 February 2025
Accepted 27 March 2025 , Available online 30 August 2025

ABSTRACT

The swift and widespread adoption of electric vehicles (EVs) has resulted in a dramatic surge in the number of batteries being produced and utilized globally. However, this growth has also led to a concerning trend: a significant portion of these batteries is discarded annually, often through improper or environmentally harmful disposal methods. Such practices pose serious environmental risks, including pollution and the release of toxic substances into ecosystems. This remaining energy capacity makes them highly suitable for repurposing and extended use in secondary applications, such as energy storage systems, renewable energy integration, or other non-automotive uses. By leveraging these batteries for secondary purposes, we can not only mitigate environmental harm but also maximize their value and utility, contributing to a more sustainable and circular economy. Second-life batteries (SLBs) present a sustainable alternative to direct disposal, helping to minimize environmental harm while maximizing the energy and resources invested in battery production. Implementing SLBs in energy storage systems (ESS) offers a practical solution to battery waste while enhancing energy efficiency. However, ensuring safety and reliability remains a critical challenge, particularly in accurately predicting the State of Health (SoH) to prevent battery-related incidents. This paper explores the implementation of SLBs in ESS, their potential benefits, and the challenges associated with their adoption. It also examines existing barriers and proposes solutions to advance research in this rapidly evolving field. By addressing these challenges, SLBs can serve as a transformative technology in energy storage, paving the way for a more sustainable and resource-efficient future.

Keywords: Electric vehicle; end-of-life; energy storage system; second-life battery; state of health

INTRODUCTION

The use of batteries in various applications is expanding so the development of potential batteries is still increasing dramatically until now. For many essential portable gadgets, like computers, mobile phones, and electric cars, batteries provide power options. After their initial useful life, batteries don't necessarily mean they're non-usable (Li et al. 2022). Following the end of their original lives, batteries with a second-life might be put to other uses. Battery recycling yields both financial and environmental advantages by extending the useful life of batteries in a variety of efficient ways. Developing sustainable second-life batteries (SLB) and battery packs may prevent the future depletion of Earth's minerals and reduce waste. To attain sustainability in the realm of battery development, it is crucial to harmonize environmental, social, and economic considerations. The criteria underscored by Cheng et al. (2022) highlight the necessity for responsible resource utilization, ethical conduct, technological advancement, and lifecycle management to guarantee that batteries make a beneficial contribution to the energy transition while preserving the integrity of both the planet and society. In the framework of solutions for the energy transition, batteries, and storage are instruments. However, to support sustainability, they must also be fully sustainable (Cheng et al. 2022). In 1800, a physicist named, Alessandro Volta at the University of Pavia, Italy proved that electricity can be produced from chemical reactions. Thus, the evolution of the first battery began with the introduction of manganese dioxide-zinc in the middle of the 20th century. However, the results are not suitable for daily use as we see now. Around the 1830s, a battery capable of providing more stable electricity was invented by John Frederic Daniell. Unfortunately, the battery uses a liquid that is easily spilled during usage. To overcome the problem, dry battery cells were introduced by Carl Gassner in 1886 (Rasmussen 2019). In 1991, Sony produced the first commercial lithium-ion battery, revolutionizing the user experience. Until now, lithium-ion batteries have been successful and popular due to their several advantages compared to previously invented batteries (Gerald 2024). In 2019, John B. Goodenough, M. Stanley Whittingham and Akira Yoshino were awarded the Nobel Prize in Chemistry in recognition of their development of lithium-ion batteries. The work of the three researchers in the 1970s and 80s has led to the creation of batteries that have the potential to revolutionize modern life (NobelPrize.org 2019).

Since batteries make up a larger portion of electric vehicles, manufacturers must plan and develop a suitable end-of-life (EOL) method for their batteries far in advance of the batteries' eventual life (Volan et al. 2021). Battery longevity is closely linked to battery durability and stability, which in turn affects a power source's performance and ultimately the life span cost. Battery life becomes a significant concern for both propulsion and stationary purposes (Lai et al. 2022). However, there is a considerable commercial risk when a battery's rate of capacity decline or usable life is unknown in particular scenarios. However, in the case of the aerospace business, the power source must last the duration of the scientific mission because it is seldom possible to maintain or take its place (Zhang et al. 2021). The battery's capacitance nature and its capacity to provide a given amount of energy are highly interrelated. The voltage drops across the battery caused by an applied current are defined by its impedance profile. Because of safety-related issues, lithium-ion batteries can only be used within a particular voltage range (Venkatasubramanian Viswanathan et al. 2022). The capacitance characteristics of a battery pertain to its capacity for storing and discharging electrical energy, which is intricately linked to its overall capacity the maximum energy it can supply. When a current is introduced, the battery's voltage diminishes due to its internal impedance, influenced by elements such as internal resistance and electrochemical processes. This impedance profile dictates the efficiency with which the battery can provide energy. In the case of lithium-ion batteries, operating within a defined voltage range is paramount for safety and durability. Surpassing the upper voltage threshold can result in overheating, thermal runaway, or potentially catastrophic failure, while falling below the lower threshold may inflict irreversible harm to the battery's chemical structure, diminishing its capacity and operational lifespan. Consequently, regulating the voltage range is vital to guarantee safe and optimal functionality.

The development of lithium-ion battery technology has significantly grown over the past several decades since these batteries offer enormous potential as power sources that may take into the electric automobile (EA) era. Globally, leading materials research organizations are concentrating their efforts on creating emerging substances for Li-ion batteries. During the previous 10 years, Li-ion batteries have established themselves as the most remarkable example of contemporary electrochemistry's success. In Figure 1, we can see the difference between other batteries and lithium-ion battery publication of research paper in SCOPUS.

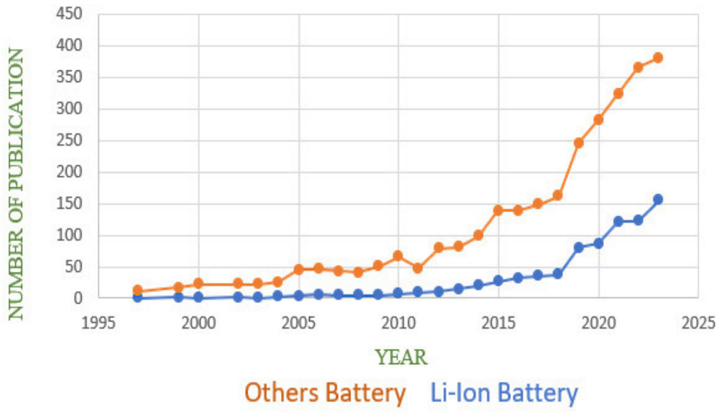

FIGURE 1. Difference between research publication Li-ion battery with other batteries.

