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Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges

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KEYWORDS

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Electric vehicles;
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SLB environmental assessment

Abstract It is estimated that by the year 2030, the cumulative of Electric Vehicles (EVs) will reach 85 million. Once EV batteries degraded to 70–80% of their initial capacity, EV owners will have to replace the EV's batteries as the residual capacity becomes insufficient for automotive use. As a result, more batteries will be discarded from EVs. These batteries could be re-purposed in other applications, where they are known as the EV Second Life Batteries (SLB). In this paper, several projects and research works are reviewed to understand the up-to-date state-of-the-art related to SLB. The technical feasibility, economics, and environmental impact of using SLB are investigated. Different applications of SLB, as well as the assessment and testing required before re-purposing EV batteries, are presented. Some of the existing projects related to SLB, such as the studies done in many countries, batteries' types, applications, and scope of the study, have been summarised. It was found that utilising SLB addresses not only an environmental concern with regards to the discarded batteries but also provides an excellent opportunity to generate revenue if assessed and used optimally. Nevertheless, some challenges do exist, such as the lack of standardised assessment and lack of reliable information due to the low number of studies related to SLB. Further studies of SLB, which could help understand the feasibility and economics of using them and standardising their assessment, are recommended.

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1. Introduction

Transportation industry is on rapid growth and becoming the second-largest energy consumer, leading it to be one of the main contributors to air pollution and CO_2 emissions [1–4]. In response to this concern came the idea of commercialising different types of Electric Vehicles (EVs) globally [2,5]. EVs can be classified into four main categories namely, Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle (FCEV), Battery Electric Vehicle (BEV), and Plug-in Hybrid Electric Vehicle (PHEV) [6–8]. According to the International Energy Agency (IEA), the number of EVs, especially BEV and PHEV, is rising over the recent years from 2013 to 2018. In IEA's May 2019 report, 5.1 million EVs were sold globally in 2018, which almost doubled compared to 2017. In China alone, over one million EVs were sold in the same year, with a market share exceeding 4%; whereas, in some other countries such as Norway, the market share of EVs has reached about 46% [9].

The battery, which is one of the EVs' essential components, will be discarded and recycled once the residual capacity falls below a specific performance point. Thus, the concept of repurposing EVs' batteries for different applications has become a prominent solution. The growing environmental concerns related to discarded EV batteries have led engineers and policymakers to consider Energy Storage Systems (ESSs) solutions as an application to utilise EV used batteries. With SLB, a new stream of revenue has been created, and the environmental concern of EV replaced batteries is being addressed [10].

Since the early 1800 s, batteries have been used and became common in ESSs applications as battery cost keeps declining due to higher industry adoption. With the cost reduction in the batteries, it is estimated that the demand for batteries will increase 14 times by 2030 compared to 2018; whereby the EV application is dominating the demand by more than 88% compared to other applications, such as ESS and Consumer Electronics (CE). On the other hand, China is leading the demand of battery market by more than 42.7%, followed by 16.9% for the European Union, 13.6% for the United States (US), and 26.8% for the Rest of the World (RoW) [11].

Projection on the global battery demand as illustrated by Fig. 1 shows that with the rapid proliferation of EVs [12–14], the world will soon face a threat from the potential waste of EV batteries if such batteries are not considered for second-life applications before being discarded. According to Bloomberg New Energy Finance, it is also estimated that the cumulative capacity of the used EV batteries could reach 185.5 GWh/year by 2025 [15]. Another study estimating that the total accumulative SLB capacity could reach almost 1000 GWh by 2030, which is proportional to the increment of accumulated EV sales (Fig. 2) [16].

Before diving deeper into SLB, it is essential to know about the types of batteries and their chemical composition. Such knowledge would help during the assessment and economic analysis, especially with the benchmarking of SLB. For exam-

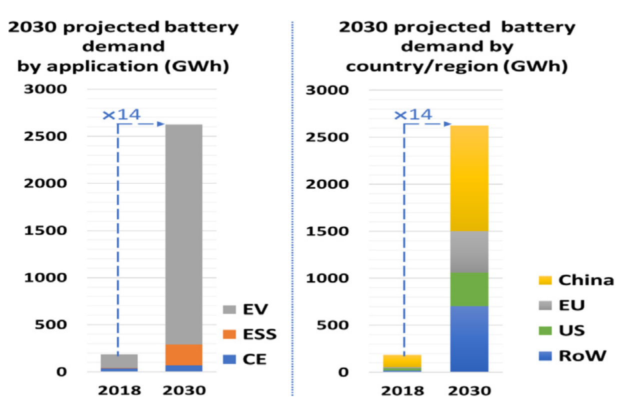

Fig. 1 Projected global battery demand by application and region in 2030 [11].

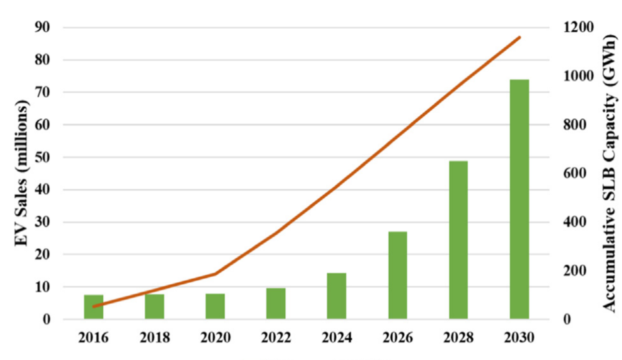

Fig. 2 Accumulative second life battery (SLB) capacity [16].

Table 1 Comparison on the different types of batteries [19].

Specifications	Lead-acid	NiCd	NiMH	LCO	LMO	LFP
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance (mΩ)	< 100	100–300	200–300	150–300	25–75	25–50
Cycle life (80% discharge)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Fast charge time	8–16 h	1 h	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Low		
Self-discharge/ month (room temp.)	5%	20%	30%	< 10%		
Nominal cell voltage (V)	2	1.2		3.6	3.8	3.3
Charge cutoff voltage (V/cell)	2.4	Full charge detection		4.2 V		3.6 V
Discharge cutoff voltage (V/cell)	1.75	1.00		2.5–3.00		
Peak load current	5 C	20 C	5 C	> 3 C	> 30 C	> 30 C
Best result	0.2 C	1 C	0.5 C	> 1 C	< 10 C	< 10 C
Charge temperature (°C)	−20 to 50	0–45		0–45		
Discharge temperature (°C)	−20 to 50	−20 to 65		−20 to 60		
Maintenance requirement	3–6 months	30–60 days	60–90 days	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
Toxicity	Very High	Very High	Low	Low		
In use since	Late 1800s	1950	1990	1991	1996	1999

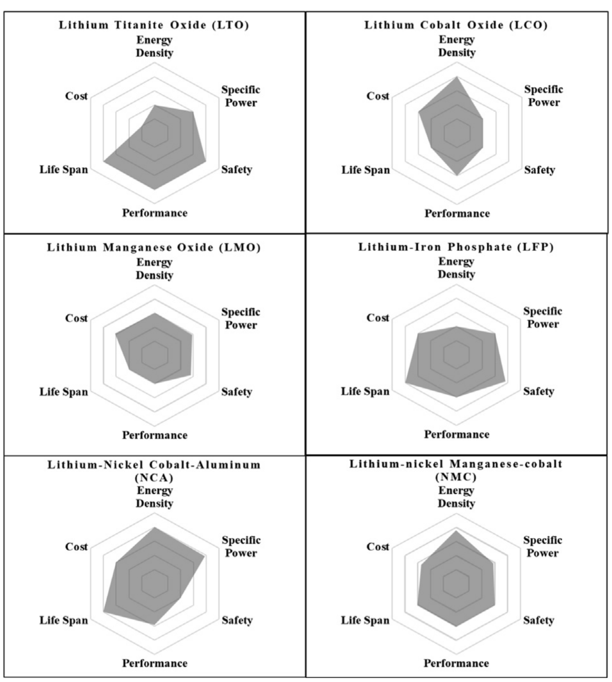

Fig. 3 Comparison of the different types of lithium-ion batteries [16].

ple, SLB could be compared to new lead-acid batteries in terms of performance and overall cost.

There are few types of batteries such as lead-acid, lithium-ion, redox flow, vanadium redox, nickel-cadmium, sodium-sulfur, electrochemical capacitors, iron-chromium, and zinc-bromine flow. Lead-acid batteries are one of the early battery technologies used in ESSs due to their track record of reliability and safety. They are typically used to start the internal combustion engines in cars and were commonly used for EVs. However, they eventually got replaced by longer-lasting lithium-ion batteries (LiBs) [17]. The characteristics of the LiBs such as high power density, long lifetime and low self-discharge resulted in popular demand for LiBs as energy storage in portable electrical/electronic products [18].

To understand the advantages of LiBs better, comparisons between three types of LiBs namely Li-ion-Cobalt (LCO), Li-ion-Manganese (LMO), Li-ion-Phosphate (LFP) and other types of batteries such as lead-acid, Nickel-cadmium (NiCd) and Nickel-metal hydride (NiMH) had been carried out by B. Diouf *et al*. [19]. The results of the comparison have been summarised in Table 1. Furthermore, LiBs come with many different types of chemistries such as LCO, LMO, LPF, Li-ion Nickel Oxide (LNO), Li-ion Titanite Oxide (LTO), Li-ion Nickel Manganese-Cobalt (NMC), Li-ion Nickel Cobalt-Aluminum (NCA), and etc. [20]. Fig. 3 shows the comparison of the different types of LiBs in terms of their cost, energy density, specific power, safety, performance and life span [16].

The objective of this paper is to present the up-to-date state-of-the-art related to SLB in ongoing researches and projects. It aims to present the existing works and their achievements in utilising SLB and using this knowledge as a base for SLB future research. Table 2 summarises the content presented in this paper according to the section.

