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RESEARCH ARTICLE

Second Life EV Batteries: Technical Evaluation, Design Framework, and Case Analysis

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ABSTRACT As the global adoption of Electric Vehicles (EVs) surges, efficient management of retired EV batteries is becoming vital. Second-life Batteries (SLBs), repurposed from retired EV batteries, offer a sustainable energy solution. This paper provides a step-by-step technical assessment, covering battery removal from cars, assessment, and integration into second life applications, focusing on the Nissan Leaf Generation 1. The assessment includes comprehensive testing and presents the results of each test. It outlines the repurposing process, calculating capacity for second life application which was a solar-powered street-light in this experiment. Economic aspects are explored, with a formula for retired battery purchasing price and the repurposing cost related. The paper also examines State of Health (SOH) degradation in the second life application, showing a decline from an initial 49.17% to 44.75% after 100 days and further to 29.25% after 350 days in the second life application. Factors affecting the degradation such as remaining capacity and internal resistance and their inter-relation were investigated. Challenges in SLB implementation are discussed, along with future recommendations. This study underscores the significance of SLBs in promoting sustainable energy systems amid growing EV usage.

INDEX TERMS Second life EV batteries, electric vehicles, lithium-ion batteries, energy storage system, SLB technical assessment.

I. INTRODUCTION

The global transition to renewable energy sources is accelerating rapidly which requires the development of scalable, efficient, and affordable energy storage solutions. EVs that utilize energy storage have been one of the key solutions to reduce air pollution and CO2 emissions [1], [2]. The number of EVs on the road has been increasing significantly every year. For example, in 2022 there were 26 million EV cars on the road with an increase of 60% compared to 2021 according to the International Energy Agency (IEA)'s Global EV Outlook 2023 [3]. At the same time, the rapid growth of EVs is resulting in an increasing stockpile of retired batteries, raising environmental concerns. It is projected that the combined storage capacity of SLB equivalent could approach nearly 1,000 gigawatt-hours by the year 2030 [4].

Such a challenge has turned into an opportunity: repurposing used EV batteries for energy storage applications, commonly known as second-life batteries (SLBs) [5], [6], [7]. In previous work, an extensive literature review has been published about SLBs feasibility in different energy storage systems (ESSs), the environmental and economic impact, and discussions of previous work done in this field [5].

In Summary, Once EV batteries' State of Health (SOH) degrade to about 70-80% of their initial rated capacity, they are recommended to be replaced with new batteries. The necessity of replacing the batteries comes from the fact that the remaining capacity does not provide the enough range that drivers desired. This degradation is expected to happen within 5-7 years of usage [5], [6], [8], [9]. However, it has been found that most available retired batteries are typically found under 60% SOH or even lower, at least in Malaysia. Despite that, batteries with lower SOH could still be utilized in other low-demand applications as second life ESS [10].

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Before being repurposed for second-life applications, these batteries undergo a series of comprehensive stages starting from dismantling, assessment, sorting and grading, selection of application, design, and integration [11], [12], [13].

One of the major motivations of SLB is the environmental impact. One way is bypassing the need for first life battery production which ESS users need for their applications. For instance, obtaining one ton of lithium-ion necessitates mining 250 tons of spodumene ore or 750 tons of mineral-rich brine, as referenced in studies [14], [15]. Such large-scale extraction and processing of raw materials are detrimental to the environment [16]. Furthermore, the water consumption involved in mining activities is substantial. It is estimated that producing one ton of lithium-ion requires 1,900 tons of water [17]. In addition to the reduction of CO2 emissions that are associated with the battery production in general [18]. Lastly, the concern of having huge number of discarded batteries that are not utilizes unless they are sent for recycling. However, recycling batteries with a good remaining SOH is such a waste of resources.

Another driving factor for the adoption of SLB is the economic advantage they offer to various stakeholders, including EV owners, repurposing companies, and ESS users who are key to fostering the growth and widespread utilization of SLBs. ESS users must find the price of SLB more economically favorable for them to consider it as a solution instead of new batteries [5], [7]. There are two main cost considerations when it comes to the repurposing which are the cost of the retired batteries, which is the major contributor to the SLB price [19], [20], [21], [22], and repurposing cost. Therefore, a proper method to calculate the selling price of SLB is needed to ensure such condition is met.

Yet, the SLB industry faces many challenges which will be further presented herein. This paper intends to provide a comprehensive process of the repurposing stages and especially the assessment that many researchers and industries need - found in Section II. In section III, the results of each stage and the final assessment outcome are presented. In section IV, the second life application and its calculation and design consideration are elaborated. In section V, the paper further dives into the cost calculation and its considerations for SLB. In section VI, several observations and further results especially the SOH degradation in the second life application and SOH affecting factors and their co-relation are presented and discussed. It concludes with the challenges that the SLB industry is facing and future recommendations.

II. SLB TECHNICAL ASSESSMENT: METHOD

In this project, a Nissan Leaf 1 (ZE0) 2012 was used. The first step is to dismantle the batteries. Dismantling SLB has been included in this section to enable us to understand the process, time taken, and resources that add to the cost of SLB.

A. BATTERY REMOVAL AND DISMANTLING

The environment of Li-ion battery dismantling is very important to consider. It must be suitable and prevent the outside environment and weather conditions such as rain, snow, and dust and must be preventive from entering other substances. The environment must not cause the intrusion of sweat while working, or cause condensation due to high temperature or humidity. It further must prevent metal powder, grease, and other foreign substances from entering. Countermeasures must be in place if such risk occurs. The floor must be dry, and the workspace must at least be the size of one entire vehicle or bigger. While conducting the dismantling, signs of work in progress must be shown to prevent outsiders from entering. Lastly, standard firefighting equipment must be in place to prevent any fire if it could occur.

Since EVs contain high-voltage batteries, there is the risk of electric shock, electric leakage, or other incidents if these components are not handled properly. Insulated protective gears must be used to prevent electric shocks. The insulated gloves must have at least insulation performance for 1000V/300A. The dismantling must be performed by 2 people. At first, the service plug must be removed to shut off the high-voltage circuits before proceeding further with the dismantling. The components of the battery pack are shown in Figure 1.

While dismantling, insulated equipment must be used in order to ensure that terminals do not touch each other via the equipment used (e.g., screwdriver). Due to the danger of electric shock and fire, careful handling must be taken. If for example, a busbar contacts the wrong terminal, the circuit becomes energized and a short may occur. Once batteries have been removed from the pack, they must be properly labeled with numbers to be identified while testing or later during the operation.

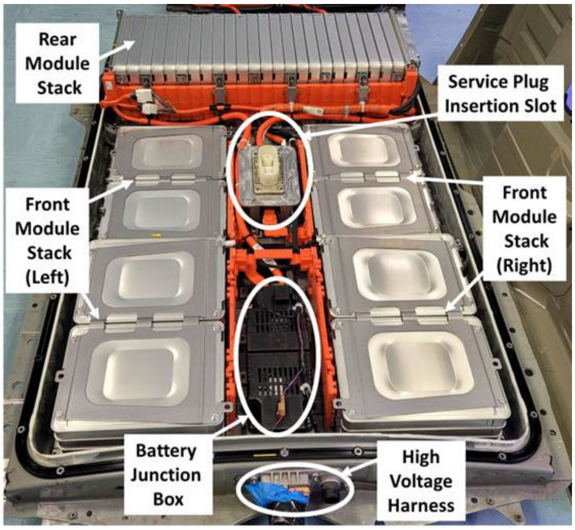

FIGURE 1. Nissan Leaf 1 battery pack components.