Batteries power the majority of today's portable gadgets, and they seem to be able to get beyond the physiological obstacles that prevent the wider deployment of such high-density energy devices for larger-scale uses, as in electric vehicles (EVs) (Maharjan et al. 2020). Decommissioned EV batteries maintain about 80% of their initial performance which, while not usable for propulsion usage, may serve admirably in additional energy storage system (ESS) usages. A 20% decrease in storage capacity from the rated value or a 20% loss in rated power density at 80% depth of depletion is considered the end of an EV battery's life, according to the US Advanced Battery Consortium (USABC) (Graber et al. 2020; Shimoi & Tohji 2024).

With the introduction of the first wave of decommissioned EV batteries, which are now being merged into the existing pool of consumer electronics batteries, it is time to unify the present body of research on this subject. This will permit future explorations in a broad variety of undiscovered locations (Graber et al. 2020; Pan et al. 2020). The state-of-charge (SOC) at which batteries may be utilized, the degradation controlled by the vehicle's battery management system (BMS), and the distance covered by battery warranties are all factors considered by the Electric Power Research Institute (EPRI) when determining if a battery needs to be replaced. The timing of battery replacement is determined in part by this study (Hu et al. 2022; Neubauer et al. 2013; Neubauer & Pesaran 2011; Viswanathan & Kintner-Meyer 2011). Since the costs of replacing batteries impact on the automobiles' lifespan, two sets of lifetime costs are shown over time, each based on differing estimations of battery replacement.

The Massachusetts Institute of Technology (MIT) conducted research that suggests a plug-in hybrid electric vehicle (PHEV) would not need its batteries to be changed throughout its useful life. The lifecycle costs of two battery sizes, one that must be replaced once and another that is intended to never need to be replaced, are compared in research done by Argonne National Laboratory (ANL). In the longevity analysis, the 2004 EPRI research assumes that there will be no need for battery replacements. Testing data, the use of statistics, and presumptions on technical improvements all support this idea. In a thorough analysis of the lifespan costs of the vehicle, the National Academy of Sciences (NAS) examines the extra costs related to PHEV, which do not include the price of battery replacement. According to NAS's battery life projections, which span from 3 to 8 years till 2030, a significant portion of PHEVs would likely need to have their batteries replaced for some time to come. According to Table 1, the additional cost for PHEVs rises from 33% to 84% when battery replacement is included in lifetime cost estimates (Wood et al. 2011).

Since most of the material analyzed throughout the process of creating this review took into account the increased usage of discharged electric vehicle (EV) batteries, the importance of EV batteries for second-life applications will become clear as this study develops.

TABLE 1. The significance of including in battery replacement for the extra expense of plug-in hybrid electric cars (PHEVs) in various PHEV cost evaluations (Wood et al. 2011)

Organization	Year	Increase in incremental cost for one battery replacement (%)
Electric Power Research Institute	2001	50–70
Argonne National Laboratory	2001	30–45
Electric Power Research Institute	2004	55–62
Massachusetts Institute of Technology	2007	42–70
Network Attached Storage	2010	35–82

The first instalments of discharged EV batteries are beginning to hit the market. This is the perfect moment to compile the previous studies in this field to support subsequent research, which has a wide range of topics to cover, to complement the ones already produced by the consumer electronics industry. Using batteries after their initial intended lifespan has been over is known as "*second-life*", and this word will be used often in this study to refer to the usage of batteries after their useful life has ended. To go into a particular area of research, there is the requirement to explain the existing second-life battery (SLB) situation to fully show the current status of this discipline. Despite extensive research, gaps remain in second-life battery (SLB) implementation, including standardization, accurate State-of-Health (SoH) prediction, economic feasibility, alternative applications, material recovery, and chemistry-specific performance. Addressing these gaps is crucial for optimizing SLB reuse, ensuring safety, and enhancing sustainability in energy storage and electric vehicle (EV) applications.

TABLE 2. Outline of this review

Categories	Description
Introduction	This part focuses on history, inventors, and research history.
Second-life battery background	This part focuses on the source, present time important, and present time situation.
Construction of a second-life battery energy storage system	This is one of the important parts of this paper. This part focused on how we can build an ESS. And at the same time this covers dismantling, testing, and remaining capacity.
Safety concern about second-life battery	Battery recycling is hazardous because of is built of lithium, magnesium, sodium etc. When we recycle or dispose of it, it is very harmful so this part covers the safety part.
Second-life battery potential market and application	The investor and researcher focus on battery recycling because of battery is reusable products and its market demand increasing every year.
Challenges of second-life battery	The battery is a sustainable chemical product that's why each step has some barriers. This sector tries to cover this area.
Summary and outlooks	This part tries to cover a summary of the full background and future of second-life lithium-ion battery.

SECOND-LIFE BATTERY BACKGROUND

SOURCE

A lithium-ion battery's cycle life or calendar life may be used to describe its longevity or service life. The amount of time a battery may be held with few discharges before its capacity decreases is known as its calendar life (Soltani et al. 2020). The lithium-ion battery market was valued at over 24 billion US dollars, and growth of more than 12% is anticipated between the years 2017 and 2024. Government regulations aimed at preventing the spread of lead, together with growing consumer interest in electronic devices, have expanded the market for lithium-particle batteries. Longer release cycles together with an increased time frame of practical usage are some crucial and vital factors, that also drive a company's growth (Bajolle et al. 2022).