2. SLB potential

Based on the manufacturers' descriptions and the existing literature, once EV batteries reached 70–80% of their nominal capacity, their role as EV first life batteries is considered to have reached to the end [21–25]. The main reason behind is that these kind of batteries will result in lower mileage and speed [21,26,27]. The percentage of residual capacity represents the battery SOH. This degradation is estimated to be happened after 5–8 years of usage or equivalent to 100,000 miles (160,000 km) of travelling [28]. However, the retired EV batteries, even with lower SOH, could still be re-purposed in other applications such as residential households or power variance in grid-scale PV plants [29]. As shown in Fig. 4, they are estimated to have another 7–10 years of the lifespan before reaching the End of Life (EOL) as SLB [8,27,30–32].

Table 2 Summary content of the paper.

Section	Summary of content
1 Introduction	The section presents the market growth of EV and the potentially discarded batteries expected in the near future. It further presents comparisons of different EV batteries and their chemical compositions.
2 SLB Potential	This section introduces the concept of SLB and the criteria of SLB. It further explains the interest of such topic based on regions. Applications of SLB and re-purposing process are presented.
3 Lifespan and Useful Life of SLB	The section presents the parameters related to batteries and their impact on them, such as the depth of discharge (DOD) and others. It further explores the life expectancy of SLB in different applications along with the methods of predicting the rest of useful life (RUL).
4 Economics of Using SLB	This section addresses some major concerns about SLB such as the suitable selling price for SLB, the cost of re-purposing and the economic comparison of SLB with new batteries. It is intended to answer whether the SLB are profitable or not.
5 Environmental Impact of SLB	In this section, the environmental impact of using SLB is presented by showing what are the harmful potentials such as global warming potential (GWP), photochemical oxidation formation potential (POFP), particulate matter formation potential (PMFP), freshwater eutrophication potential (FEP), metal depletion potential (MDP) and fossil-resource depletion potential (FDP) indicators that have been eliminated or minimised. Their impacts on raw materials, water and electricity will also be presented.
6 SLB Assessment and Testing	Preparation of SLB assessment and methods of assessment of state of health (SOH) are presented in this section. Examples of such methods are direct measurement, empirical estimation, model-driven, data-driven and hybrid.
7 Challenges of SLB	This section intends to present the existing challenges of SLB which could slow down the widespread of SLB in the industry.
8 Summary of Existing Work	Information related to some existing SLB studies, including the countries where the project had been carried out, the capacity of the battery, applications, approaches and scope are presented.
9 Conclusion	A summary of findings and possible solutions and recommendations to SLB's challenges are presented in this section. Furthermore, research gaps are identified for future research considerations.

It is worth mentioning that not all EV owners will change their batteries even though the battery's performance falls below 70–80% of its original capacity as they may not need the full capacity to reach their destinations. Nevertheless, eventually, all EV batteries must be replaced [33].

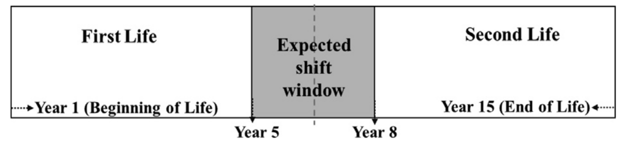

Fig. 4 Shifting point of first and second battery life [8].

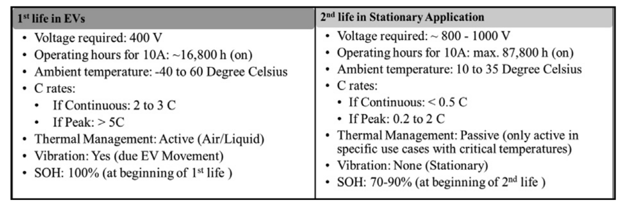

Fig. 5 Comparison of first and second life battery application requirements [27].

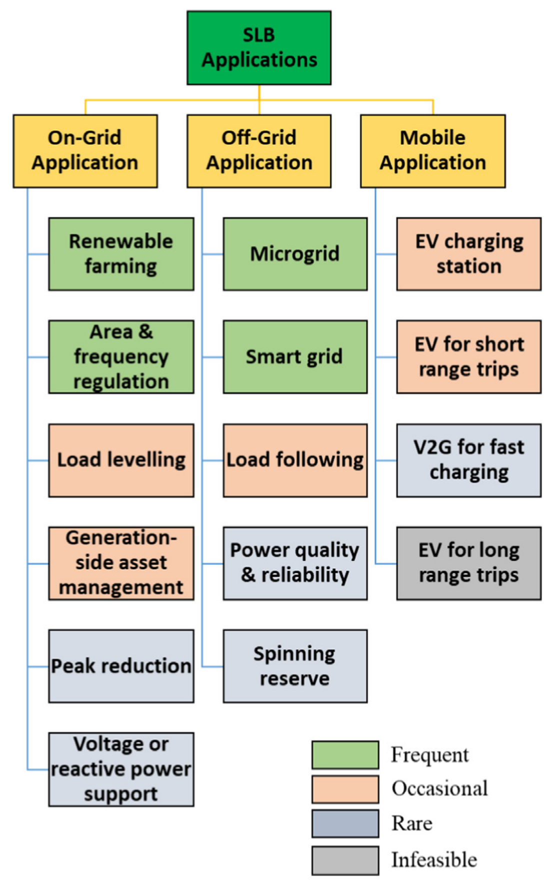

Fig. 6 SLB ESS Applications [21].

Industries and researchers have started their testing on the SLB for their new roles. Based on the related literature and recent news, it has been noticed that some regions have yet to have any ongoing projects on SLB testing such as Asia (except for eastern region), North Africa, South America, Middle East and Australia [15]. Studies and testing of SLB should be expanded to these regions. Further studies are needed as the different climate conditions in these countries will affect the batteries' ageing process [21,27]. Examples of such initiatives are (i) 2000 retired batteries from Mercedes EVs which were dismantled in Elverlingsen, Germany to form a stationary battery that is capable to hold 9 MW energy [17]; (ii) SLB packs from 85 used Toyota Camry Hybrid cars have been utilised to provide 85 kWh of storage capacity for photovoltaic (PV) system at Lamar Buffalo Ranch [34].

Re-using EV batteries for second-life applications could contribute to a 56% reduction in CO_2 emissions compared to natural fuel gas, especially during peak demand [5]. Aside from the environmental benefit of re-purposing the EV batteries, it could be a source of a revenue stream for products which would have been disposed anyway [29]. Furthermore, it could lead to cost reduction in grid-scale LiBs systems [35].

Using these batteries in different applications would require some integrations and rearrangements. Standard voltage for typical industry systems is about 800–1000 V. System requirements of EV battery compared to the re-purposed industry are presented in Fig. 5. It can be further seen from Fig. 6 that ESS implementations vary, and they could be used in many applications. However, when it comes to SLB applications in ESS, the suitability may vary [21].

With the growth of EV market worldwide, EV Charging during power outages is becoming a real concern. According to [36], the planned power outages, to prevent wildfires, in California highlighted a critical issue with EVs which is its charging during power outages. Such power outages could be planned and for a short time or could be for a longer time and unavoidable, often in some developing countries due to the demand is higher than the generation.

To address such issue, Tesla [37] came up with a system named Powerwall, which is a battery pack powered by solar panels that stores energy for usage during power outages. The storage could be used for both home usage and EV charging. The system will have a charging threshold to determine how much to share the energy storage with the EV charging. The system will follow the priority charging system, as shown in Table 3. The system is applicable for both private and public EV chargers. As for the fast charging, it will depend on the capability of the EV to fast charge not only the charger. The EV must support EV fast charging at first place.

In 2019, Tesla implemented hybrid superchargers that utilizing solar power and battery energy storage system. These hybrid superchargers have similar concept with Powerwall, where they are used to fast charge the EVs during power outages. As an alternative for the new batteries that used in Tesla Powerwall and other similar ESSs, SLB could be used as energy storage system for EV chargers during power outages.

According to the Energy Storage World Forum [38], ESS, in which SLB could be utilised in, are widely applicable to

Table 3 Tesla Powerwall priority charging system.

Power Source	Home Load	EV Charging
On Grid	Any load	Fast/Normal EV charging
Power Outage while energy storage above threshold	Low load	Fast/Normal EV charging
	High load	Slow EV charging
Power Outage while energy storage below threshold	Any load	No Charging