For Nissan Leaf 1, each module contains 4 cells, 2 connected in parallel, connected in series with another 2 parallel cells as shown in Figure 2. Terminal 1 is the positive while Terminal 3 is the negative terminal. Terminal 2 is used for the BMS to monitor and control the charging and discharging of internal cells. Terminal 2 is not to be used for any high-current charging or discharging. Table 1 below shows the overall information of the 2012 Nissan Leaf Generation 1 (ZE0).

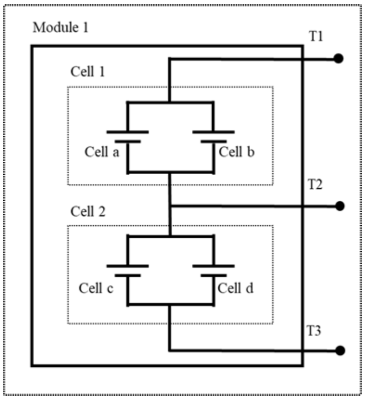

FIGURE 2. Nissan Leaf battery module internal structure.

TABLE 1. General information of 2012 Nissan Leaf Gen. 1 battery pack.

Item	2012 Nissan Leaf Generation 1 (ZE0)
Battery Type	Lithium-ion - Laminate type
Chemistry Used	LiMn2O4 with LiNiO2/Graphite
Pack Weight	294 kg
Pack Dimensions	1570.5 mm × 1188 mm × 264.9 mm
Module Weight	3.75 kg
Modules Total Weight	180 kg (48 × 3.75 kg)
Module Dimensions	320 mm × 225 mm × 36 mm
Pack Total Voltage	364.8 V
Module Voltage	7.6 V
Cell Voltage	3.8 V
Max. Cell Charge Voltage	4.2 V
Min. Cell Charge Voltage	2.5 V
Pack Total Capacity	24 kWh
Module Capacity	65 Ah
Cell Capacity	32.5 Ah
Number of Cells	192
Number of Modules	48 (2P2S)
Cooling	Passive - Sealed Unit

Before repurposing the EV retired batteries, it is crucial to inspect them and assess them to be able to find any malfunction and the remaining capacity which the State of Health (SOH) is based on. In this section, the battery assessment is discussed in detail.

Prior to dismantling, extracting the data from the BMS would be great as it stores the historical data of the batteries and could be helpful in diagnosing the batteries' SOH. Once done, then technical tests are to be carried out. However, before proceeding to any technical test, it is important to visually inspect the batteries for damage or abnormalities. Then the following tests shown in Figure 3 are to be carried out which are based on the available literature on second life EV batteries, manufacturers' manuals, and other standards such as UL 1974 and IEC 61960 [23], [24], [25], [26], [27], [28].

B. OPEN CIRCUIT VOLTAGE (OCV) TEST

One of the most fundamental tests is the OCV measurement. The purpose of the OCV tests is to measure the State of Charge (SOC) of the battery. First, before dismantling the battery pack, the OCV across the entire pack is measured. Then once the module or cells have been dismantled, the OCV of each Module/Cell is measured. If the module contains internal cells that are measurable such as the Nissan Leaf, then these cells' OCV is also measured. The total combined OCV measurement of the cells should match the module's measured OCV and the total combined OCV measurement of the modules must match the measured OCV of the entire battery pack. Any discrepancies must be noted, and faulty cells pinpointed for more testing. Batteries within the acceptable range of OCV that is set by the manufacturer shall pass this assessment. Batteries that have failed to meet the minimum acceptable measurement shall be further examined and eventually discarded to recycling as they are not suitable for SLB. Such a test could be carried out simply using a multimeter.

C. INCOMING HIGH VOLTAGE ISOLATION TEST

The Incoming High Voltage Isolation Test for batteries is an important safety and performance assessment step. It is meant to ensure that terminals within the battery system are adequately isolated from other parts of the accessible external parts that could conduct electricity. This test helps prevent electrical shorts, which can lead to fires or electric shocks. Moreover, it verifies that the battery's insulation is effective and intact, which is vital for the safe operation of the stationary ESS. This test is done between both positive and negative terminals and any touchable metal components, as shown in Figure 4. After applying a 500 VDC for at least 60 seconds, insulation resistance should be a minimum of 100 Ω/V for DC circuits and 500 Ω/V (or 50,000 Ω) for AC or combined circuits. Batteries failing these criteria are discarded. Such a test could be carried out using the Megger tester.

D. CAPACITY TEST

The battery's capacity shall be tested to determine the remaining capacity that is usable for the second life application. The battery is charged according to the manufacturer's guidelines at room temperature until it's fully charged with a 0.2 C rate. After charging, it is left to rest in room conditions and a full charge for 1 to 2 hours. After this, the battery is discharged using the 0.2 C rate until it's fully drained. The capacity at the end of this discharge is to be recorded. The discharge battery's capacity is calculated using recorded current and time data. This is often auto-computed by some measuring devices such as PowerLab, Arbin Battery Tester, Chroma Battery Tester, and many others. This data is then compared with the manufacturer's original or received battery

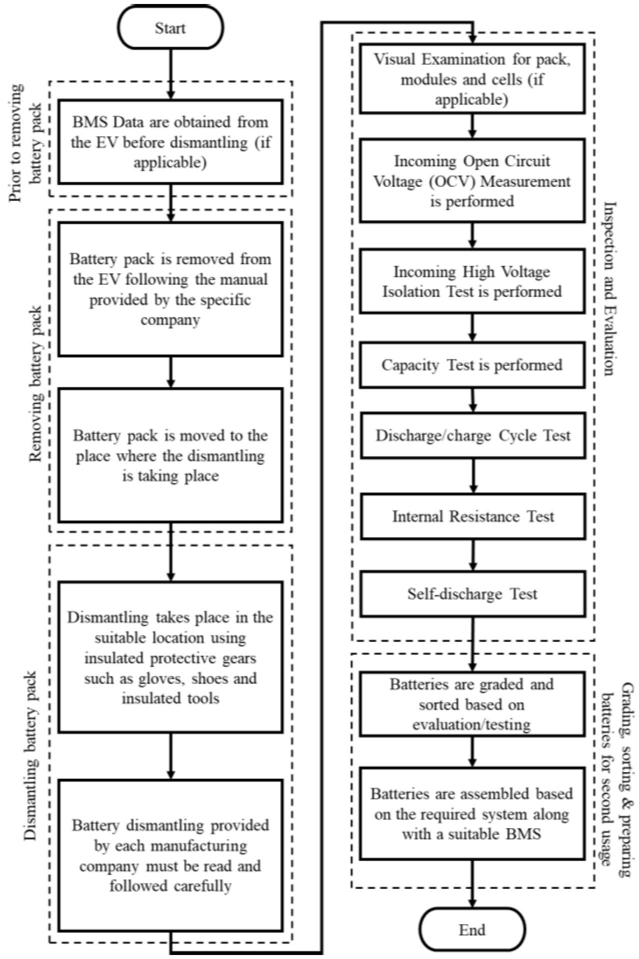

FIGURE 3. Second life EV batteries assessment guide.