China, the United States, the United Kingdom and Germany have seen a sharp increase in the demand for electric vehicles (EVs) due to the cost and emissions standards in recent years. China sold over 250,000 EVs in 2016, i.e. 75% increase over 2015 (Parvez Mahmud et al. 2019). A few key factors that support global components of the sector as a whole are the product's long life, its dimension, and easy to use. According to another analysis by Grand View Research Inc., the global lithium-particle battery market is expected to reach 93.1 billion US dollars by 2025, growing at a compound annual growth rate of 17%. Advertising desires are expected to be driven by the increased use of lithium-particle batteries in EVs, convenient consumer hardware, and matrix stockpiling frameworks that are derived from the material's strong vitality, density and high well-being level (Knobloch et al. 2020; Martins et al. 2021). The ESS is anticipated to grow at the fastest rate throughout the forecast period, with a compound annual growth rate (CAGR) of 21% from 2017 to 2025. This may be attributed to the improvements in air and solar energy technology in countries like China, the United States, and Germany. In 2009, the global battery market generated 47.5 billion US dollars in sales. Rechargeable batteries accounted for 76.4% of total sales, while primary batteries made up 23.6%. It was predicted to climb to 82.6% by 2015. In 2016, 48.3% of the global offer was made in the Asian Pacific region, which dominated the market (Ferrantino et al. 2019). Research and development have led to significant advancements in rechargeable battery technology, resulting in increased specific energy and power, longer runtimes, and exceptional power delivery (Usai et al. 2022). Around 1900 tonnes of water are required to produce one tonne of lithium, and unless batteries are recycled with an efficiency of 90%, the present supply of lithium is expected to be insufficient to meet demand by 2023–2025 (Mossali et al. 2020). Skarvelis-Kazakos et al. projected that by 2030, even in the worst-case scenario, around 17.6 GWh will be accessible from second-life EV batteries, or about 3.6 GWh, even with a severe recession (Skarvelis-Kazakos et al. 2013). According to Sathre et al.'s base-case assumption, 15 TWh will be served by SLBs after the year 2050 (Sathre et al. 2015). The capacity of different EV batteries available in the market is shown in Table 3.

TABLE 3. List of available batteries in the market and their corresponding capacity (Ambrose et al. 2014)

Brand names	Battery (KWh)	Range (KM)	Energy cost per KM ($)
BMW I3	22	135	0.033
TESLA S 85	60	275	0.044
MERCEDES B	28	136	0.04
FORD FOCUS	23	110	0.04
NISSAN LEAF	30	160	0.038
HONDA FIT	20	112	0.036

By calculating the average capacity of EV batteries that are currently available in the market (34.44 kWh), figuring out how many EV batteries are there, and taking into account that a battery's second-life begins when its depth of discharge (DOD) is 80% of its main ability, it is possible to estimate that by 2026, 4526.94 MWh will be made available from second-life batteries. Venkatapathy and associates made an effort to define the elements that determine when these traction batteries transition from their first to their second-life. These characteristics include age, environment, and cost, with cost being the most significant factor (which suggests that second-life batteries are less expensive than new ones) (Karthik Venkatapathy 2015).

SIGNIFICANCE OF SECOND-LIFE BATTERY

It's intriguing to see that lithium-ion batteries, or LIBs, are gaining traction as a renewable energy source and energy storage option for EVs. But there are worries about how these batteries can affect the environment, particularly in terms of disposal. Although there have been studies on the availability of lithium, there are still questions about how these batteries will be managed in the waste stream and if recycling infrastructure will be able to recover valuable elements from batteries that are destroyed. It's critical to take preventative measures to avoid any unanticipated environmental effects from the anticipated increase in the use of electric vehicles (Choi & Wang 2018). Furthermore, Figure 2 shows the process flow chart of a full battery life, including the second-life feature.

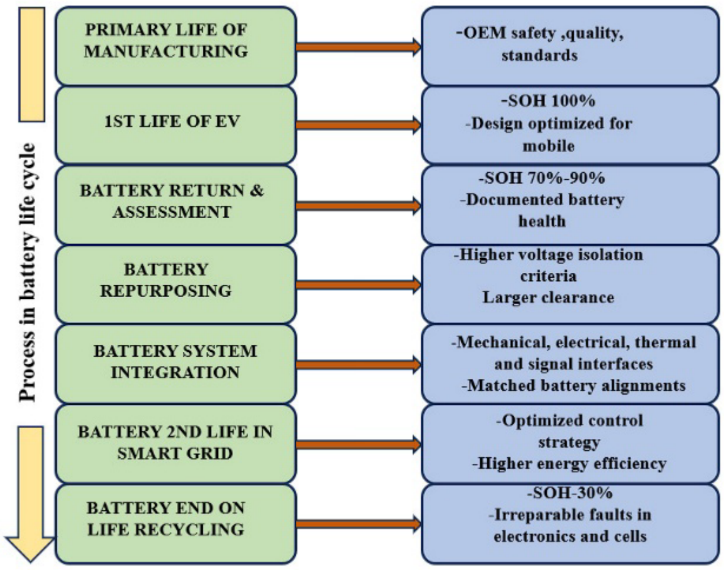

FIGURE 2. Process flowchart of a battery life cycle enhanced with 2nd life functionality (B. Gohla-Neudecker* 2015)

Car manufacturers and original equipment manufacturers (OEMs) impose stringent safety regulations throughout the design and manufacturing phase of a battery's life cycle. Consumer electronics and stationary applications usually employ batteries that adhere to strict safety regulations and are closely monitored while in use. Batteries for electric vehicles (EVs) have a residual capacity of 70–90%, making them suitable for a second-life provided they meet strict technical requirements and have a recorded set of specifications detailing their prior use in the vehicle. However, to guarantee correct grid connection and integration with the current industry requirements of

800V-1000V systems, significant hardware changes, and software adjustments are required to repurpose these batteries for stationary applications (Haram et al. 2023) While some OEMs are developing plug-and-play capabilities for a battery's extended life, certain prerequisites need to be fulfilled to guarantee its secure and efficient operation. The need to thoroughly research and utilizes second-life batteries is growing as there is a greater-than-ever production of old batteries.

We may examine a 24 kWh Nissan Leaf battery as an example to have a better understanding of the possibilities of used EV batteries. This battery can hold up to 80% of its original energy, or 19.2 kWh after its traction usage is over. It can produce around 15 kWh of energy at an 80% depth of discharge (DOD), which is ideal for low C-rate applications over a number of years (Warner 2015). This emphasizes how important it is to recycle used EV batteries and make use of their residual energy. Research states that by 2028, there should be around 548 GWh of used EV battery capacity accessible worldwide (Falk et al. 2020). Roughly, 240 GWh of this will be used in China, a sign of the nation's rising interest in using second-life batteries.