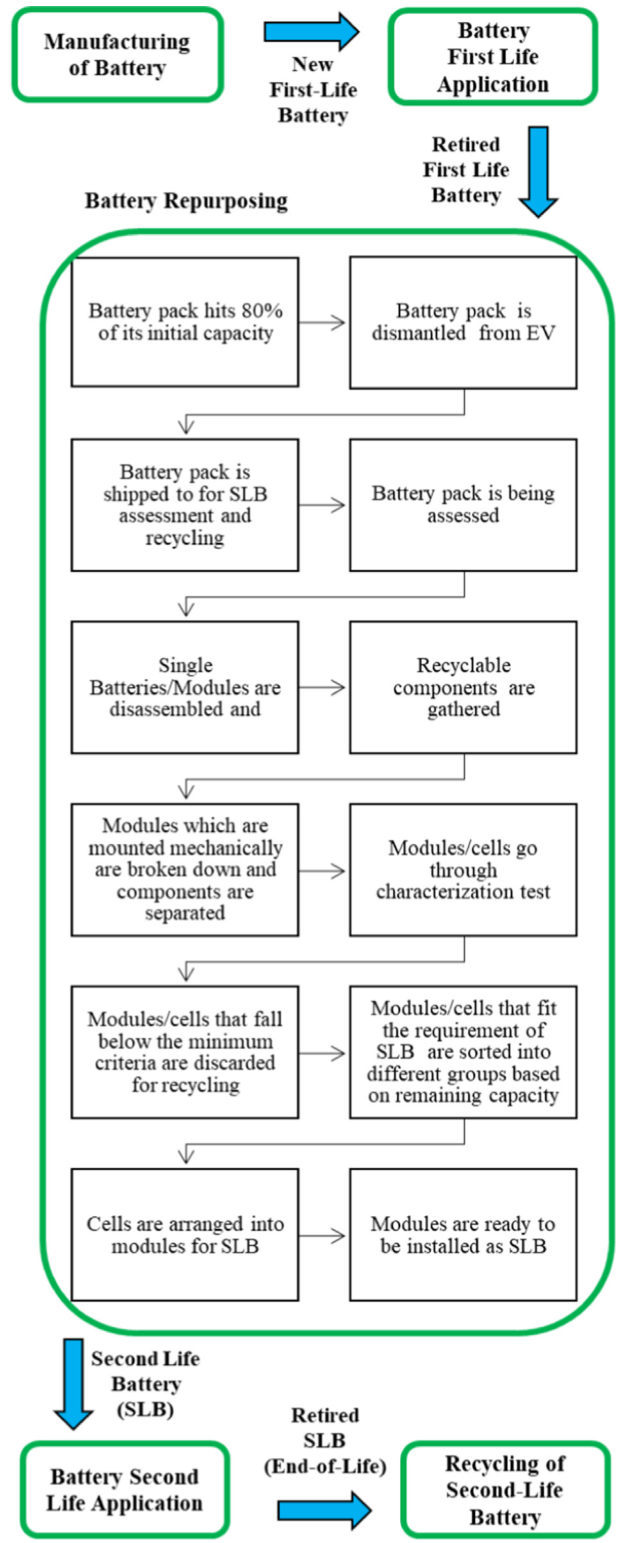

Fig. 7 Second Life Battery cycle [42].

applications for Grid Operators and Utilities or for behind-the-meter customers. Examples of applications for the former are Energy Arbitrage, Flexible Peaking Resource known as Resource Adequacy, Frequency Regulation, Reserve Capacity (Spin/Non-Spin), Voltage Support, Black Start, Transmission & Distribution Deferral and Transmission Congestion Relief.

Whereas Time-of-Use Bill Management, Increased Self-C onsumption/Self-Sufficiency from Solar Plus Storage, Demand Charge Reduction and Backup Power or known as Uninterruptible Power System can be found in behind-the-meter applications. For example, In 2018, almost 1 GWh of SLB were installed in different applications in China, in which most were placed in the telecommunication base stations as backup power [15].

In a recent collaboration between Nissan and 4R Energy Corp [39], the used batteries discarded from Nissan Leaf EVs are sent to the 4R Energy Corp factory for the assessment. The batteries are then categorised into three grades, namely (i) Grade A batteries where these batteries are still in excellent condition and could be re-used in the new EV battery pack; (ii) Grade B batteries that will be used for industrial machinery such as forklifts and large ESSs; and (iii) Grade C batteries in which these batteries will be used in backup supply power units.

However, these batteries have to go through several processes before being used for second-life applications. The battery life cycle will go through multiple stages, processes and sub-processes such as battery return, assessment, integration and recycling [27,40,41]. Fig. 7 shows the battery re-purposing process proposed by [42] combined with the existing general process in the literature on repurposing and refurbishing the discarded EV batteries before they are ready to be used in the new application.

The process may change depending on the level of dismantling. For example, retired batteries could be used directly as a whole pack, as a pack consists of a certain number of modules or it can be used as a pack of cells [43]. A module typically consists of a small number of cells connected either in series, parallel or series-parallel. Due to lack of standardisation and SLB emerging as a new concept, dismantling is carried out manually rather than automated [43]. When reassembling, the joining requirements will change based on the desired structure. For cell level, they are joined by electrode-to-tab within the cell or case sealing of outer cell container. For module level, cell-to-cell (i.e. tab-to-tab / tab-to-busbar) electrical and structural joints. For pack level, module-to-module electrical and structural joints [44].

Another factor to consider when dismantling and assembling SLB is cell structure design. The most commonly used cell structures for EV LiB are cylindrical, prismatic, and pouch [44–47]. Cylindrical cells are formed by a single sheet with a separator inserted between anode and cathode and covered by a metal case in a cylindrical shape. Prismatic cells are large sheets of anodes, cathodes, and separators rolled up and pressed into a flat cubic shape. Pouch cells are electrode sheets that are cut, stacked, and connected using current collectors [44,48]. When it comes dismantling, cylindrical cells are typically the most difficult ones to dismantle, followed by pouch cells and prismatic cells. For an example, on Tesla Model M3, there are 4416 cells connected and glued together very tightly, making it more challenging to dismantle compared to another two type of cells. For pouch cells, there will be 4 cells put together typically with some adhesive glue forming a module, such as those found in Nissan Leaf. As for the prismatic cells used in BMW I-3, they usually come in single form with bigger capacity that make the dismantle process easier [49].

The removal of the EV battery needs to be done by a competent person by following the guidelines given in the manual provided by the manufacturer. During the batteries' removal process, it is recommended to fully discharged the batteries and put the EV into Natural Mode (N-Mode) so that it could be dragged once the batteries have been removed. High Voltage (HV) terminals of the battery need to be disconnected to guarantee the safety of the personnel [43]. Then batteries are transported to the location where further assessment and reassembling are performed. Lithium-ion batteries are considered as class nine hazardous material; thus, they must be handled according to the standards that are set by international organisations such as International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), United Nations (UN), Underwriters Laboratories (UL) and Society of Automotive Engineering (SAE). Standards such as IEC62281 and J2950 are examples that could be considered when transporting LiBs [50,51]. Assessment details will be further discussed in Section 6 on the SLB Assessment and Testing.

3. Lifespan and Useful life of SLB

To predicate the RUL of a battery, serval methods that have been used by researchers such as empirical / semi empirical [52], module-driven [53], data-driven [54] and hybrid [55]. Table 4 presents the different methods to predicate the RUL along with their advantages and disadvantages [56–59].

Table 4 RUL predication of a battery.

Method	Description	Advantages	Disadvantages
Empirical method	It is the direct/ indirect utilisation of experiments and observation in a study	Simple structure and lower computational effort needed	Lower accuracy especially in nonlinear studies such as batteries
Model-driven method	A method that utilises mathematical modelling to describe and estimate the degradation process	Higher accuracy with higher generalisation ability	Higher computational effort and mechanism knowledge needed
Data-driven method	A method to utilise the historical data to estimate the RUL of a battery without the need for a deep understanding of the degradation process	Higher flexibility with no deep mechanism knowledge needed	Lower generalisation ability
Hybrid method	It combines two more methods to overcome the shortcoming of a single method.	Higher accuracy with more dimensions of information	Higher complexity with a higher possibility of source error

Automotive manufacturers have launched some projects and the electricity utility company to analyse the feasibility of re-purposing the EV batteries and optimise the SLB in other possible applications [60]. The battery chemistry, state of charge (SOC), DOD swing, the number of cycles, the charge, and the cell temperature are used to determine the quality and lifespan of the retired EV batteries. Some studies have been conducted, with the concepts ranging from off-vehicle storage to home batteries' modelling.

In one of the works, SLB comprised of NiMH and Li-ion batteries have been used in the grid system to estimate the lifespan of the SLB based on the real DOD rates [61]. The method used to estimate the lifespan of the SLB is based primarily on the usage data from Technology Strategy Board Coventry and Birmingham Low Emissions Demonstration projects. A statistical approach was used to estimate the remaining lifespan of the SLB based on the vehicle usage data. It is estimated that SLB could last for 6 years to support 750 ancillary services and about 15 years to support the network deferral. Network deferral is defined as the charging and discharging processes of ESS, where it will be charged during the night and discharged during the on-peak hours to meet the feeder's demand. The charging/discharging of the batteries is done once per day for four months per year to a DOD of 50%. It is also likely for the SLB to last about 7 years to support the energy management that operates over 5 days per week with a DOD of 50%. It is worth noting that cyclic ageing and the effect of averaging driver usage were being considered in the work while the effects of capacity fade and calendric ageing were not [61]. Capacity fading is defined as the inability to deliver the needed power at rated voltage, and it is related to the increment of internal resistance [62]. While calendric ageing is defined as the concomitant loss of capacity due to the incremental cell age caused by the battery's chemical deterioration [63,64].

The impact of different DOD on the lifespan of SLB has been further experimented in a recent study as ESS [65]. In the study, SLB was defined as a battery that has about 80% residual capacity. Three different DODs with different range of discharge and charge points were experimented to determine the lifespan. Lastly, two scenarios were considered, with the first scenario considered 70% residual capacity as the EOL for the SLB while the second scenario uses 60% as the EOL of the SLB. It was found that if 60% EOL was considered rather than 70%, it could extend the lifespan of SLB for about two times. Similar result could be obtained by reducing the DOD from 80% to 50%. Other findings done by [8,27,30–32,66,67] also concluded that lower DOD will extend the lifespan of a battery. Impact of DOD on SLB lifespan has been tablet in Table 5.

The battery lifespan is an essential aspect for a typical EV to offer 8–10 years of warranty [28,40,61], seeds the idea of Sunbatt project in Spain [40]. In the project, affordable EV batteries were re-used for second life applications, connecting the automotive and electricity sectors. The RUL in EVs and PHEVs SLB was analysed using MATLAB. Several ageing mechanisms, such as calendric ageing, C-rate, DOD, temperature, and voltage, were considered in the model. Sunbatt project works in two approaches; simulation (MATLAB) and empiric tests (Sunbatt container). A container was developed in the project to shelter the electrical and electronic equipments. The container was thermally isolated, and the cooling/heating system was incorporated to avoid high working temperature, which will affect the ageing of the battery as well as the safety related issues.