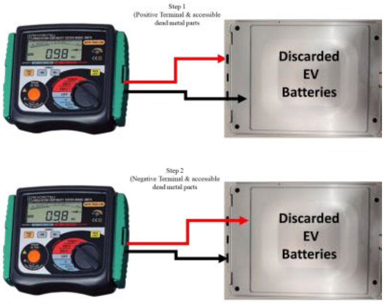

FIGURE 4. Incoming high voltage isolation check.

capacity data. Batteries that pass the test are grouped based on their available capacity.

As for the maximum charge voltage and minimum discharge voltage, they vary depending on the type of battery. For such information, it must be referred to the EV manufacturer. In many cases for Lithium-ion batteries, the minimum voltage is 2.5V and the maximum voltage is 4.2V. As for module testing which is the case for this experiment (Nissan Leaf 1), since the batteries are arranged in a 2P2S configuration, the maximum voltage would be 8.4V, and the minimum voltage would be 5V. At first, since the voltage is neither at maximum nor minimum voltage, the battery/module/cell is fully charged to maximum voltage. Then the battery is to rest for 1 to 2 hours before fully discharging the battery to minimum voltage as shown in Figure 5. Lastly, the battery is fully charged to maximum voltage. It is worth noting that the last step of fully charging the battery is not necessarily a part of the capacity test method, but it is helpful for the next step which is the full discharge/charge cycle test.

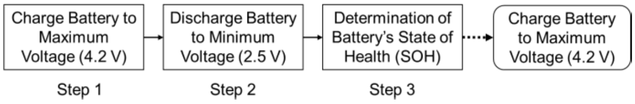

FIGURE 5. Charging and discharge steps for capacity measurement.

Once the test is completed, the SOH related to the remaining capacity is calculated. In a direct measurement, the SOH concerning capacity is defined in (1) as the ratio of the measured capacity during the assessment, Q_m to the battery's nominal capacity when it was new, Q_n.

$$\mathrm{SOH}[\%] = (Q_m/Q_n) \times 100 \tag{1}$$

E. DISCHARGE/CHARGE CYCLE TEST

Batteries are tested by discharging and charging them at least once at room temperature and the temperature, voltage, and current of their cells and modules are closely monitored. This is important to monitor any irregularities while charging and discharging. It is further recommended to discharge the batteries at the maximum expected condition when placed into the second life application. For example, if the batteries are expected to be discharged at 20A in the second life application which is higher than 0.2C for the Nissan Leaf module, then the batteries are to be discharged in that manner. However, if the maximum discharging current is lower than 0.2C which has already been tested in the capacity test, this step is no longer needed which was the case for the solar-powered streetlight. If any battery experiences an abnormality, especially in temperature, they are to be further examined and eventually discarded if deemed so.

F. INTERNAL RESISTANCE TEST

Internal resistance (IR) test must be conducted on the whole battery pack if it is meant to be used as a whole or on the individual modules or cells. According to the available literature, there are many ways of conducting the internal resistance test such as Alternating Current (AC) methods, EIS and thermal loss methods, Current steps method: Current-off, Current steps method: Switching Current, and others [29]. A common method for measuring internal resistance involves sending current pulses through the battery. By observing the resulting voltage drop across the battery and using Ohm's law, the resistance is determined [29], [30]. Using the current-off technique, the internal resistance is gauged by determining the voltage variation relative to the current when toggling between discharge and charge modes, allowing for a brief pause between measurements. On the other hand, the current switching technique measures the internal resistance by assessing the voltage shift in relation to the current when transitioning from discharge to charge mode at maximum amplitude. Both techniques are depicted in Figure 6.

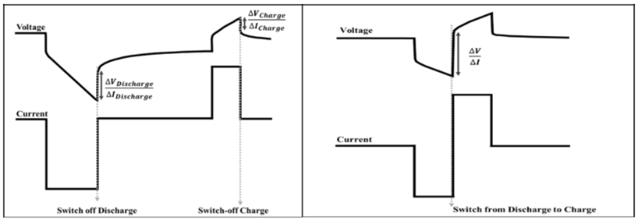

FIGURE 6. **Current steps method: current-off (a) & Current steps method: Switching current (b) [5].**

The battery is charged until it's fully charged. After charging, it remains in this state for 1- 2 hours under a room temperature of 20 C° ± 5 C° in accordance with IEC 61960-2003. Following this, the battery is discharged at a constant current rate until its capacity reaches 80% to 90% SOC when the internal resistance test is performed. While authors such as in [31] conducted the internal resistance test after the battery was charged up to 50% SOC and rested for 2 hours. Many well-known devices are used to determine the internal resistance such as Chroma Battery tester that utilizes IEC 61960-2003 regulation in determining the internal resistance. The battery is discharged at a constant current I_1 of 0.2C. After 10 seconds of discharging the voltage is recorded as U_1. Then the discharge current is increased to 1C and would be indicated as I_2 and the corresponding voltage (U_2) is recorded after 1 second. The internal resistance is calculated as follows:

$$R_{dc} = \Delta U/\Delta I = (U_2 - U_1)/(I_2 - I_1)\Omega \tag{2}$$

For a more accurate measurement of the I_R and to reduce disturbances from electrochemical and concentration polarizations, some testers present an improved method such Arbin Battery tester which produces 10 pulses of an enhanced shape. In this refined I_R method, data points are collected at P_2 after T_1 and at P_3 just before the current increases, as depicted in Figure 7. An average is taken over these ten pulses as shown in (3).

$$I_R = \text{Avg.}[(\text{Voltage at } P_2 - \text{Voltage at } P_3)/2(I_{IR})]\Omega \tag{3}$$

Any battery with abnormal internal resistance is discarded. Unfortunately, all EV manufacturers do not provide the initial value of internal resistance when the batteries are new. Therefore, identifying the internal resistance increment percentage is not possible. As a result, only batteries with abnormal internal resistance are discarded and the battery SOH will depend on the remaining capacity as the major indicator of SOH.

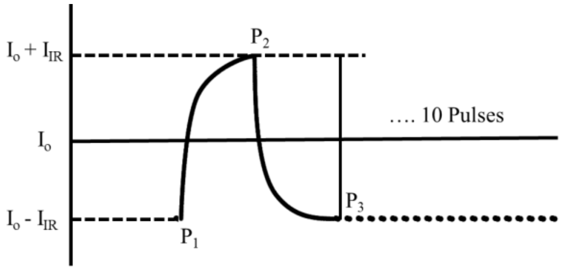

FIGURE 7. **Internal resistance test with 10 pulses.**

G. SELF-DISCHARGE TEST

The self-discharge test is to be conducted on the cells and modules that are intended for second life application. If the entire pack is to be used as a whole, then the battery pack should also be subjected to the test. Batteries are charged fully up to their maximum voltage and then stored at room temperature 20 C° ± 5 C° for a minimum of one day. The Open Circuit Voltage (OCV) of these charged batteries is recorded at intervals of 5-10 minutes, 1-2 hours, and 24 hours post-charging, and after any longer storage duration or at more frequent intervals if mentioned by the manufacturer. Batteries that exhibit a self-discharge rate exceeding the manufacturer's guidelines (if any) are to be discarded. The remaining batteries, which pass this assessment, will continue to the next processing stage.