PRESENT CIRCUMSTANCES OF SECOND-LIFE BATTERY

This research evaluates the carbon footprint, cumulative energy demand (CED), and overall environmental consequences related to the manufacturing, use, and EOL of seven automobile lithium-ion batteries (LIBs) using a thorough life cycle assessment (LCA). This category includes nickel manganese cobalt oxide (NMC333, NMC532, NMC622, and NMC811), lithium manganese oxide/nickel manganese cobalt oxide (LMO/NMC532), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP) batteries. When these batteries approach the end of their original lifetime, the research also looks at stationary ESS that may employ them (Tao et al. 2021). Prior efforts along these lines were conducted at the Rochester Institute of Technology (Richa 2016) and the University of California, San Diego (Al-Alawi et al. 2022). The creation of a 2 MW, 2800 kWh second-life battery energy storage system (SLBESS) in Hamburg, Germany, with an emphasis on grid support, is noteworthy and the result of a collaborative effort involving BMW, Vattenfall, and Bosch. More than a hundred cars batteries were employed in this project (Casals et al. 2019; Geng et al. 2022). Besides the BMW project described before, Daimler has started experimenting with 15 MWh and 13 MWh of energy storage in Hannover and Lünen, while Volkswagen has a 10kWh pilot project in Berlin (Reinhardt et al. 2017). Conversely, Nissan made the switch to commercial SLBESS in 2015 after doing earlier test programs. Recently, Nissan has used the Leaf electric cars (EVs) second-life batteries to power standalone solar illumination projects. Utilizing nickel metal hybrid (NiMH) batteries to power a 40kW photovoltaic (PV) system is another notable advancement. This specific solution just modifies the battery connections; the EV battery casings remain the same. Notably, the system enables simple manual pack replacement and is built to withstand a whole disability in the case of an individual battery cell inability (Al-Alawi et al. 2022; Casals et al. 2019; Geng et al. 2022; Horesh et al. 2021). In addition to these efforts, Table 4 offers further information. Conversely, people have also started building SLBESSs out of used laptop batteries and other consumer electronics batteries as well.

TABLE 4. Leading projects of second-life battery (Reinhardt et al. 2017)

Joint ventures	Description	Location
The Mobility House Remondis	The battery storage device has a combined capacity of 13 MWh and utilizes deteriorated EV batteries sourced from Daimler EV vehicles.	Germany
BMW	An 18-month pilot project will be conducted to showcase the intelligent charging of EVs and optimize the efficiency of the power grid. The initiative will include the involvement of 100 owners of BMW i3 vehicles.	USA
Nissan Sumitomo	The system, consisting of 16 Nissan Leaf LIBs, efficiently manages and regulates the energy generated by a solar plant, with a capacity of 600 kWh and a demand of 400 kWh.	Japan
Bosch	The system consists of 2,600 battery modules extracted from 100 electric automobiles. It has an output of 2 MW and a capacity of 2.8 MWh.	Germany
Renault	"E-STOR" is an on-grid energy storage system that avoids power grid overload and ensures a balance between supply and demand.	Europe
Mitsubishi	Optimizing the energy consumption of retired batteries in a bi-directional manner.	Paris
General Motors	The GM headquarters site is powered by 5 Chevrolet Volt LIBs, a 74 kW solar array, and two 2 kW wind turbines.	USA

CONSTRUCTION OF A SECOND-LIFE BATTERY ENERGY STORAGE SYSTEM

EVALUATION METHODS FOR BATTERIES ELIGIBLE FOR SECOND-LIFE USAGE

The penetration of electrical vehicles (EVs) is exponentially rising to decarbonize the transport sector resulting in research problems regarding the future of their retired batteries. Landfill disposal poses an environmental hazard, therefore, recycling or reusing them as SLB are the inevitable options (Iqbal et al. 2023). EV batteries enter their second-life with a solid technological foundation and a reliable track record from their prior usage in cars. The batteries leave EVs with a recorded set of parameters that may be used to identify their exact ageing characteristics, both calendrical-wise and cyclically, and with a residual capacity of around 70–90% as shown in Figure 3. While there are efforts underway to achieve plug-and-play battery second-life, especially hardware changes and software adjustments based on the brand of EV battery are required to guarantee electrical power and stationary use.

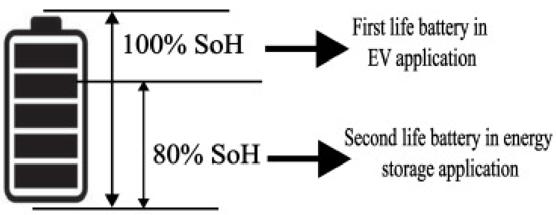

FIGURE 3. SoH definition from Vehicle OEM and Battery manufacturer (Vignesh et al. 2024)

The breakdown behaviors, lithium plating, surface layer creation, and other parasitic activities use lithium ions, which are then unavailable for cycling between the positive and negative electrodes and cause power reduction. Energy fading may also be caused by surface coatings. If lithium ions are caught within electrically separated active ingredient particles, they might potentially be lost (Birkl et al. 2017). The existing industry standard states that a synchronization process including battery reuse is required for 800 V to 1000 V systems. Table 5 shows that there are significant differences in the technical requirements for batteries between first life and 2nd life batteries applications (Gohla-Neudecker 2015).

TABLE 5. The technical requirements for batteries between mobile and stationary applications

Categories	1st life in EV	2nd life in stationary application
Voltage level	400 V	800 V – 1000 V
Working hour 10a	16 800 h (on)	Max. 87 600 h (on)
Room temp	-40 – 60 °C (in operation)	10 – 35 °C (in operation)
C-rates	Continue 2 – 3 C Peak > 5 C	Continue < 5 C Peak 0.5 – 2 C
Thermal concept	Active	Passive
Vibrations	Yes	None
State of health (SOH)	100%	70 – 90%

The energy-intensive nature of the recycling process itself deters prospective investors from taking on the risk involved with becoming pioneers (Tao et al. 2021). The business of ESS remanufacturing relies primarily on the astounding 80% capacity of batteries that are rejected, and it just needs a little starting investment. The absence of a global cell standard is the main problem in refurbishing obsolete batteries. The evaluation processes were categorized by Gladwin et al. as follows: evaluations of the power supply management system, the voltage of the output, SOH pack of batteries impedance, and capacity, in that sequence.