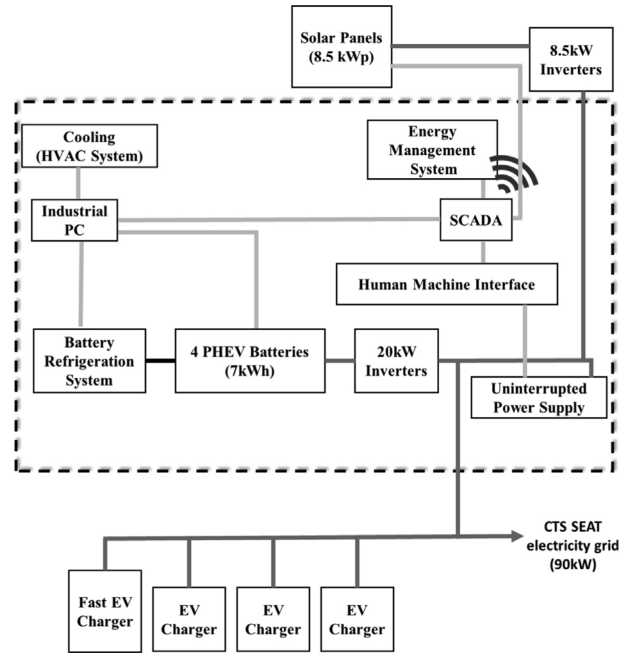

Fig. 8 Sunbatt Demonstrator [40].

The Sunbatt container, as shown in Fig. 8, was tied to a PV system with 8.5 kWp generation power, three EV chargers, a fast EV charger and a local electricity grid that can offer up to 90 kW peak power. The analysis of the SLB was conducted for four different stationary applications, namely, support to fast EVs charge, self-consumption, area regulation and transmission deferral. The cooling system, Human-Machine Interface and Uninterrupted Power Supply are some of the necessary elements of the system. It should be noted that once the battery lost 20% of its initial capacity, it is considered to be the EOL of a battery, i.e. if SLB started at 80% of the SOH, then the EOL for SLB will be at 60% of the SOH [22].

Several cases such as different assumptions of EOL point and other scenarios were considered. With 60% EOL assumption, it can be seen from Table 6 that among the four scenarios, fast EV charge has the most extended lifespan of about 15 years

Table 5 Impact of DOD on SLB lifespan [65].

DOD	Range	Lifespan at 70% EOL	Lifespan at 60% EOL
80%	95–15%	4 years	8 years
65%	85–20%	5.1 years	11 years
50%	65–15%	8 years	16 years

Table 6 SLB lifespan of different applications [40].

Application/Scenario	SLB years of expected service
EV charge support	15 years
Self-consumption (building)	5.9 years
Area regulation	4.7 years
Transmission deferral	5 years

of SLB services. EV chargers, coupled with PV systems, have been one of the most commonly used SLB mobile applications [21]. The authors have argued that re-purposing EV batteries is an excellent alternative to the new and costly LiBs. Such a claim will be compared with others' in Section 4.

Authors in [68] have explored the lifespan of SLB in other applications, namely energy arbitrage, island installations and autonomous use. Energy arbitrage application is the scenario where the energy is bought at a lower charge rate, especially at night to charge the batteries, and to be consumed when the electricity is more expensive during peak hours. It is assumed that the SLB is having almost 100% DOD and estimated to support this application for eight years. While in the island installation, Renewable Energy Source (RES) was incorporated in the system to charge the batteries when there is excessive energy production. These batteries were discharged to a house when the RES production is insufficient to meet the demand. In this scenario, DOD of the battery was 50%, with an estimation to have a lifespan of more than twenty years. In the autonomous applications, RES is used to power up the batteries. However, the grid will still be connected to the system, and served as the secondary source of the energy when the RES is insufficient to support the demand. With a 50% DOD, it is expected that the lifespan for SLB will be around eight years. The estimation of the battery lifespan in this work was studied through equations, and the variable parameters were identified from the second life requirements.

The first European SLB system was installed in 2014 by BMW in a smart grid application in Hamburg, Germany [27]. The system contained eight used BMW i3 LiBs packs used during the development of the pre-series vehicle. The ventilation system was made to keep the system temperature within 10 °C and 35 °C. The authors emphasised the importance of matching similar-aged batteries; however, it is quite challenging. The batteries selected for this project had a similar first life history such as temperature profile (typically for central European climate), moderate average user driving profile and average travelling distance (less than 50,000 km). Contributions from work done by the authors are as following: (i) providing a methodical and analytical basis to assess SLB operation, (ii) proposing an efficient control strategy to maximise the system performance, and (iii) minimising the battery cell ageing as much as possible. The system installed served as buffer fast charging processes for EVs with low SOC. The proposed control strategy randomly chooses a fully charged string to provide the needed charge power to EVs, which minimises the stress on the grid. Once the charging process is completed, the system will wait for the off-peak hours to recharge the system's strings that have been used. Such process has resulted in the common "stand-by hump" to be around 60% of the SOC, which can be noticed in the SOC distributions. According to the authors, the control strategy helps to save the cost by recharging during off-peak hours, avoiding high sudden power demands and minimising the chemistry's calendrical ageing mechanisms of the battery.

According to authors in [29], the literature review done on SLB degradation behaviour is still insufficient. In their proposed system, lithium-ion NMC/C battery effects were evaluated in terms of SOH and ageing. The batteries were deployed in two different applications: household demand management, which represents low demand applications; and power smoothing application to solve a grid-scale PV plant's power variance. However, their experiment on the ageing of the first and second life was conducted in a laboratory so that the battery operating environment could be fully controlled. Testing was conducted at the cell level as well as the stack level. It was observed that internal DC resistance increased significantly in most batteries. Their findings found that degradation behaviour, especially in the first life, has a significant impact on the SLB performance. The results indicated the potential of re-using the battery for a second life. After experiencing Full Equivalent Cycle of 300,000 km driven distance in their first life, batteries could still provide a long-lasting second life under laboratory environment. It must be noted that retired batteries in this experiment had 95% residual capacity. The findings showed that once the ageing evolution starts to accelerate, battery lifespan would not be extended if the batteries were used in less demanding second life applications compared to other types of applications. It has been concluded that not all batteries are suitable for SLB usage. This conclusion was made based on the facts that the number of cycles that batteries can stand once hitting the ageing knee would not be enough to make profits by extending the operation. Furthermore, safety issues will be a concern while maintaining cells with adverse conditions.

In [69], an equivalent electric current ageing model of a nickel manganese cobalt (NMC) chemistry prismatic cell was simulated using MATLAB-Simulink. The model was created using 262 cells packed in modules with a nominal voltage of 362 V. The study analysed the anticipated lifespan of the SLB integrated with Battery Management System (BMS). Note that the SLB did not go through the re-purposing process. The work consisted of two scenarios whereby the SLB was supporting the gas turbine system to provide area and frequency regulation services. The SLB in-charge to support the peak occurred in the power grid and to ensure a stable working condition of the gas turbine. In this work, two scenarios had been modelled by the authors. The first scenario worked so that the average demand from the set points during the earlier minutes is used to help the turbines work under a softened load. The purpose of this scenario was to reduce the complication caused by the temporary fluctuation between set points. Based on the average power demand from the earlier minutes, the recalculated working setpoint was transferred to the gas turbine to obtain the softening. As a result, the turbines response becomes softer and displaced by one minute while batteries provide or consume the shortage or excessive energy, respectively. The SLB in this scenario lasted more than 2000 battery life cycles before reaching their EOL, corresponding to 46.53% of the SOH. In other words, the SLB lasted for 84 days before they reach the EOL and 22,293 kWh of energy was drawn from the SLB to supply in the scenario. While in the second scenario, the gas turbine will always be working in constant acceleration, deceleration or power states to eliminate transitory inefficiencies and at the same time to increase the lifespan of the turbine by ensuring that it never works near to the maximum acceleration rates. The SLB work in the second scenario is similar to scenario one; however, the battery pack's maximum allowable power is 60 kW. In the second scenario, the battery reached its EOL with less than 800 battery life cycle, corresponding to 51.43% SOH. This means that a total of 15,919 kWh was drawn from the battery to provide the energy required for 36 days. Based on both scenarios, it was concluded that higher load is the main cause of the battery ageing.

4. Economics of using SLB

Most of the costing studies highlighted that battery cost is a significant contributor to EVs' high price [70–73]. Thus, some car manufacturers are looking for ways to reduce the EVs' cost by re-purposing the degraded batteries returned by the car owners [16]. Utilising SLB could create substantial financial opportunities for individuals and industries, namely EVs owners, battery re-purposing companies, SLB users and battery recyclers [16]. Firstly, the EV owners could benefit by obtaining the value recovery of their discarded batteries. Secondly, battery re-purposing could create a new industry and business opportunity. These new business companies could be in charge of assessing, rearranging, and repackaging the discarded EV batteries to suit the SLB application. Thirdly, and most importantly, the SLB users would be the largest shareholder as their role could be either individuals or industries. They will be able to buy ESS for much lower price when using SLB. Lastly, battery recyclers could also benefit from SLB. During assessment, rearrangement and repackaging, some battery cells will be discarded. The unsuitable battery cells, which has fallen below specific criteria, can be recycled to extract valuable battery materials from [16,62]. However, there are uncertainties and questions related to the economics of using SLB that need to be addressed. For example, what is the suitable price that SLB should be sold at? What is the cost of re-purposing and recycling process? Will SLB being utilised in ESS is more economically profitable than using new lithium-ion batteries if the environmental benefit is overlooked?

A study was conducted to estimate the selling price of SLB, where it could be half of those new batteries [74], as illustrated by Fig. 9. All the costs involved in the re-purposing such as testing, assembling, transportation and others were considered.