III. TECHNICAL ASSESSMENT: RESULTS

In this section, the results of the testing described in the previous section are presented.

A. OPEN CIRCUIT VOLTAGE (OCV) TEST

Once the battery back was removed from the car, the OCV across the main terminals was measured. After dismantling the pack into modules, each module was measured as a module and each module contained 2P2S cells, counted as two cells. Each cell of the module was measured as well as shown in Figure 8.

The sum of the two cells was compared to the measurement of the module to spot any abnormal differences. No differences were observed when comparing the sum of the two cells of each module and the actual measurement of the module. The highest difference recorded was 0.75%, which is considered normal. The sum of all modules (summed as 378.38V) was compared with the total OCV of the pack which was measured as 378.32V. Therefore, all the modules have passed the OCV measurement assessment.

B. INCOMING HIGH VOLTAGE ISOLATION TEST

The isolation test was done using the Megger tester and all measurements were found to be above 200M ohm (maximum amount by device) which indicates that the batteries are well isolated.

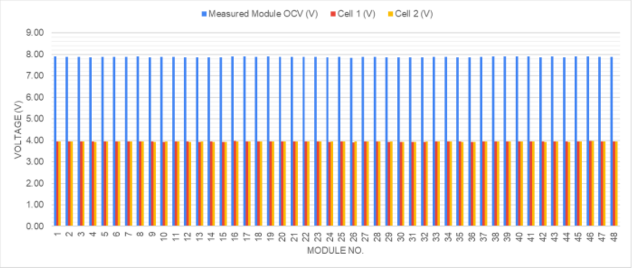

FIGURE 8. OCV measurement for modules and cells.

C. CAPACITY TEST

The capacity test was carried out as described in the methodology. Modules were first fully charged until 8.4V and then rested for 1 hour before fully discharging to the minimum voltage of 5V at a constant current of 0.2 C which would be 13A for the case of Nissan Leaf Module of 65 Ah. The constant current is simply calculated by multiplying the module-rated capacity by 0.2, resulting in 13A. For different batteries with different capacities (Ah), the 0.2 C would be different. The data in Figure 9 show the measurement of capacity for all the modules. The remaining capacity percentage (%) is calculated using (1) by dividing the measured capacity by the rated capacity. The overall average was found to be 31.48 Ah which represents 48.43% SOH. The maximum capacity found was 32.99 Ah which represents 50.76% SOH while the lowest capacity found among all 48 modules was 29.54 Ah which represents 45.45%.

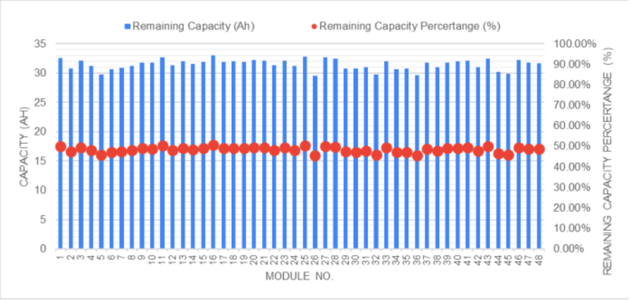

FIGURE 9. Capacity test measurements.

D. INTERNAL RESISTANCE TEST

All EV manufacturers do not provide the initial value for the internal resistance test which makes it hard to identify how much the internal resistance has increased during the first life of an EV battery. Nevertheless, the internal resistance test must be carried out to spot any abnormalities in the batteries. As for this experiment, batteries were fully charged with a 0.2 C rate (13A) and rested for 1 hour. Then the batteries were discharged at the same current rate until 90% SOC. The internal resistance measurement was then performed using Arbin Battery Tester as described in Figure 7 and equation (3). Figure 10 shows the results obtained for all the modules.

If the initial value of the internal resistance is known, then the internal resistance test becomes more relevant as it can indicate that the battery is near its end of life if increased significantly. Batteries with high internal resistance negatively affect the power delivery compared to those with lower internal resistance which consequently impact the system performance. Lastly, batteries with high internal resistance could lead to heat generation during charging or discharging. Excessive heat can result in thermal runaway, a dangerous situation where the battery can catch fire or explode.

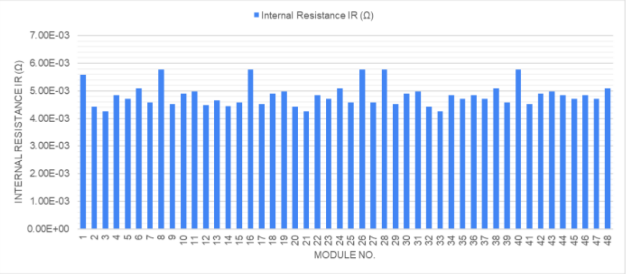

FIGURE 10. Internal resistance measurement.

E. SELF-DISCHARGE TEST

Self-discharge tests are important as the self-discharge rate is an indicator of the battery's overall health and quality. An unusually high self-discharge rate might suggest defects or damage to the battery. Furthermore, it is helpful to understand batteries self-discharge when dealing with batteries in certain applications that are expected to sustain long periods without being charged/discharged. This helps in predicting how long the battery will last in its operational environment. As for this experiment, the batteries were fully charged with a constant current of 0.2 C (13A). Once they were fully charged, they were put at rest for a full day. OCV test was conducted 3 times, one after 5 minutes, another after 1 hour, and lastly after 24 hours. The OCV was recorded for each module and both cells of each module as well. Figure 11 shows the self-discharge test for each module. No significant drop in voltage was observed nor were there any major differences between the two cells of each module.

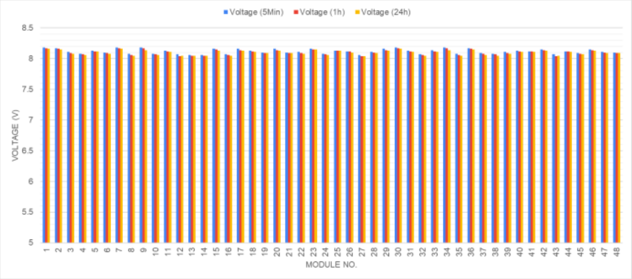

FIGURE 11. Self-discharge measurement.

F. ASSESSMENT OUTCOME

The assessment was done with the above-mentioned tests and all modules have successfully passed the assessment. The average SOH for all modules was found to be 31.48 Ah which represents 48.43% SOH. Ideally, Second Life EV Batteries are best when utilized while having 70-80% SOH. However, at 48.43% SOH, these batteries are still of good value when repurposed. Such batteries with lower SOH could be suitable for low-demand applications.