DISMANTLING

Dismantling the old battery packs is the initial step in building SLB energy storage systems (Abdel-Monem et al. 2017). The disassembled components may be grouped according to the various cell types and packaging used by different manufacturers (Canals Casals & Amante García 2016; Li et al. 2023) to facilitate the components' selection for SLBESSs. These many battery cell forms, battery sections, and battery sets constructed. It is essential to disassemble battery packs in a confined space devoid of ambient air to prevent cathode oxidation. The research also states that when the battery is dismantled, the solid electrolyte interface (SEI), which develops on the battery electrodes as a consequence of chemical reactions that occur in the cells, may be removed to significantly increase battery performance (Choi & Aurbach 2016). It is necessary to look at this laser-driven method of removing SEI before adding further cell types to the SLB manufacturing line.

FIGURE 4. Present time top EV vehicles battery cell types and their phase

Figure 4 we can see the world's top EV vehicle company and their battery cell type (Choi & Aurbach 2016). It is necessary to take into account advanced management technologies when using second-life battery usage.

TESTING

A battery power and capacity are based on efficiency. A three-step assessment process was provided for sorting through a huge quantity of batteries to identify those that might be used again. Typical duty cycles indicative of different stationary applications has been used in the experimental assessment of the "second-life" of Li-ion cells/modules. To confirm crucial points and the requirement for cooling during operation, thermocouples and an infrared camera have been used to monitor the samples under examination in addition to electrical testing. As a result, simpler duty cycles that were more appropriate for the samples were accessible and more in line with their actual "SOH" had to be developed. Two distinct applications were the focus of the two operational cycles. The pro cycle came first, followed by the light cycle (Di Silvestre et al. 2021). Up to 90% of the sample's nominal capacity was reached during the "Pro" life cycle testing. Following a finite number of cycles, the "Light" life cycle continued without adverse effects; the sample capacity stayed constant, and the efficiency of the energy, as well as the lesser amount of maximum current, maintained about 87%. According to Martinez-Laserna et al.'s publication, these tests were carried out on both battery modules and individual cells. The modules were created in heterogeneous stacks, which had cells with varying SOH, and homogeneous stacks, which had cells with identical SOHs. Similar experiments were also described in (Mignoni et al. 2023), together with the relevant explanations and images, and the inclusion of electrochemical impedance spectroscopy (EIS) measurement. These tests aid in quantifying the battery model parameter in addition to evaluating the battery state (Chen et al. 2021).

REMAINING CAPACITY ESTIMATION

The batteries' remaining capacity is an important consideration for battery remanufacturing to make a significant contribution to the second-life cycle. Sen et al.'s (Sen et al. 2017) assessment of the SLB second-life was based on a few sets of parameters, including a fixed depth of discharge (DOD) of 60% and a total lifetime of 20 years. The longevity of the second life was calculated as 20 years less than the first life depending on those previous assumptions. However, other noteworthy studies rely their estimate on the existing data instead of using such predefined parameters, Winarno et al. (2017) is the most well-known of them. The battery packs were removed and dismantled at the EOL estimate. It was discovered that, based on the usage pattern, the second-life's lifetime would vary after the first one ends. Table 6 displays the various estimates for various usages, such as energy management, network deferral, and auxiliary services.

TABLE 6. Remaining lifespan summary (Winarno et al. 2017)

Application	2nd life	Remaining life (yr)
Ancillary service	1500 cycles 10% p.a.	6
Network extension	50% per day for 4 months	15
Network extension & ancillary service	Combination of A and B	4
Energy management	50% per days 5 days per weeks	7
Energy management & ancillary service	Combination of A and C	3

BATTERY ENERGY STORAGE MAKING PROCESS

Many distinct phases make up this renovation procedure. Regarding related labor and expenses, it depends on the functionality selected. Discrepancy, in any case, is convenient and makes it easier for people to engage in a field that is always changing. Additionally, it streamlines the workflow as seen in Figure 5 (Bowler 2014).

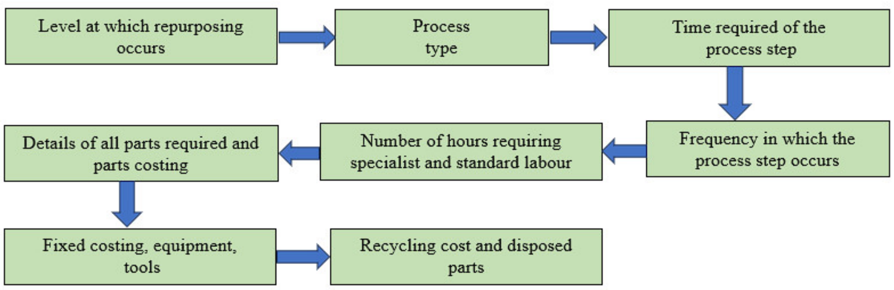

FIGURE 5. Parameters for process step-based refurbishment (Bowler 2014)

Figure 5 shows how the process stages are divided into pack design and repurposing situations since the expenses associated with repurposing increase with vehicle pack design or reprocessing scenarios. The typical procedures like cleaning, testing, and inspection don't change the battery's characteristics. Any packs or modules that exceed the specified boundaries are disposed of by the disposal point. Modules are packed using the sorting criteria by the its sort. Information is commonly accessible via the planning and development of service concepts as well as necessary production resource planning. Anything below 100% denotes a repair-type procedure that may not be applied to all packs or sections, while 100% denotes a procedure that is applied to all packs or modules. When applicable, warranty data may provide this parameter. Either entity-based repurposing or fixed pricing may be used, together with the inclusion of equipment tools. The cost of recycling discarded pieces of obsolete battery modules or parts (Zhao et al. 2021). The batteries that were found to be appropriate for second-life applications during the assessment phase will be used to create SLBESS. By examining various battery chemistries in a single SLBESS, such as lead-acid, lithium titanate, and NiMH batteries as low-voltage and high-voltage batteries, Mukherjee et al. made some noteworthy advances in this field (Diaz-Gonzalez et al. 2020). They then took into account the differences between the battery chemistries to design a battery management system (BMS) using distributed control. According to Einhorn et al., series connections between cells with varying capacities and chemistries may result in a significant improvement in energy output from SLB packs (Martinez-Laserna et al. 2018). Similar research was done in for the use of SLBESS in frequency response utilization in the grid. In, where the modular design of a cascaded multilevel converter was suggested for SLB application, the modular method was also preferred ((Saez-de-Ibarra et al. 2015; Saez-De-Ibarra et al. 2016).