The selling price consists of the buying price, repurposing cost and a profit margin. SLB buying price should take into consideration on the cost of new batteries. Regardless the decline of new batteries cost, SLB should always offer a cheaper cost for customers to consider. In one of the studies [75], it was argued that the buying price of the SLB formula should consider the new battery cost. Furthermore, the condition or SOH of the battery must be taken into account along with the battery re-purposing cost. Lastly, they introduced a new factor named "discount factor" to encourage the use of

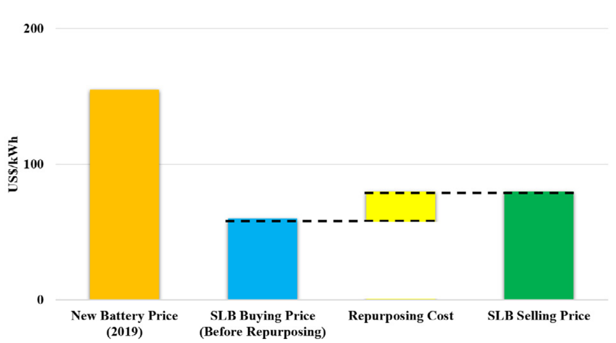

Fig. 9 Comparison of new batteries and SLB selling price [74].

SLB from the suppliers and EV owners which otherwise, they have no use for the discarded batteries. The buying price is then calculated as shown in (1).

$$V_{used} = V_{new} \times f_{health}(1 - f_{reuse} - f_{discount}) \quad (1)$$

where,

V_{used}: The buying price of SLB in nth year.
V_{new}: The price of new batteries of similar capacity in nth year.
f_{health}: SOH of the battery (%) *.
f_{reuse}: SLB re-purposing cost (%) **.
$f_{discount}$: The discount factor (%).

*If the SOH is determined through some proper asessemnt. If the SOH not determined through assessment, it is assumed to 3% degradation per year of EV usage.

**The value is given in percentage form. It is proportional to the cost of new batteries and could be assumed 15% as presented in the study.

On the other hand, other studies have attempted to estimate the cost of re-purposing process and categorise the cost according to the work done. Fig. 10 shows the SLB re-purposing cost categories and their relative details [76].

Fig. 11 presents the breakdown of the costs involved during the re-purposing process [72], in which it has a similar estimation pattern to the one proposed in [74]. It is worth mentioning that the battery cost named "Batteries" in Fig. 11 is referring to the buying price of retired batteries.

A detailed study was conducted to estimate the cost of dismantling EV batteries at each stage of the process [43]. The study was performed on a real EV battery named, Smart For-Four battery which had a capacity of 17.6 kWh. The time and manpower required for each step were recorded and converted into equivalent cost. In this cost analysis, the cost per kWh was presented in three different levels namely whole battery pack (without further dismantling), the module level and the cell level (Table 7). Transportation of batteries after removal from EV was not included, indicating that either it was not added to

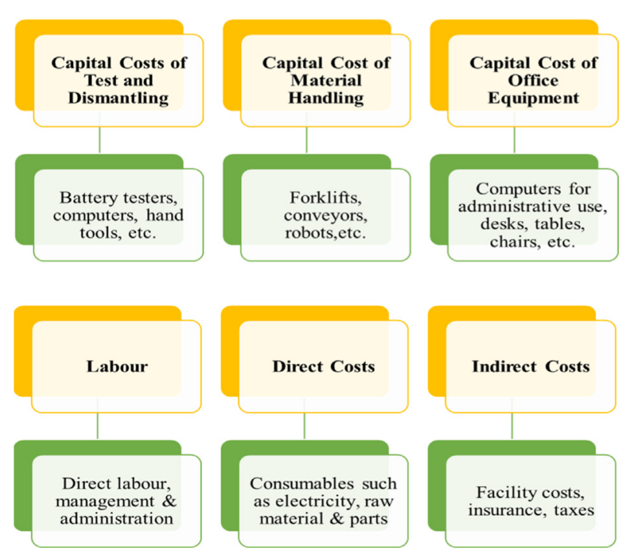

Fig. 10 SLB re-purposing cost categories.

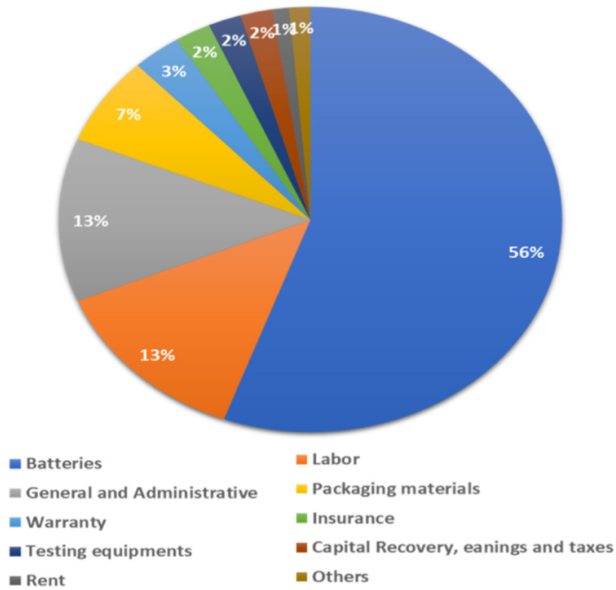

Fig. 11 Re-purposing cost contribution to SLB selling price.

Table 7 Cost analysis of re-purposing EV batteries [43].

Cost item	Battery	Module	Cell
Battery removal from EV	€ 117	€ 117	€ 117
Battery Assessment	€ 442	€ 442	€ 442
Disassembly to modules	N.A	€ 500	€ 500
Disassembly to cells	N.A	N.A	€ 275
TOTAL	€ 588	€ 1058	€ 1333
COST / kWh	€ 32	€ 60	€ 76

the cost or it was done at the same assessment location. Cost of repackaging, BMS and wiring was not included as well.

Based on the available literature of SLB, the cost of re-purposing and the selling price vary from optimistic estimation to reasonable and to relatively high. For example, it was estimated that the selling price of SLB would be around \$44/kWh, including the cost of re-purposing set at \$20 [77]. Such figures are too optimistic compared to the experimental results presented in Table 7 [43] as well as the selling price estimated by the Global Battery Alliance [78] in their 2018 report (starting from \$60 to \$300 per kWh). The study projected that the selling price would drop to \$43/kWh in 2030. Casals *et al.* [79] investigated the economics of using SLB in a residential application and concluded that buying SLB becomes profitable for consumers if it is bought at €38.3/kWh. Such conclusion seems to agree with [77], yet deemed as too optimistic from a re-purposing point of view [80].

Authors in [65] performed a data-driven and semi-empirical economic analysis of SLB. In their system, the SLB model of NMC lithium-ion batteries were coupled with a PV system. A comparison of new LiBs and SLB was made to understand the economics of SLB and predict the capacity fade over time. The SLB was assumed to have an 80% SOH, and costs about 80% of the new LiBs. Different scenarios have been tested, such as difference DOD and EOL scenarios, as presented in Table 5 in the previous section. Direct comparison between new LiB and SLB is difficult as their initial cost and lifespan are different. In this study [65], they used Benefit-Cost Ratio (BCR) in which its calculation caters for the initial capital cost, system's annual revenue, Operation & Maintenance (O&M) and discount rate. The results for the four scenarios are presented in Table 8. The results show that new LiBs are more profitable than SLB if the SLB costs 80% of the new LiBs.

Table 8 LiB and SLB benefit-cost ratio [65].

Battery	EOL	Useful life	BCR
New LiB	60%	17.3 years	0.93
	70%	11.4 years	0.76
SLB	60%	11 years	0.78
	70%	5.1 years	0.47

Break-even point is achieved for the same system if the SLB cost less than 60% of new LiBs. It was further found that operating SLB-dependent systems with 50% DOD ranging from 15% to 65% is more economically favourable than other scenarios. Furthermore, SLB cost could be competitive with the new lead-acid batteries [40,68] which are still at disadvantage when considering their short lifespan [76,81]. In 2018, almost 1 GWh of SLB were installed in different applications in China, in which most were placed in the base station as backup power. Despite being degraded, SLB could still perform better in terms of life degradation and energy density than lead-acid batteries [82].

In summary, cost analysis of SLB and their economics are yet to be further investigated. While many researchers agreed on the methods of estimating the selling price of SLB and re-purposing cost, the variation in their presented figures is significant. As of now, the selling price ranges from \$44 to \$300 per kWh according to the studies in which most of them agreed that it would cost less than \$100/kWh. Besides, the cost may vary from one country to another. Therefore, more cost analysis studies are recommended in different countries.

5. Environmental impact of SLB

The transportation sector is known to be the most significant contributor to greenhouse gas emissions, as well as the other hazardous pollutants globally. The pollution issues caused by the non-EVs has seeded the idea of electrification of transportation. The main reason behind is that EVs do not produce emissions during their lifetime usage. A life cycle assessment (LCA) is required to understand EVs' environmental impact clearly [78].

The use of EV batteries as ESSs contributed two main concepts to waste management, offering a cleaner solution to tackle emissions, natural resource weaning and climate change mitigation. Firstly, the concept of waste management for extending a product's life cycle [83] is applied. This is simply another way of reiterating the old re-use concept, but now there is a specific use on a larger scale for the product in question. Applying this concept to EV batteries gives the battery a "second life" or a specific second use as an ESS. The benefits of re-using the EV batteries for another 5–7 years provides a cleaner solution to the environment. For example, the utilisation of SLB could reduce the gross energy demand and global warming potential by 15–70% [84]. The second concept of waste management which is Zero Waste [85], is applied by not building the additional warehouses, which prevents us from creating the waste, i.e. the warehouses, in the first place. Other by-products waste from the construction process are also prevented. Construction of warehouses may lead to the destruction of flora and fauna, which should be preserved as natural absorbents of carbon dioxide footprints.