No abnormalities were observed when testing for OCV, insulation test, capacity test, charge/discharge cycle test, internal resistance test, and self-discharge test. However, differences were observed when testing for capacity test and internal resistance. Therefore, these batteries are grouped based on similarities in remaining capacity and internal resistance. Grouping batteries based on similarities in remaining capacity and internal resistance is essential for optimal performance and safety. They discharge and recharge at consistent rates, ensuring no battery is overworked which leads to enhanced safety and prolonged battery life.

Beyond the technical assessment discussed herein, additional testing and diagnostic procedures, particularly focusing on chemical degradation and its assessment [32] and fault diagnosis [33] are recommended.

IV. SECOND LIFE EV BATTERIES DESIGN

The first thing to consider for EV SLB is the application that will be used in. In previous work [4], [6], the suitability of SLB for different applications was discussed and are summarized in Figure 12.

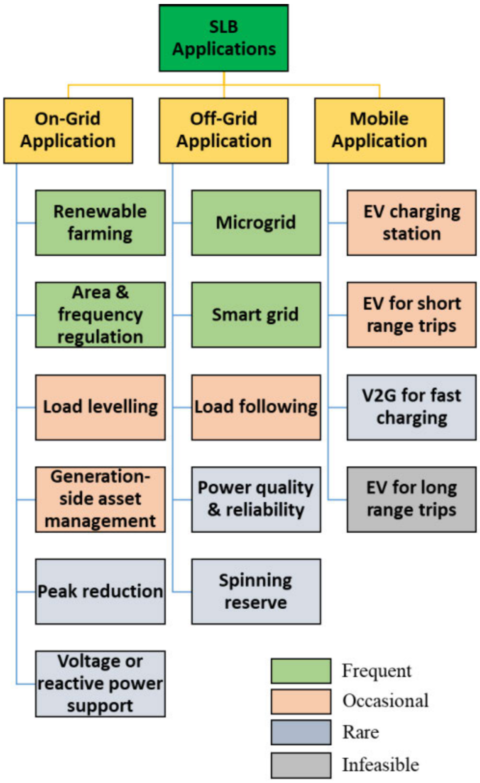

FIGURE 12. SLB suitability for different applications [5].

As for batteries with an average of 48.43% SOH, they could be used in low-demand applications such as Energy Storage Systems (ESS) for different applications that do not require high discharge current. An example of such an application would be solar solar-powered streetlight with ESS. Therefore, this application was chosen to run the experiment and observe the system performance and degradation over time.

The system consists of a solar panel rated at 300 W, a controller, and Maximum Power Point Tracking (MPPT), a streetlight rated at 120 W, and batteries that are designed to hold energy for 2.5 days to accommodate for the variability in weather and the potential absence of sunlight on certain days. Figure 13 presents the overall system.

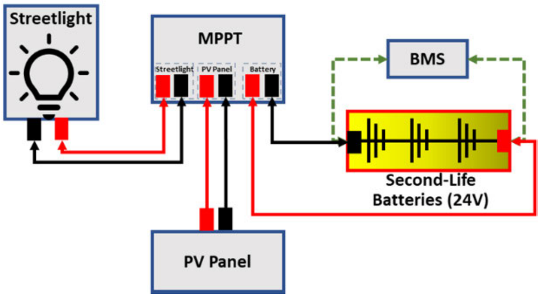

FIGURE 13. Overall system - solar-powered streetlight with ESS.

Once the power rating of the streetlight is identified, it is proceeded to battery sizing. The steps and calculations are shown as follows:

- Streetlight power rating: 120 W
- Required hours of operation daily: 12 h
- Required no. of days of storage: 2.5 days

$$\begin{aligned}\text{Battery Size} &= \text{Power Required} \times \text{Hours per Day Required}\\ &\quad \times \text{No. of Days Required} = 120\text{ W} \times 12\text{ h}\\ &\quad \times 2.5 = 3,600\text{ Wh} \qquad (4)\end{aligned}$$

It must be noted that sometimes the Depth of Discharge (DOD) is taken into account when calculating the battery size for any application. For example, if the desired DOD is 50%, then the battery size would double and become 7200 Wh. Smaller DOD results in an extended battery life as discussed in many past works [13], [34], [35], [36], [37], [38], [39], [40], [41].

$$\begin{aligned}\text{SLB required} &= (\text{Battery Size})/(\text{Rated Capacity}\\ &\quad \times \text{Nominal Voltage} \times \text{SOH}*)\\ &= (3600\text{Wh})/(65\text{Ah} \times 7.6\text{V} \times 0.4917)\\ &= 14.82\text{Modules} \approx 15\text{Modules} \qquad (5)\end{aligned}$$

∗ *This is SOH % is the average of the 15 modules used which is slightly different from the overall average.*

∗∗ *This method of calculation applies to any energy storage application.*

Since lithium-ion batteries are being used, they must be coupled with a Battery Management System (BMS). Proper BMS can help to maximize the battery's lifespan. This includes monitoring and managing the battery's SOC, temperature, and cell balance. There are several types of BMSs in the market. Some come as very basic BMS that help to control the balancing while other advanced options are available. Depending on the application and budget limits, different BMS are recommended. For this application, DALY BMS was used. Such BMS could help to balance the cells and show the readings and measurements on an application at a reasonable cost of nearly USD 40. In its other version, it has an extra feature of sending the data online. The importance of safety considerations in Second Life applications cannot be overstated and must be prioritized, especially in larger systems. For substantial installations, integrating a comprehensive fire-fighting system is essential. In this experiment, considering the specific location and budget constraints, a sensor and alarm are used to alert the security personnel nearby, taking advantage of the streetlight's proximity to the security office.

The arrangement of batteries in either series or/and parallel configuration depends on the system's requirements in terms of voltage, current, and power. For this system, the voltage is required to be around 24V. Therefore 3 modules are connected in series making nearly 24V. The rest of the batteries are connected in parallel to make up the system desired of 3,600 Wh. The connection diagram of the batteries (5 series × 3 parallel) and BMS is shown in Figure 14 below along with the actual implementation.

Once the system was designed, it was put into the site where it is installed in Selangor, Malaysia which is a tropical country with hot and humid weather. The batteries were placed inside an enclosure with water and dust resistance as shown in Figure 14 while Figure 15 shows the system on site while operating.

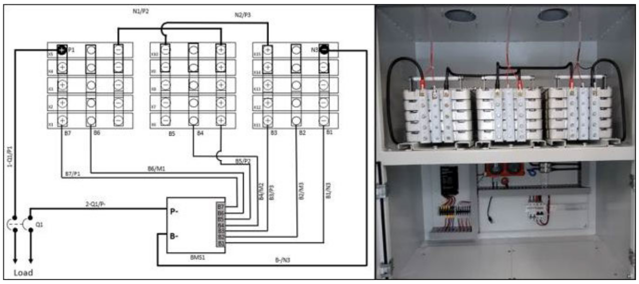

FIGURE 14. SLB connection diagram with BMS (a) & actual implantation of SLB (b).