In the past, a significant amount of research was focused on determining the ideal SLBESS size. Saez-de-Ibarra et al. used a two-stage method to tackle this goal for solar photovoltaic power plants: first, they determined the amount of storage needed for a single day, and then they determined the amount of capacity needed for a whole year (Tang & Wang 2023). They tested their approach on a photovoltaic facility in Spain. A similar methodology was used by Koch-Ciobotaru et al. (Cheng et al. 2022). to establish the appropriate SLBESS rating based on data from the Spanish energy market, to maximize revenue in the demand-response program for residential applications (Wu et al. 2020). More broadly, four factors may be used to determine the size of the system: age, cost, control algorithm, and system size need.

SAFETY CONCERN OF SLB

After the second-life battery energy system component, the assembly procedure completes the manufacturing of these storage systems once the SLBESS components have been chosen. As a result, this stage requires installing the converter circuits and the battery management system in addition to connecting the batteries in the proper configuration. A study of battery-related accidents is carried out, using EV batteries as an example, taking into account the timing of the incident, the kind of battery system involved, the particular kind of accident, and the location of the event (Meghana et al. 2022).

Time: A review of pertinent accident data across time indicates that there was no discernible rise in battery-related incidents concomitant with the dramatic rise in EV ownership. This result points out the important developments in battery technology as well as higher production quality standards.

Power supply: Lithium-ion batteries (LIBs) with a cathode made of $LiNi_xMn_yCo_zO_2$ ($x + y + z = 1$; NMC) have a much greater percentage of battery-related incidents than LIBs with a cathode made of lithium iron phosphate ($LiFePO_4$, LFP). This discovery suggests that energy density and safety have a statistical relationship, meaning that a battery with a greater energy density has a larger risk to safety.

Kind of accident: Accidents involving batteries may happen in a number of situations, such as charging, driving, misusing the battery (such in crashes), and even while the battery is not moving. It is noteworthy that automobile crashes are not always the cause of these incidents. As a matter of fact, the majority of reported accidents involve spontaneously generated explosions, flames, or smoke. There are now three types of methods available to improve battery safety, as Figure 6 (Meghana et al. 2022) shows.

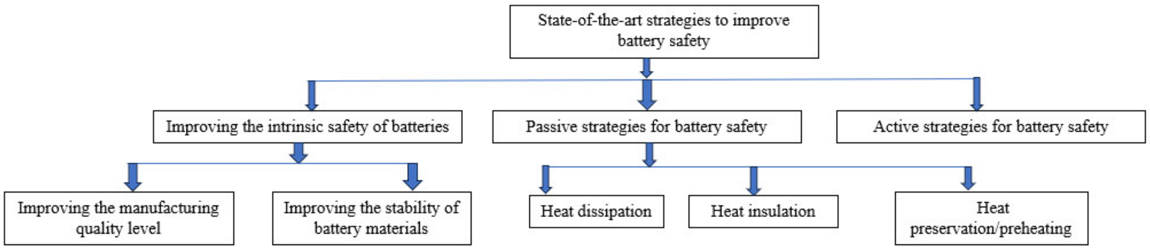

FIGURE 6. State of art improves Li-ion battery safety concern (Meghana et al. 2022)

The safety of the battery itself is referred to as its intrinsic safety, and it has a direct impact on the probability of incidents involving batteries. The materials used in the cell (e.g., NMC or LFP), the cell's design (e.g., separator thickness, negative-to-positive electrode capacity ratio), the degree of manufacturing quality (e.g., impurity control, fabrication accuracy), and the battery's consistency and reliability are some of the factors that contribute to a battery's intrinsic safety. Ensuring battery safety begins with achieving appropriate production and manufacturing quality. But even with excellent manufacturing quality (Chombo & Laoonual 2020), an NMC battery with a high energy density still performs less safely intrinsically than an LFP battery. As a result, creating LIBs that are both very energy dense and highly safe continues to be a difficult issue (Wang et al. 2020).

The chemical composition of batteries significantly influences their environmental impact and performance. Different battery chemistries come with their own set of environmental concerns, including the extraction of raw materials, the potential for pollution during disposal, and the emission of greenhouse gases during manufacturing.

disposal of these batteries can result in soil, water, and air contamination due to the leaching of toxic substances. However, recycling can reduce the climate impacts of battery electric vehicles by approximately 8.3%.Different materials used in the positive electrode, such as Lithium cobalt oxide (LCO battery), lithium manganese oxide (LMO battery), lithium iron phosphate (LFP battery), lithium nickel cobalt manganese oxide (NCM battery), lithium nickel cobalt aluminum oxide (NCA battery), have varying environmental impacts. Heavy metals like nickel, cobalt, and manganese can pollute and change the pH of the environment. (Gang Li et al, 2024)

Currently, battery system thermal management which emphasizes heat dissipation, heat preservation, and heat insulation is the primary means of achieving passive safety (Feng et al. 2018). This strategy is used to keep the battery temperature from rising over the typical operating temperature. In addition, problems like lithium plating and local overcharging are serious worries when a battery works at low temperatures, besides the safety hazards connected with high temperatures. Making sure there is enough heat insulation is another crucial component of passive safety. The main goals of heat insulation are to lessen the effects of thermal runaway in batteries, stop heat from spreading from a single cell's thermal runaway, and to stop the run away from getting worse inside the battery, which could cause the system to explode and catch fire.

SECOND-LIFE BATTERY POTENTIAL MARKET AND APPLICATION

Neubauer et al. investigated how the size of an SLBESS module affected the cost. They calculated the cost of buying old batteries and building second-life Li-ion battery energy storage system for module sizes up to 24 kWh capacities (Lieskoski et al. 2024). They also examined the different rates of defects at the cell level. It was shown that when the defect rate reached 1%, the purchase cost was logically at its lowest. But because additional work was needed during the testing stage, the cost of producing SLBESSs using these defective cells inevitably increased (Feng et al. 2020).

Possible applications for second-life scenarios include those in which rapid frequent power flow is not anticipated, and capacity and density are not crucial factors. The review of scientific research yielded an extensive amount of possible battery applications, and expert interviews helped to generate creative concepts. To simplify things, the apps have been divided into three groups based on mobility (mobile, semi-stationary, or fixed). An equally competent new battery will set a maximum selling price restriction for reused automobile batteries. It is challenging to fully understand the word "equally capable" since, depending on the application, this might include a variety of characteristics such as quantity of energy, particular power, protection, transmission and interface, form factor, etc. (Rahil et al. 2022). In Figure 7 and Table 7, we can see the possible place for application and also frequently, we can use the SLB.