From an environmental point of view, the primary benefit of SLB is eliminating the first life battery manufacturing which has many environmental concerns. First of all, to collect 1 ton of lithium-ion, 250 tons of the mineral ore spodumene or 750 tons of mineral-rich brine are required during mining [86,87]. Extraction and processing such raw materials at this scale are harmful to the environment [14]. Secondly, the amount of water needed during the activities of mining. Each 1 ton of lithium-ion requires 1900 tons of water [88]. For example, lithium-ion mining consumes 65% of the region's water in Salar de Atacama, Chile [88]. Thirdly is the electricity consumption during the manufacturing of LiBs. Manufacturing a 1kWh of LiB requires 50–65 kWh of electricity which if it was a coal-fired power plant, it is equivalent to 55 kg of CO_2 emission [89]. Other potential environmental concerns are classified as follows [28]:

- Global Warming Potential (GWP)
- Photochemical Oxidation Formation Potential (POFP)
- Particulate Matter Formation Potential (PMFP)
- Freshwater Eutrophication Potential (FEP)
- Metal Depletion Potential (MDP)
- Fossil-resource Depletion Potential (FDP)

In the study conducted by [28], they have quantified such potential environmental concerns. Table 9 compares the potential environmental indicators at three stages namely, battery manufacturing, first use and second use. Before the second use of the battery, it should be noted that they went through a remanufacturing process which includes interfering with the chemicals and electrical parts of the battery in this study. Therefore, it could be safely assumed that the harm potential from the SLB is much lower than the second use presented in this study since SLB do not go through remanufacturing processes.

The LCA study was conducted to observe the environmental impact of using SLB in the selected scenarios to extend the batteries lifespan in less demanding applications [90]. The study was conducted in Spain's smart buildings and focused, explicitly, on lithium iron phosphate (LFP) technology. In the context of this work, the first-life of the battery considered as an LFP battery which will be used in an EV for 2500 cycles until the capacity falls below 80% while the second-life LFP battery will be used as an ESS (supplied from the grid) in a smart building for 1500 cycles. Every cycle is assumed to be on the daily use of charging and discharging cycle.

As it can be seen from the stages of scenario one: manufacturing of the LFP battery, usage of the battery in the EV for 2500 cycles until the capacity falls below 80% (first-life application), usage of the battery in the smart building for 1500 cycles until the capacity drops below 60% (second-life application), and finally discarding the battery. However, in scenario two, after the LFP battery's disposal, a new first-life battery with a smaller capacity will be manufactured and ready to be used as ESS. The system obtains the energy from the grid and it will supply the energy to the smart building for 1500 cycles.

It can be seen in Fig. 12 that scenarios one and two are similar to scenarios three and four, respectively. The major difference is that instead of storing the energy from the grid, the energy supply to the battery in the later is obtained from solar PV.

Among the four scenarios, scenario three that is obtaining the energy supply from solar PVs has the lowest GWP indicator values compared to those powered by the grid; especially scenario two, which has the highest GWP indicator value. Furthermore, based on the GWP indicator values of all the scenarios, integrating solar PV and second-life LFP battery is more

Table 9 Potential environmental concerns related to batteries [28].

	Battery Manufacturing	First use	Second use
GWP (kg CO_2/kWp)	0.097	0.0760	0.0630
POFP (kg NMVOC/kWp)	1.95×10^{-4}	1.51×10^{-4}	1.28×10^{-4}
PMFP (kg PM10 eq./kWp)	1.62×10^{-4}	1.47×10^{-4}	1.22×10^{-4}
FEP (kg P eq./kWp)	1.70×10^{-4}	1.15×10^{-5}	9.5×10^{-6}
MDP (kg Fe eq.//kWp)	0.042	1.5×10^{-4}	1.0×10^{-4}
FDP (kg Oil eq.//kWp)	0.0277	0.023	0.02

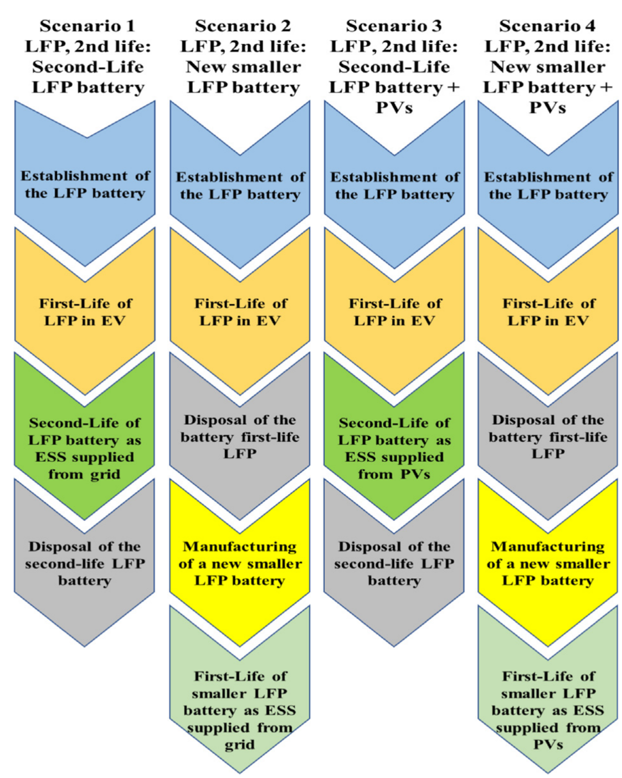

Fig. 12 Graphical representation of the scenarios of the LCA study [90].

Table 10 Eco-indicator and GWP results of LCA study [90].

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
LFP Battery Manufacture	577.70Pt	577.70Pt	577.70Pt	577.70Pt
LFP Battery Usage	1015.36Pt	1015.36Pt	1015.36Pt	1015.36Pt
Second LFP Battery Manufacture	N.A	288.85Pt	N.A	288.85Pt
Second Life Application	1128.24	1057.73Pt	883.05Pt	873.83Pt
TOTAL	**2721,32Pt**	**2939.64Pt**	**2476.11Pt**	**2755.74Pt**
GWP Indicator	**28218.68 kg CO_2 eq.**	**29429.89 kg CO_2 eq.**	**25205.42 kg CO_2 eq.**	**27169.94 kg CO_2 eq.**

beneficial in lowering the GWP as presented in Table 10. The table further presents the eco-indicator point (Pt) for each scenario. Eco-indicator is used to estimate the environmental damage impacts of a product in terms of human health, ecosystem quality, and resources [91,92].

In one of the works [68], batteries usage is only advisable in association with RES. During the first life in an EV, an equivalent of 35,000 kg CO_2 is emitted, while the re-used batteries emissions depend on the energy source and type of applications. It has been observed that GWP increased by 30% when the batteries are used for energy arbitrage applications. In comparison, the re-use of EV batteries in island installation has a reduction of 32% GWP. Ultimately, SLB minimises the environmental impact since the manufacture of new batteries with similar capacity has been eliminated. This means that 4 kg of CO_2 eq. will not be emitted during the manufacturing process [93]. Therefore, the study concluded that using the repurposed battery for applications that are not supported by RES is not environmentally friendly.

There is no doubt that most researchers, based on the available literature, agreed on utilising retired batteries for a second life application as a way to a greener and more sustainable society. The use of SLB will help preserve raw materials, water, electricity and reduce the CO_2 which is targeted to be eliminated. It is aimed to cater to huge energy demand estimated by 130,000 TWh per year with CO_2 free by 2050 [94].

6. SLB assessment and testing

Prior to the assessment, battery preparation stage needs to be discussed. During the preparation stage, batteries are removed from the EV by a competent person. The concerns at this point are the hazards associated with lithium-ion batteries [95,96] and the presence of high voltage [14] which both require a competent person to handle it. According to [43], it will require at least two persons to complete the task in addition to the tools and machinery. Once the battery pack is removed, it can go through the assessment and dismantling process as described below:

1. Inspection & handling
2. Connection of the electrical test equipment
3. Initial voltage set & balance
4. Battery characterisation
5. Disconnection of the electrical test equipment
6. Final Inspection as one pack
7. Removal of package top
8. Extraction of Battery Junction Box (BJB) and removal of busbar
9. Disconnection & extraction of Cell Management Controller (CMC)
10. Disconnection & extraction of BMS
11. Dismantling of the pre-charge circuit
12. Extraction of modules
13. Removal of modules' cover
14. Extraction of cells.

The process, starting from battery removal to extraction of cells, may take 8–16 hours depending on the dismantling level, the number of manpower and specific tasks. It would take less time for the automated process [43]. Table 11 presents the estimated times required for the dismantling process.

The primary purpose of assessment is to identify the SOH of SLB. Determining SOH is complicated since many factors are involved, and it is argued how SOH is defined. It is meant to determine the limitations of the battery once it gets repurposed for second life applications. Identifying capacity and power degradation, which a battery experience both over time, could reasonably estimate SOH [97,98].

Fig. 13 shows some of the methods of finding the SOH presented by Berecibar *et al* [99]. SOH estimation methods were classified into experimental techniques (direct measurements and model based on measurements) and adaptive battery methods.

Advantages of experimental techniques lie on the minimum computational effort and possibility of BMS implementation. However, it could be associated with some drawbacks, such as lower accuracy compared to adaptive methods, where high accuracy is one of the main criteria. However, adaptive methods require high computational effort and having difficulty in integrating BMS into the system.

Electrochemical Impedance Spectroscopy (EIS) and Current Pulses direct measurements are the examples of experimental techniques found in [100,101], which will be explained further. On the other hand, examples of adaptive methods are Kalman Filters [102] and Neural Networks [103,104].

In a direct measurement, the SOH concerning capacity is defined in (2) as the ratio of the measured capacity during

Table 11 Dismnetalling required time [43].