V. SLB TECHNICAL ASSESSMENT: COST ASSOCIATED

The price of EV SLB depends on various factors such as the battery's SOH, its remaining capacity, age, the specific chemistry and design of the battery, and market demand. The SOH, which represents the remaining capacity of a battery relative to its original capacity, is a crucial metric and so far, has been the major contributor to deciding the SOH. In some regions, there might be incentives or subsidies available for repurposing or recycling batteries, which can also affect prices. Additionally, the availability of SLB affects the price as well. SLB prices in countries with huge numbers of retired batteries such as China, the US, Germany, South Korea, and Japan might be cheaper compared to countries that rarely have or have fewer EVs like Malaysia. The reason is that most manufacturers ship back the batteries once they have been removed from the EV and replaced with new ones from different countries to the country of manufacturing. Interestingly, it was found that the selling price of EVs already includes the cost of shipping the retired batteries once replaced. If such batteries are utilized as SLB in the same country without shipping, this will help to reduce the selling price of the EV.

FIGURE 15. System installed onSite.

However, a generalized estimation could be derived from the cost of new Lithium-ion batteries ranging around USD 150. To further understand what goes into the buying price of the SLB, the following formula (6) is derived.

$$C_{SLB-Buying} = C_{new} \times F_{SOH} \times (1 - F_{lifespan}) \times (1 - F_{discount}) + F_{incentive} \tag{6}$$

where as:

- $\mathbf{C_{new}}$: The buying cost of new lithium-ion batteries (Per kWh). The price of new batteries is taken into consideration as such batteries become competitive to SLB given the continuous price drop of new batteries over the years.
- $\mathbf{F_{SOH}}$: The measured SOH percentage (%).
- $\mathbf{F_{lifespan}}$: Factor for lifespan (%). Since the battery's SOH degradation is not linear and SOH degrades faster as the SOH drops, a lifespan is considered. Therefore, it is important to know how long the battery has been used before repurposing. For that, a 3% to 5% drop per year of usage is considered. Therefore, if the battery has been used for 7 years with an average of 4% drop every year, then it becomes (1 – 0.28 = 0.72).
- $\mathbf{F_{discount}}$: A discount factor that is considered when buying the retired batteries. It could be based on the physical condition of the batteries, or any other reason or special condition deemed needed. This also includes the risk factors associated with second usage and the

possibility of malfunction. In addition, there will be a cost for repurposing and the retired batteries buying price should allow those repurposing companies to make profits. A 10% to 20% is used to account for all these factors or as deemed suitable.

- **$F_{incentive}$**: If the government is providing incentives to the SLB users, this should also partially benefit the sellers of the retired batteries. If no incentives are provided which is the case in most countries as of now, this factor shall not be considered.

For example, if a battery pack with an average of 70% SOH and has been used for 5 years and considering the new price for lithium-ion is USD 150 and $F_{discount}$ of 15% while not considering $F_{incentive}$, then the buying price per kWh is calculated as follows:

$$\begin{aligned} C_{SLB-Buying} &= \text{USD}150 \times 0.7 \times (1 - 0.04 \times 5) \times (1 - 0.15) \\ &= \text{USD}71.4/\text{kWh} \end{aligned} \tag{7}$$

Table 2 below shows the ranges of SLB SOH and the estimated price per kWh for each range along with suitable systems. The price presented in the table is only for the batteries excluding additional charges that are associated with repurposing such as labor, administration, facilities, and additional equipment which will be further discussed.

TABLE 2. SLB estimated price per kWh.

SOH Level	Remarks	Price per kWh
High SOH (80%-100%)	• Such batteries have much of their original capacity left. Therefore, they are more valuable. • They are suitable for energy storage applications, backup power, or even repurposing for lighter EVs like electric bicycles or scooters.	\$80 to \$140 per kWh
Medium SOH (60%-79%)	• Such batteries still have a substantial capacity left, but might not be suitable for high-demand applications. • They can be used in stationary energy storage applications, such as solar energy storage or grid stabilization.	\$55 to \$100 per kWh
Low SOH (40%-59%)	• Such batteries have limited capacity, making them suitable for low-demand applications or as a supplementary energy source. • Might be used in smaller off-grid projects or in applications where weight or size isn't an issue, but energy storage is required.	\$20 to \$60 per kWh
Very Low SOH (<40%)	• These batteries might not have a useful second life in terms of energy storage and might be closer to the end of their life. • Potential applications might be limited to very basic or short-term energy storage needs. • Batteries with less than 20% SOH are considered to have hit the end of their life. They are recommended to be sent for recycling.	\$10 to \$30 per kWh

To understand more about SLB economics, one must understand the other costs associated with SLB, especially at the repurposing stage. Table 3 details the different categories of possible expenditure when repurposing SLB. The table below does not include the standard costs that any company would need such as the office/space rental, admin, utilities, and others. To avoid confusion, the list could be worth considering if an established company intends to incorporate SLB repurposing into its existing operations.

TABLE 3. Cost associated with SLB Repurposing.

Category	Remarks
Battery Dismantling / Collection	• Labor for disassembly from vehicles. • Transportation costs (trucks, fuel, drivers, forklifts) from collection points to repurposing facilities. • Packaging and safety precautions during transport.
Testing and Sorting	• Equipment costs for battery testers and diagnostic tools to determine the remaining capacity, internal resistance, and SOH of the battery, module, or cell. • Labor for the testing and sorting process. • Software or databases for recording and analyzing the results.
Safety and Environmental Precautions:	• Safety equipment and personal protective equipment (PPE) for workers handling batteries. • Infrastructure for fire safety and spill containment. • Environmental costs for disposing of unusable or hazardous components safely.
Rental Costs	• Rent for storage space, especially if requiring climate-controlled conditions. • Rent or purchase of equipment if not owned outright.
Repackaging for Second-Life Application	• Materials for new casings or enclosures (especially if deploying as stationary storage solutions). • Labor for repackaging and system integration. • New BMS or other electronic systems to manage the SLB.
Transportation and Installation	• Transportation cost from the repurposing facilities to the site. • Labor for system installation. • Consumables of electrical parts such as wires and connectors.
Certifications and Approvals	• Cost for getting the repurposed batteries or systems certified (e.g., safety standards). • Possible costs associated with inspections or approvals from local or national authorities.
Warranty and After-Sales Support	• Potential costs related to warranty claims and maintenance. • Costs for maintaining a support team or helpdesk.
End-of-Life Disposal	• After the second life, batteries may need to be recycled or disposed of, incurring additional costs

Estimating the cost associated with repurposing second-life batteries (SLB) is a complex endeavor that requires its dedicated study. Many factors contribute to the overall cost of

SLB repurposing, including labor costs, rental expenses, and other variables that can vary significantly from one country to another. The efficiency with which a company can provide the necessary resources is another influential factor. Additionally, the cost is influenced by the advanced features and quantity of assessment equipment used. The sophistication and quantity of equipment directly impact the efficiency and speed of the assessment process. For instance, in the case of the Nissan Leaf 1, it required approximately 83 individual hours for dismantling, assessment, and repackaging, as demonstrated in Table 4. This assessment was conducted using a battery tester equipped with 4 separate channels, but if more channels were available, the assessment time would be substantially reduced. It is important to note that this entire process was conducted manually, without any automation. The introduction of automation would not only further reduce the required time but also save costs.

TABLE 4. Dismantling time required for Nissan Leaf Gen. 1 battery pack.