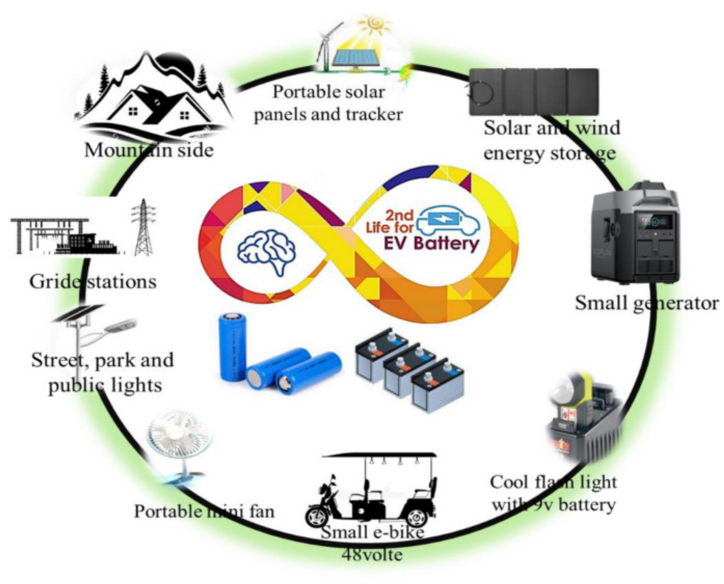

FIGURE 7. Possible application of second-life battery energy storage system (Zahoor et al. 2024). https://doi.org/10.1007/s11356-024-33979-3).

TABLE 7. Summary of the possible second-life uses (Michelini et al. 2023)

Mobility degree	No.	Category	Application
Mobile	1	Commercial EVs	Short-range EVs
	2	Industrial vehicles	Tractors, transport trolleys, automated guided vehicles (AGVs), excavators, dumpers, wheel loaders
	3	Lightweight vehicles	Golf carts, three-wheel vehicles
	4	Lead–acid replacement	Automotive starting, automotive lighting, automotive ignition, industrial trucks
	5	Mobile robots	Robotic vacuum cleaners
	6	Consumer electronics	Leisure time gadgets, kitchen appliances
	7	Marine applications	Full propulsion, hybrid propulsion, spinning reserve, load-levelling, shore-stations
	8	Rail transport	Trams power supply
	9	FC-based transportation	Energy buffer for H2FC
Semi stationary	1	Mobile power supplies	Power stations for construction sites
Stationary	1	Lead–acid replacement	Uninterruptible power supplies
	2	EV chargers	On-grid buffer storages at charging station, off-grid buffer storages at charging station
	3	Special grids	Micro-grids, smart grids
	4	Residential ESS	Load following purposes, residential ESSs connected to a RES
	5	Commercial ESS	Peak shaving purposes, load following purposes, backup purposes
	6	Industrial ESS	Load equalization, sustainable firming, controlling spinning reserves and areas, peak shaving, and transmission stability

The first significant group of potential second-life apps is "mobile applications", or those that depend on the battery-moving while in use. Reusing the batteries in a short-range EV is one potential usage. In actuality, the battery's range is enough for the majority of everyday travel, even though EOFL is often described as the point at which the battery retains 70–80% of its capacity (Mishra et al. 2021). Another option is to use the batteries for internal energy management in some vehicles, golf carts, three-wheel vehicles, industrial vehicles like pallet trucks, tractors, and forklifts, as well as micro-mobility vehicles like electric wheelchairs, e-bikes, and e-scooters (Albertsen et al. 2021). SLBs may also be used as reserve capacity in motor vehicles or other mobile second-life applications, including rail (such as the propulsion of trams and trains) or maritime (such as propulsion, backup, and load levelling) applications. "Semi-stationary" refers to second-life applications where the batteries are anticipated to be moved regularly but are not meant to run while moving. Automotive mobile charging stations and power generators or stations used in distant places are two examples (Hua et al. 2021; Martinez-Laserna et al. 2018; Olsson et al. 2018). Moreover, the expected lifetime for this kind of application is 15 years, provided the battery is utilized from 80% to 60% SOH.

Lastly, there are stationary instances of second-life batteries displacing lead-acid batteries in applications that are stationary, much as in the case of mobile applications. For instance, an uninterruptible power supply (UPS) or backup power for telecommunications. The expert interviews and literature study produced a broad range of potential stationary, semi-stationary, and mobile applications that can be supported by SLBs. Applications range widely, from buffer storage to supplementary services on the general energy grid, and from transportation to residential settings. This illustrates how flexible SLBs may be in a multitude of domains, catering to current markets and creating new ones via the related use of various battery management system (BMS).

Second-life batteries for various purposes and a summary of those with the required elaborations is provided in this section.

GRID-STATIONARY APPLICATION

A battery can no longer hold enough energy after using 70% to 80% of its original capacity. Spent batteries may be put to good use in a variety of industries, including smart grid, microgrid, renewable energy, area and frequency control, and more (Braco et al. 2020). These enormous amounts of SLBs are perfect for use in stationary energy storage since they may be combined to generate a variety of MWh-capable packets (Rana et al. 2023). SLB use in electricity networks may lessen the effects of "peak shaving", or peak load demand. According to experiments, the method successfully settles the conflict between photovoltaic intermittency and varying consumption of energy, resulting in a 64% – 100% reduction in grid usage. To address issues like frequency fluctuation and power surplus, Matsuda et al. looked into the viability of reusing an EV battery for a renewable power grid on a remote island (Matsuda & Tanaka 2017). They did this by using real-world data gathered over seven months on Koshiki Island to determine the necessary battery requirements. The quantity of energy supplied by the battery storage facility decreases as the renewable energy production increases. In a similar way, the quantity of energy produced by the storage facility increases when the renewable energy generation decreases. Therefore, via charging cycle activates control, the ESS contributes to reducing the intermittency caused by the RESs. When compared to off-peak hours, the cost of using power is greater than during peak hours. In this case, energy arbitrage is seen to be a good option. A device for storing energy may be employed when energy expenses are minimal. Refurbished batteries are thus the most sensible substitute on this market (Aguilar Lopez et al. 2024). The SLBESS is activated when assets used to generate electricity are momentarily shut down for maintenance. The frequency of a grid has to be maintained within an acceptable range of its normal frequency. Variations in load may lead to a discrepancy in supply and demand. Consequently, there is irregularity in frequency. To maintain the grid frequency within the intended range, frequency regulation is also required. SLBs are capable of offering auxiliary grid functions including area control and frequency (Casals & García 2017). It also costs less than a brand-new battery.