Cost item	Battery	Module	Cell
Battery removal from EV	60 min	60 min	60 min
Battery Assessment	440 min	440 min	440 min
Disassembly to modules	N.A	300 min	300 min
Disassembly to cells	N.A	N.A	165 min
TOTAL	**500 min**	**300 min**	**965 min**

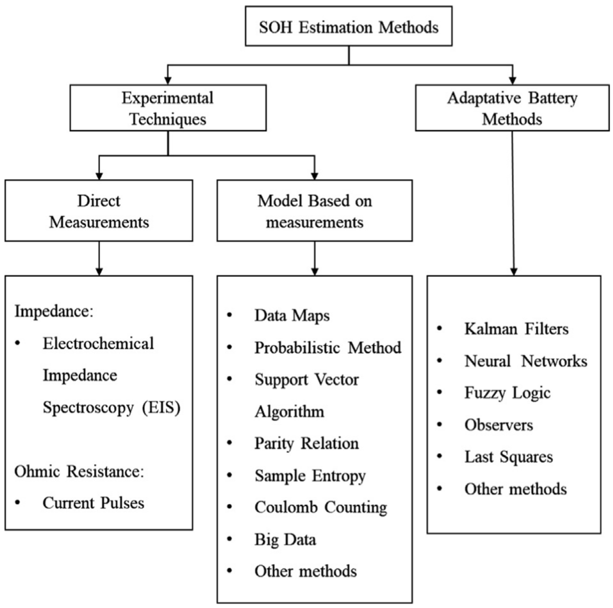

Fig. 13 SOH estimation methods [99].

the assessment, Q_m to the battery's nominal capacity when it was new, Q_n [98].

$$SOH[\%] = \frac{Q_m}{Q_n} \times 100 \tag{2}$$

A 20% drop in capacity indicates that the battery should be replaced and can be considered for second life application. On the other hand, 200% increment in internal resistance or impedance is an alternative indicator for battery replacement with regards to the power fading [98,105,106]. The SOH with respect to impedance is defined in (3) where Z_m is the measured impedance when performing the assessment, and Z_n is the nominal impedance of a new battery [98]:

$$SOH[Z] = (2 - \frac{Z_m}{Z_n}) \times 100 \tag{3}$$

LiBs resistance can be categorised into ohmic and polarisation resistances. Ohmic resistance encompasses electrode materials resistance, electrolytes resistance, separators resistance, and contact resistance. On the other hand, the polarised resistance is caused by polarisation during the electrochemical reaction. Note that the increment in internal resistance has a direct impact on the battery's power characteristics. Hence, to ensure good performance and be aware of a battery's remaining lifespan, it is crucial to measure the internal resistance of the battery.

However, the internal resistance of a battery cannot be measured directly [107]. Alternating Current (AC) methods, EIS and thermal loss methods are some of the popular methods used to obtain the internal resistance [101]. Authors in [101] have elaborated the details of determining the internal resistance, especially the current steps methods. The well-known general approach of the internal resistance measurement is conducted by applying current pulses to the battery. The voltage drop across the battery will be measured; then, the resistance is calculated using Ohm's law [101,108].

In the current-off method, the internal resistance is measured by calculating the voltage change over the current when switching off the current from discharge and charge modes with a short rest time between both measurements. While the current switching method is measured by calculating the voltage changed over the current when switching from discharge to charge mode under full amplitude condition. Both methods are as illustrated in Fig. 14 and Fig. 15 [101].

However, it is worth noting that measuring the internal resistance of complex loads such as batteries will be complicated due to the nature of capacitive and inductive characteristics. When using AC methods, battery behaviour strongly depends on the frequency of alternating current measurements. Usually, these measurements are carried out at a constant frequency of 1 kHz. It is concluded that this measurement technique is only suitable to compare the internal resistance of the same type of battery.

While in work presented in [107], under the constant temperature of 40 °C for full charging and discharging, the battery internal resistance increased rapidly with higher C-rates, which resulted in the depreciation of the battery life cycle. The batteries at different temperature experience different ageing process. Similarly, internal resistance measurement varies with the ambient temperature variation [109,110]. It further emphasised the effect of DOD on the internal resistance of a battery. Operating the battery at higher DOD increases the internal resistance over time. Lastly, the authors highlighted the importance of SOC during the measurement of a battery's internal resistance. Internal resistance measurement changes based on the SOC of the battery during testing.

A case study with regards to the SLB assessment was performed for echelon use [100]. The study was conducted on 24 modules of Chery S18 EV $LiFePO_4$ batteries. The EV was driven for three years, with a travelling distance of more than 50,000 km. The car was manufactured in 2010 and tested in 2017 with at least 1000 life cycles. The nominal capacity of each modules is 40 Ah with an overall system capacity of 12.8 kWh. The batteries were sorted into two packs, with 12 cells in each pack. The modules underwent a capacity calibration. SOH of the modules was determined using (1). As for the DC internal resistance, it was determined using pulse current test. Initially, the batteries were charged to 50% SOC and rested for two hours. Then the batteries were discharged at a pulse current of 1 C for 10 s. The batteries were rested for another 40 s before they were charged at a pulse current of

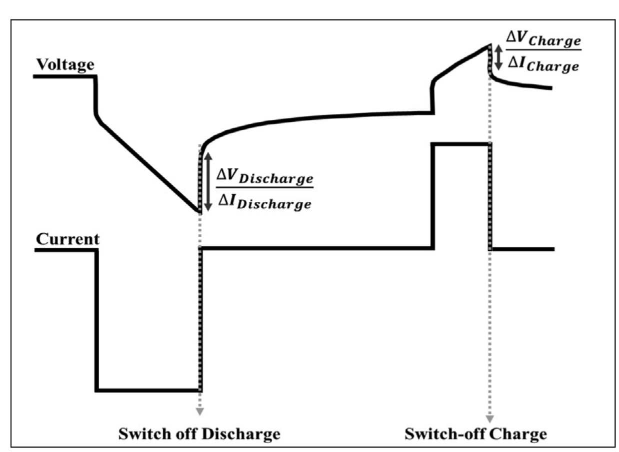

Fig. 14 Current steps method: Current-off [101].

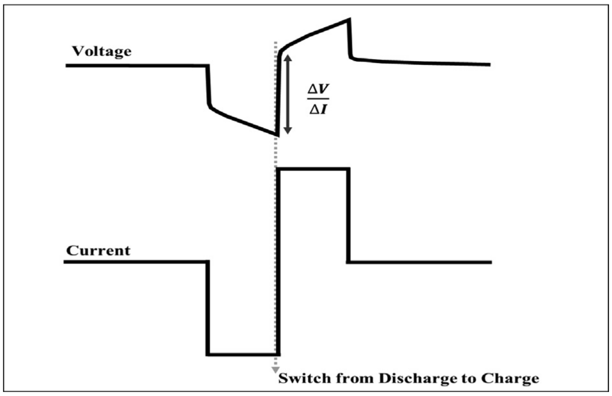

Fig. 15 Current steps method: Switching Current [101].

0.5 C for 10 s. The DC internal resistance was calculated using (4) with reference to the literature in [111].

$$R_d = \frac{\Delta U}{\Delta I} = \frac{(V_1 - V_0)}{I_d} \tag{4}$$

From the results, the authors found that batteries with high capacity were associated with lower internal resistance. However, that is not always the case as some modules did not follow the trend. The authors found that different batteries have experienced different ageing process in their first life through the research. Fig. 16 (a) and Fig. 16 (b) show the results of the measured SOH and DC internal resistance of the battery modules, respectively.

Not only LiBs have been investigated but also lead-acid batteries for a potential SLB use in France has been carried out [62]. The objective of this study was to determine the SOH of an SLB using a low-cost method with reliable results. The authors proposed to measure the internal resistance in two stages of measurement through the voltage drop method. Initially, the open-circuit voltage was measured and followed by pulsed load current (minimum of 0.5 C). The internal resistance was then calculated using the variation of voltages, which was then divided by the load current according to Ohm's Law. This method of testing utilises low-cost measuring devices such as voltmeter and a clamp amperemeter. Their methodology in the experiment was broken down into three phases (Fig. 17).

In the first phase, the measurement of the open-circuit voltage was performed. Batteries with a lower voltage than the cut-off voltage provided by the manufacturers were not considered

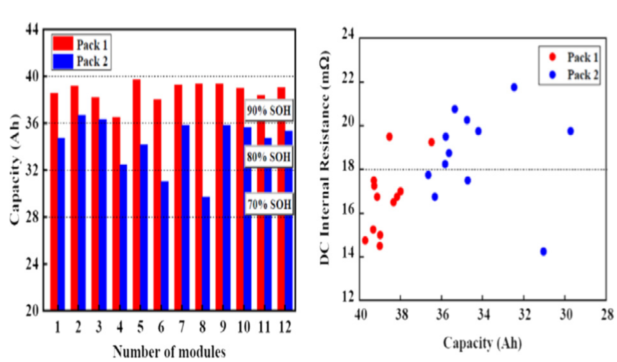

Fig. 16 Modules SOH (a) and DC internal resistance (b) [100].

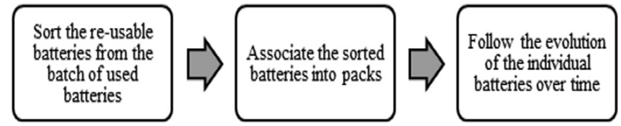

Fig. 17 Methodology phases presented in [62].

for re-use. In the second phase, internal resistance was measured as described above. Based on the internal resistance, batteries were assembled into packs to avoid the circulating current, which usually happens at the interconnections of batteries that have high variation in the internal resistance. The last phase was to determine the increment of the SLB internal resistance after three months. Measurement is to be performed once every three months. In their large-scale experiment conducted in France [62], 42 batteries were chosen using the method mentioned above. The preliminary measurement was done on phase two (during assembling of the packs) and phase three. The results have shown a change in internal resistance over time.

In summary, it could be concluded that there are multiple methods and approaches to estimate the different parameters of batteries. Different methods of SOH such as direct measurement [112], empirical estimation [113], model-driven [114], data-driven [115] and hybrid have advantages and disadvantages as presented earlier when estimating RUL in Table 4. Depending on the situation, the suitable SOH estimation method is considered. For example, direct measurement is the least complicated yet, it may not be as accurate as compared to other methods. Model-driven uses equivalent circuit models (ECM) or electrochemical models (EM) to estimate the SOH of a battery [58,114]. They are usually combined with adaptive filter algorithms such as Kalman filter (KF) and extended KF (EKF) presented in Fig. 13 [99]. In comparison, the data-driven method could be used if data from the battery's first life is obtained. They are argued to be more prevalent in academia, where statistical and machine learning approaches are included [58].