Item	No. of Workers Needed	Hours required	Total Individual hours
Battery removal from EV	2	1 hour	2 hours
Modules Removal from Battery Pack	2	3 hours	6 hours
Full Battery Assessment (Nissan Leaf 2012)	1	70 hours	70 hours
Battery Arrangement and Repacking (Assuming Full Pack)	1	5 hours	5 hours
TOTAL			83 hours

It has been observed that many studies underestimate the time required to perform the assessment which questions the method of assessment. To perform the assessment, at least one cycle of charging and discharging should take place with a constant current of 0.2 C as discussed earlier. To perform a full cycle with such a current rate will require time depending on the remaining capacity. The higher the remaining capacity, the longer time is needed. For example, when conducting a complete cycle test, involving both charging and discharging, on a Nissan Leaf 1 module with 50% remaining capacity and a charge/discharge current of 0.2C (equivalent to 13A for a 65 Ah module), the process would take approximately 5 hours to complete. It is important to note that these batteries undergo a specific sequence: they are initially charged, then fully discharged, and finally fully charged during the testing procedure. Therefore, the time required must be taken into account.

Once the repurposing cost is determined, then the selling price of the SLB for the second life application can be calculated. The selling price of the SLB would normally include but not limited to, the selling price of the SLB, $C_{SLB-Buying}$, the repurposing cost, $C_{Repurposing}$, which will include all the applicable categories, and lastly a profit percentage, $F_{Profits}$, as shown in equation (8).

$$C_{SLB-Selling} = C_{SLB-Buying} + C_{Repurposing} + F_{Profits} \quad (8)$$

In conclusion, the pricing strategy for SLB must ensure that they remain more affordable than new batteries, taking into account the SOH and the residual lifespan. For example, if an ESS requires 50 kWh capacity and the available SLB is found at 80% SOH, the equivalent necessary capacity of SLB would be 50 kWh divided by 0.8, amounting to 62.5 kWh. Therefore, the cost for 62.5 kWh worth of SLB (at 80% SOH) should be less than the cost for 50 kWh of new batteries, considering that SLBs are expected to have a faster degradation rate.

VI. OBSERVATIONS AND DISCUSSIONS

In this section, various interesting observations and results are discussed.

A. CAPACITY MEASUREMENT VS C RATE (DISCHARGE CURRENT)

As stated in the capacity testing, a standard C rate must be used to determine the SOH. A test was conducted on an SLB sample to observe the measured capacity with different C rates and their effect on capacity measurement. Figure 16 shows the different C rates conducted and their respective results on the same battery sample. This affirms the importance of standardizing the assessment and specifically the C Rate used for capacity measurement.

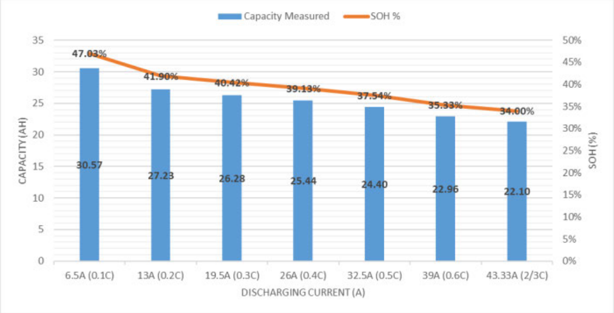

FIGURE 16. Capacity test at different C Rates.

B. CAPACITY DEGRADATION & INTERNAL RESISTANCE RELATION

Another interesting observation was the relation between the SOH degradation with respect to remaining capacity and the internal resistance. Going back to the literature on batteries, the degradation happens in two forms. The first is the capacity fade and the second is the power fade caused by the increasing internal resistance over time. Therefore, over time, the batteries' capacity will drop, and the internal resistance will increase. However, these two are not necessarily proportional as found in this experiment and shown in Figure 17. For example, module no. 16 had the highest remaining capacity, yet it had one of the highest measurements for internal resistance.

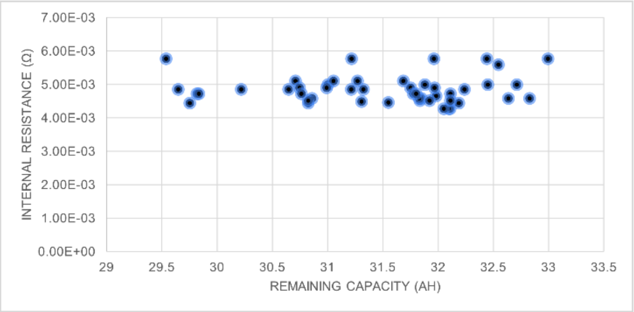

FIGURE 17. Capacity vs internal resistance.

C. SLB SOH DEGRADATION IN SECOND LIFE APPLICATION

After the batteries were placed into the second life application which was the solar streetlight, the batteries were re-assessed after 100 days of operation. Figure 18 shows the initial remaining capacity, the new remaining capacity (after 100 days of operation), and the drop in capacity in each module after 100 days of operation with respect to the initial value measured. The results indicate that not all batteries will degrade at the same rate and not necessarily batteries with higher remaining capacity will degrade slower or even faster than those batteries with lower remaining capacity as shown in the figure. It is to be noted that the module number used here is different from the numbering used in the initial testing.

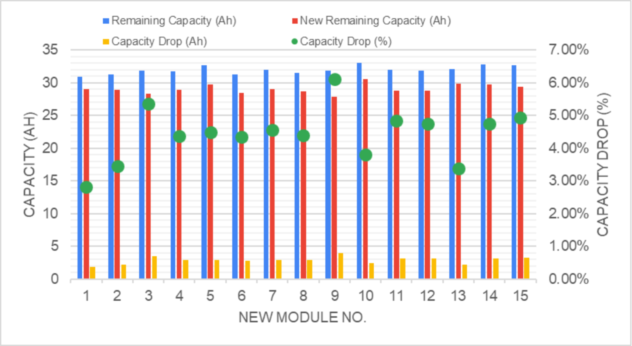

FIGURE 18. SLB Re-assessment after 100 days of operation.

Furthermore, the relation between the capacity degradation and internal resistance was investigated again after 100 days of operation. The results show no proportional relation between the capacity degradation and initial internal resistance as shown in Figure 19. The overall results point out that the degradation rate depends on other factors of which might be chemical and not necessarily proportionally related to the remaining capacity or the internal resistance.

The average SOH with respect to the remaining capacity after 100 days was found to be 44.75% with a drop percentage of 4.43%. The batteries were tested again after 150 days, 250 days, and 350 days of operation respectively and the SOH was recorded accordingly as shown in Figure 20 (50-100 days interval). It must be remembered that these batteries were placed in a hot and humid location under the direct sun which expose them to higher temperature, ranging from 30 C° to 38 C°, which affects the degradation as further discussed in the next sub-section.