STATIONARY OFF-GRID APPLICATION

Energy storage technologies are used to guarantee dependability since sources of clean energy are sporadic. If additional batteries are employed, the cost of maintaining energy will increase. Here, recycled batteries may be used as a system for storing electricity to guarantee both financial and ecological gains. SLB was used for a tiny off-grid wind turbine (Dulout & Villa 2019). The objective of the research was to determine the SOH of SLB using low-cost methods that yielded reliable results. An off-grid solar EV charging station was equipped with SLB. The purpose of the research was to determine if using electric vehicle batteries for second-life uses using simple control techniques was feasible (Haram et al. 2021).

MOBILE PROGRAM

Although Li-ion batteries are expensive, they are not commercially viable for use in fast-charging stations. However, SLB is far less expensive and may be used in power buffer quick charge stations and provide intermediate storage. A hybrid PV-SLB-tram network (TN) architecture-based DC rapid charging system for EVs was proposed by Hegazy et al. (Zhang et al. 2023). The multiport interleaved power converter (MIPC) plays a crucial role in regulating the direction of power flow. The storage system within the TN could be integrated into this proposed system. Nevertheless, a notable obstacle hindering the expanded market share of electric vehicles (EVs) is the insufficient infrastructure for EV charging. The solution involves implementing a battery charging system where the utility refuels the EVs, establishing a connection between the transportation and utility sectors. As a result, when not in use, an electric vehicle with a restored battery can contribute power back to the grid. Due to its advantages over traditional internal combustion engines (ICE) cars, both environmentally and financially, EV sales have surged. One significant problem, however, is the lack of infrastructure for charging. A suggested DC fast charging system is constructed using the architecture of a hybrid photovoltaic-SLB tram network. In this instance, the power flow is monitored by a MIPC (multiport interleaved power converter). And further use for the system is a tram network holding system. A second-life battery may be employed in many different industries, but not all of them will profit equally.

CHALLENGES OF SECOND-LIFE BATTERY

Determining the economic advantages of SLB adoption is the most difficult task, even though it may seem appealing from the standpoint of capital cost investments. Although the cost of new LIBs is progressively going down, SLB application may someday pose a challenge. Customers would choose new LIB over SLB if the environmental effect is ignored and the cost of LIB decreases to the point where it may be as costly as SLB, which is limited by repurposing costs. Moreover, a stable source of used batteries, a productive manufacturing facility, and an appropriate distribution network to reach consumers are all necessary for the SLB to succeed as a product. Moreover, sufficient demand for such a product has to be created via the creation of public knowledge and desire (Dimitrovski et al. 2022).

Development of appropriate legislation, required incentives, and business models is also required. This also covers the method of figuring out and offering the SLBESS warranty. Battery data accessibility is essential for these using a program in the battery management system to monitor the batteries since they were first used is one method of doing this. Although it is not anticipated that the cost of SLBs would surpass that of new batteries shortly, this might change if significant advancements in battery technology occur. Development of the market and policies are necessary, but given the advantages that SLB usage offers, these should not be too difficult. The various SLB usage barriers are shown in Table 8 (Kampker et al. 2023).

TABLE 8. Challenge of second life of lithium-ion battery (Kampker et al. 2023)

Objectives	Challenges
The primary obstacles pertaining to first-life termination, gathering, and transportation	(1) There is uncertainty over the number of EOL batteries that have a satisfactory SOH to be utilized as second-life batteries (SLBs). (2) The challenge of determining whether a battery method is still appropriate for rededication. (3) Transportation incurs high costs as a result of regulatory measures and entails inherent safety hazards.
The primary obstacles in relation to screening	(1) A laborious, complex, and non-standardized identification procedure. (2) The wide range of batteries available makes it difficult to determine and restore their SOH consistently. (3) Determining the SOH without access to battery management system (BMS) data is a laborious process that necessitates the use of specialized equipment. (4) Reusing a battery is made more difficult by the lack of data from its first life.
The primary obstacles in relation to disassembly and processing	(1) A matching battery string's assembly is difficult. (2) There may be a need to create a new BMS and/or energy management system (EMS) in order to regulate decommissioned batteries. (3) Lack of extensive expertise in the processing and integration of SLBs.
The primary obstacles in relation to rentability	(1) Price competition comparing SLB and FLB systems. (2) Used things are seen as having a reduced value. (3) The "willing price to pay" is lowered when residual value and capacity are uncertain.
The primary legal obstacles	(1) If manufacturers continued to be responsible for their batteries, they may be able to prevent a second use. (2) The insurance business has issues due to a lack of historical data. (3) Privacy issues prevent the OEM from providing first-life consumption statistics.
Other important barriers	(1) Safety issues with using discarded batteries for a second time. (2) The need for all parties engaged in the repurposing process' supply chain to coordinate.

SUMMARY AND OUTLOOKS

This research has thoroughly examined the considerable potential that used batteries possess for usage in a second-life. Several challenges have been identified in the circumstances of recycling and reusing, and some solutions have been proposed. Applications of LIB in the second-life batteries are explored as a way to expand into the mainstream industry. Firstly, the data on battery degradation after the first usage is presented, together with the potential solutions using comparative analysis to reduce it and qualify the retired battery for reuse. This paper's main conclusions may be summed up as follows:

1. Adding a second usage phase to a battery is required to increase its lifespan.
2. It is possible to build second-life battery energy storage systems using a regular production process that includes manufacturing, testing, and modelling.
3. SLBESS costs need to remain competitive.
4. There are now various obstacles to SLB usage.

Throughout the whole SLBESS manufacturing process, standard safety procedures must be followed. With an emphasis on the impact and interplay of operational stress elements, the behaviour and empirical models of LIB ageing were described. The review that has been provided concludes that it is highly challenging to generalize ageing behaviour in terms of how operational circumstances affect it. All of the examples in the summary of findings illustrate the difficulties in simulating the LIB ageing behaviour.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Tenaga Nasional for their financial support under the grant 202205003ETG.

DECLARATION OF COMPETING INTEREST

None.

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