7. Challenges of SLB

Currently, implementation of SLB is facing some barriers and challenges. Some of such challenges are predicted to be overcome by some initiatives and policymaking while others are still uncertain. In this section, major challenges of SLB are presented, which some of them related to each other such as:

1. Uncertainty of SLB's economics
2. Lack of automation in battery dismantling
3. Variety of EV Battery's types and chemistries and availability of SLB
4. Difficulty to accurately identify the battery's SOH and RUL
5. Absence of standards and policies
6. Unavailability of first life data

As of now, the concern regarding SLB cost benefits is the most challenging part of the SLB wide implantation. Individuals and industries are not confident if SLBs are cost-effective solutions. As presented earlier, variation in predicting the cost of the SLB is quite significant. SLB may seem attrac-

Table 12 Summary of existing work.

Authors	Country	Battery used	Application	Approaches and Scope of the study
Gohla-Neudecker *et al* [27]	Germany	Li-ion NMC/C batteries	Buffer EV fast-charging integrated into a smart-grid	The study used residual capacity, internal resistance along with geographical climate, user driving profile and mileage to match similar batteries designed for the SLB usage. Further analysis was conducted such as the analysis of SOC, C-rate and cell temperature. The focus of the study was to provide the methodical as well as analytical basis to assess SLB operation and finding an efficient control strategy to maximize the system performance and minimize the battery cell ageing.
Tong *et al.* [32]	United States	LiFePO4 based battery cells	Off-grid photovoltaic EV charging station	Only a measurement of the residual capacity of used batteries to be implemented in the project was carried on. No further assessment mentioned about the batteries prior to the SLB usages. The study was conducted to analyse the plausibility of using EV batteries for the second-life application using simple control methods. It further modified the system using equivalent circuit and tested for other scenarios.
Strickland *et al.* [61]	United Kingdom	NiMH battery pack	1) Frequency response 2) Network deferral 3) Energy management	The aim of the study was to examine the first life usage and collect its data. Once it reaches 80% of its initial capacity, it will be considered for second life applications. Three different applications were considered in the study. Prior to the implementation in SLB application, the used batteries were subjected to Open-Circuit Voltages tests as well as impedance measurement to identify the capability of the batteries to deliver the required power.
Dulout *et al.* [62]	France	Lead-acid batteries	Off-grid small wind turbine	Both residual capacity and internal resistance were used to identify the SOH. Then criteria of selection were set such as the SOH identified earlier along with the voltage level. Selected batteries were sorted according to the variation of internal resistance. The scope of the study was to identify the SOH of SLB using a low-cost methods with reliable results.
Martinez-Laserna *et al.* [29]	Spain	Li-ion NMC/C batteries	1) Residential demand management. 2) Power smoothing plant system	SOH was defined by the combination of residual capacity and internal resistance. Both parameters along with cell surface temperature, current and voltages were monitored in both 1st and 2nd life battery. The scope of this study was to determine the effects associated with li-ion NMC/C battery SOH. The study further investigated the battery ageing history in SLB performance in two different applications.
Casals *et al.* [40]	Spain	Li-ion NMC batteries	1) Fast EVs chargers 2) Self consumption 3) Area regulation 4) Transmission and distribution deferral	The objective of this study was to determine the remaining lifespan of retired EV batteries in four different stationary applications that focus on economic and environmental benefits. This work (Sunbatt Project) used empiric test and simulation to calculate the remaining lifespan of the batteries. They have defined the SOH as a ratio of residual capacity over initial capacity which was tested against time.
Casals *et al.* [68]	Spain	Li-ion batteries excluding NiMH batteries	1) Energy arbitrage 2) Island installations 3) Autonomous use	The LCA of the EVs was defined in this study, with SLB being used in a less-demanding application. Eight different second-life scenarios were presented and the impact on the environment by the EV's battery on the scenarios was determined. The study did not take into consideration on the detailed technical assessment of the used batteries but it focused on the environmental scope while using the simple measurement of residual capacity as a reference for SLB capacity.
Casals *et al.* [69]	Spain	Li-ion NMC batteries	Gas turbine system to provide: 1) Area regulation 2) Frequency regulation	This study aimed to identify the expected lifespan of SLB which are re-used to support gas turbine systems under two working scenarios, where detailed technical assessment of the used batteries prior to usage was not performed. However, during the second life application, factors affecting the calendar and cycling aging such as temperature, SOC, DOD and C-rates were monitored and studied.
Tong *et al.* [117]	United States	LiFePO4 based battery cells	PV integrated in a single house with PHEV charging station	The scope of this work was to investigate the feasibility of a SLB pack in a smart grid-connected PV battery ESS. An empirical test on the SLB had been adopted in this work. Simple residual capacity measurement was carried out along with equivalent circuit based extended Kalman filter used to estimate the SOH of the batteries in the second life application.

(*continued on next page*)

Table 12 (*continued*)

Authors	Country	Battery used	Application	Approaches and Scope of the study
Zhang *et al.* [100]	China	LiFePO4 based battery cells	N.A (Laboratory testing)	The study was conducted to understand the retired EV batteries and their attenuation states. It also investigated the different capacity testing protocols and conducted a comparison of these protocols to achieve a balance between calibration accuracy and test duration time as it is argued that capacity calibration takes longer time than it should, leading to a reduction in effectiveness in analyzing retired batteries. As mentioned in Section 6, the authors used the residual capacity and internal resistance to estimate the SOH. Residual capacity was defined as a ratio of measured capacity after first life over the nominal capacity while current pulse methods were used to determine the internal resistance of the used batteries.

tive from the capital cost investment's point of view. However, they may not be cost-effective in the long run considering their shorter life compared to new LiBs [65]. The cost of re-purposing, including dismantling, assessing, implementing a BMS, and repackaging, might cause the SLB price to be beyond beneficial [43,65]. Furthermore, in the future, SLB implementation could be a challenge as the cost of new LiBs is dropping over the years [16]. If LiBs price drops to the point that it could cost the same as SLB, which is hindered by re-purposing cost, customers would prefer new LiB over SLB if the environmental benefit is overlooked. Another challenge for SLB is the lack of automation of dismantling [43]. The process of dismantling batteries is done manually and requires manpower and a competent person to deal with. Such a process could heavily influence the selling price of SLB.

As presented earlier in Fig. 13, batteries come in different types, shapes, and chemistries; adding a new concern and challenge to the usage of SLB [16,77]. Firstly, the SOH assessment will differ for the different types and chemistries, making the assessment process become more complicated and possibly, adding to the assessment cost. Battery types in this context refer to the battery's structural designs, either cylindrical, prismatic, or pouch. Secondly, availability of SLB of similar types and chemistries. Since they come with different voltage levels, capacities, chemistries, and types, finding similar batteries becomes challenging. It is due to the fact that matching batteries is important for a better second life application performance and longer lifespan. [16,21,116]. Another major challenge is the accurate measurement of a battery's SOH and RUL. In the absence of standards, inconsistency in assessing batteries would be there. Inconsistency in assessing the measuring batteries would discourage investors and SLB users from buying. Lastly, it may not be considered as a challenge but rather an opportunity to simplify the assessment process. If the battery's first life data are stored, it is easier to estimate its SOH and RUL more accurately [16].

8. Summary of existing work

In order to understand the latest advancements and up-to-date state-of-the-art related to the topic, summary of some existing projects that have been discussed in this paper, has been tabled in Table 12. Information related to SLB, including the countries where the project had been carried out, the capacity of the battery, applications, approaches and scope of the study have been presented in the table.

9. Conclusion

Based on the literature presented in this paper, it is concluded that SLB could be used in second life applications with substantial economic and environmental benefits. The economic impact of re-purposing EV batteries could lead to a price reduction in EVs and offer a reasonable price for SLB users. SLB could be utilised in many applications in which, the suitability and lifespan in each would differ. Other factors such as the DOD is found to be heavily influencing the lifespan of SLB. Thus, the right application and suitable DOD are to be considered when implementing SLB.

SLB is a new stream of revenue for products which would have been disposed of anyway. However, there are still some uncertainties of such findings, especially from an economic point of view. Overall, researchers agreed on their benefits yet wonder on the breakeven point at which the price of such new batteries should be sold, compared to new batteries to be more favourably economic. Further studies in different countries are recommended to address such uncertainties.

Furthermore, the environmental impact of using SLB leads to less air pollution and CO_2 emissions when utilised over the new LiBs. When SLB is serving as ESS, the manufacturing process of batteries is eliminated. Among the battery life cycle, manufacturing is the highest contributor to the environmental indicators such as GWP, POFP, PMFP, FEP, MDP and FDP. The use of SLB over new batteries has a positive impact on raw materials, water and electricity, which would be preserved.

Nevertheless, the widespread of SLB is eventually facing some challenges such as the availability of similar SLB characteristics at large scale and difficulty in assessing SLB accurately. However, such challenges could be overcome with the rapid growth of the EV industry, SLB standards, automation of assessment and further economic studies. Examples of such standards are the newly released standard, UL1974 and J2997 by SAE which is still under development.

Although some demonstration projects, laboratory tests and a few commercial ventures exist, most of them were in the context of application-focused on the development of ESSs. However, no conclusive study on the SLB has been done in countries with a tropical climate such as in South-East Asia, where the ambient temperature and humidity differs. The existing literature shows that batteries ageing is greatly affected by different ambient temperatures that vary in different climates/countries. When it comes to automotive in South East Asia, it is one of the world's most dynamic regions. As a result, the EV industry's growth is inevitable, and tons of discarded EV batteries will eventually create a problem if it has not been appropriately taken care of. SLB is an unregulated industry in the region, and further studies and policymaking should be in place.

By identifying such research gaps, it is intended to implement a project in Malaysia to study the second life EV battery for ESSs. This project aims to study the performance analysis and economics of second life EV batteries in ESS as well as utilising SLB for peak shaving application for industry users. The findings will be published in the near future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests nor personal relationships with other people or organizations that could inappropriately influence (bias) the work presented in this paper.

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