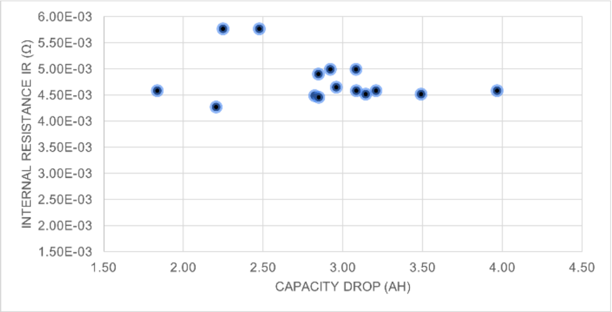

FIGURE 19. Capacity drop (after 100 days) vs initial internal resistance.

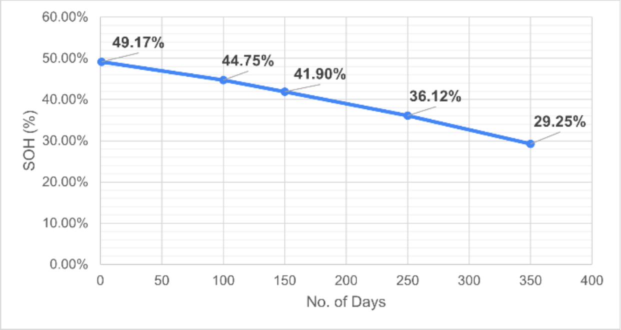

FIGURE 20. SLB SOH degradation over time.

Another factor that could have contributed to the fast battery degradation in such application is the unstable and varying charging voltage and current of the solar panel.

D. SLB SOH DEGRADATION AND TEMPERATURE RELATION

To investigate the effect of temperature on the batteries' SOH degradation, a system with a similar pattern was designed and operated inside a laboratory that is air-conditioned. The batteries used had an average SOH of 47.10% when placed into the system. A test was supposed to be carried out after 100 days of operation. Due to some circumstances, the test was performed after 112 days only and not 100 days.

It was observed that the average SOH drop after 112 days was around only 2.71% mainly because of lower temperature in the air-conditioned lab (20-25C°) compared to streetlight under the sun (30-38 C°) which the batteries had a 4.43% SOH drop after 100 days of operations. The results indicate that higher temperature results in faster degradation for the batteries. Therefore, consideration of temperature must be taken into account when designing the system.

E. SLB CHALLENGES

While conducting this research and exploring the field of SLB, many challenges have been faced and found and in this sub-section, some of these challenges are briefly discussed.

Table 5 below describes the aspects and the challenges and concerns related.

TABLE 5. SLB challenges and concerns.

Aspect	Challenge / Concern
Availability	The availability of retired EV batteries is not proportional to the number of EVs in many countries such as Malaysia. This is a result of shipping back the retired batteries to the manufacturer which are generally in limited countries.
Variability	Second-life batteries have varying degrees of capacity loss, internal resistance, and degradation, requiring careful selection and management for specific applications. Furthermore, the batteries come with different chemistries, sizes, and other different characteristics that make it challenging to combine.
Safety Concerns	Dealing with lithium-ion batteries carries the risk of fires as many incidents happened. These batteries shall be subjected to the proper testing before repurposing. Furthermore, addressing issues related to thermal management, internal shorts, and fire risks is a must to ensure the safety and reliability of SLB.
Chemical Degradation	As seen in the results, the degradation has many factors of which is chemical degradation. Most of the existing testing and assessments are mainly focused on capacity testing and internal resistance. Changes in electrode materials and electrolytes impact capacity and impedance and thus require advanced analytical methods for diagnosis, especially from the chemical part of it.
Lack of Standards	As of now, the SLB lacks the proper and standardized assessment. There have not been efforts made by internationally recognized bodies to make a standard for SLB except for Underwriters Laboratories (UL) and their UL 1974 standard titled “Safety Evaluation for Repurposing Batteries”. The standards should cover the whole process of SLB from removing from the car to the second life application, in terms of assessment methods and safety.
Regulations and Policies	Regulatory frameworks need to be established or adapted to address the unique challenges and opportunities presented by SLB. The regulation starts from the first life to the second life and lastly to the end-of-life. The regulation could include adapting standards concerning the assessment and safety of SLB and developing clear end-of-life criteria that consider economic feasibility, balancing the benefits of continued use with the potential for repurposing or disposal for recycling.
Absence of Government Support / Incentive	Failure to address the accumulated unused retired batteries could result in significant environmental harm. Therefore, it is crucial for governments to provide support and incentives that promote the use of SLBs, making them a more financially appealing option.
Lack of Automation and Rapid Assessment	The lack of automation and rapid assessment for SLBs can impede their widespread adoption, increase costs, and reduce efficiency. Implementing automation and efficient evaluation processes is critical to maximize the economic benefit of repurposing these batteries.

VII. CONCLUSION

SLBs are a great environmental and economical option for ESS. SLBs can be used for stationary ESS, storing excess renewable energy and providing backup power when needed. Repurposing battery modules or cells offers more flexibility, as these units can be replaced and matched more efficiently for stationary energy storage compared to using the whole battery pack as it is.

Proper assessment is to be carried out and suitable applications are to be determined. It is highly important to select the appropriate application for SLB as the application’s suitability varies based on the intended use. For example, applications demanding high charge/discharge current and those subjecting batteries to high temperatures should be avoided. Research indicates that high temperatures and high charge/discharge rates have an adverse impact on the batteries’ SOH as demonstrated in the results.

From an economical point of view, SLBs are arguably more cost-effective than new batteries for certain applications, as their reduced capacity is still suitable for many stationary energy storage needs. At the same time, the SLB market growth will further help other stakeholders such as the EV owners that benefit from buying EVs at cheaper prices given that the manufacturer will not have to ship back the retired batteries once replaced. In addition, the EV owners can sell their retired EV batteries for second-life applications, thus recouping part of their initial investment in the EV. SLB market growth will also help to establish companies taking take care of the assessment and repurposing, thus creating more jobs, and expanding the industry.

However, the confidence in the good economic value of SLB is not yet certain for some potential users due to the deregulation of SLB. The price of SLB could significantly vary depending on the availability of retired batteries in that region/country. However, the EV market is expanding and thus, the availability of SLB is expected to increase, leading to a growing market for repurposed batteries.

On the hand and as of now, no incentives nor support are provided by the governments to encourage the growth of this industry which has a huge impact on the environment. Thus, the regulators and governments should step in to contribute to the growth of this industry to make the SLB more economically favorable option.

From an environmental point of view, repurposing SLB reduces the environmental impact associated with battery disposal, by extending their useful life. Furthermore, reusing batteries conserves raw materials and reduces the need for mining and manufacturing new batteries. Lastly, utilizing second-life batteries for ESS helps lower greenhouse gas emissions by integrating more renewable energy.

In terms future technological advances, ongoing research is needed to develop more efficient ways of assessing, refurbishing, and integrating second-life batteries to maximize their potential. For example, advanced AI-driven algorithms could improve SOH prediction accuracy. Moreover, Enhanced diagnostic techniques, such as X-ray imaging and electrochemical impedance spectroscopy, would provide deeper insights into battery SOH. Lastly, developing methods to recycle and recover valuable materials from retired SLB will help to contribute to a circular economy for battery materials.

Overall, the utilization of second-life EV batteries presents a promising avenue for sustainable energy storage, offering environmental benefits and economic opportunities given that some technical and regulatory challenges are being addressed.

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