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A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies

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ABSTRACT The number of used batteries is increasing in quantity as time passes by, and this amount is to expand drastically, as electric vehicles are getting increasingly popular. Proper disposal of the spent batteries has always been a concern, but it has also been discovered that these batteries often retain enough energy perfectly suited for other uses, which can extend the batteries' operational lifetime into a second one. Such use of batteries has been termed as the "second-life," and it is high time to adopt such usage in large scale to properly exploit the energy and economics that went into battery production and reduce the environmental impacts of battery waste ending up in landfills. This paper aids in that quest by providing a complete picture of the current state of the second-life battery (SLB) technology by reviewing all the prominent work done in this field previously. The second-life background, manufacturing process of energy storage systems using the SLBs, applications, and impacts of this technology, required business strategies and policies, and current barriers of this technology along with potential solutions are discussed in detail in this paper to act as a major stepping stone for future research in this ever-expanding field.

INDEX TERMS Second life battery, battery energy storage system, electric vehicle, battery management system, disposal, battery aging, economic and environmental values, recycling and waste management.

NOMENCLATURE

A. ABBREVIATIONS

SLB	Second-life battery
EV	Electric vehicles
ESS	Energy storage system
USABC	US Advanced Battery Consortium
DOD	Depth of discharge
PHEV	Plug-in hybrid electric vehicles
ICE	Internal combustion engine
SLBESS	Second life battery energy storage system
NiMH	Nickel metal hybrid
HEV	Hybrid electric vehicles
PV	Photovoltaic
SOH	State of health
SOC	State of charge
PNGV	Partnership for a New Generation of Vehicles
DP	Dual polarization
SEI	Solid electrolyte interphase
OCV	Open circuit voltage
IPIT	Impedance parameter identification test
HPPC	Hybrid pulse power characterization test
BMS	Battery management system
PPE	Personal protective equipment

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OSHA	Occupational safety and health administration
NFPA	National fire protection association
BESS	Battery energy storage system
DSM	Demand Side Management
RES	Renewable energy sources
RE	Renewable energy
TN	Tram network
MIPC	Multiport interleaved power converter
V2G	Vehicle-to-grid
PECV	Pure electric commercial vehicle
EIS	Electrochemical impedance spectroscopy
OEM	Original equipment manufacturers
EU	European Union
NA	North America
PEPC	Pure electric passenger car
PECV	Pure electric commercial vehicles

B. SYMBOLS

I_L	Load current
R_e	End resistor
R_t	Terminal resistance
R_c	Resistance of the capacitor
U_b	Determines the SOC
C_b	Chemical energy storage capacity of battery
C_c	Surface effects
R_{Th}	Thevenin equivalent resistance
C_{Th}	Thevenin equivalent capacitance
U_{oc}	Open circuit voltage
R_o	Battery resistance
U_L	Battery terminal Voltage
U_{Th}	Thevenin equivalent voltage
R_{pa}	Effective resistance for electrochemical polarization
R_{pc}	Effective resistance for concentration polarization
C_{pa}	Electrochemical polarization capacitance
C_{pc}	Concentration polarization capacitance
R_{int}	Internal resistance
$R_{self-discharge}$	Resistance for self-discharging
A(T)	Reaction rate evolution with respect to the temperature
$(\frac{i}{i_0})$	Electrochemical reaction rate
ΔV	Over-potential
Q_{loss}	Capacity fade
A_h	Depth of discharge
C_{PN}	Capacitance of the PNGV model
U_{PN}	Voltage across C_{PN}
U_{pa}	Voltage across C_{pa}
U_{pc}	Voltage across C_{pc}

I. INTRODUCTION

With the ever-increasing use of batteries, the concern about handling them after they have served their useful life is becoming more and more prominent [1]. Modern battery chemistries such as lithium-ion cells are yet to have truly efficient recycling facilities; and a huge amount of discarded batteries end up in landfills without any recycling at all. In face of such a situation, the idea of employing this enormous army of retired batteries for a second useful life after the first one is gaining momentum. The term generally employed for such batteries is ''second-life battery (SLB)'', and electric vehicles (EV) are currently being regarded as the primary source of these. This is partly because of the current expansion of EV adoption (which will result in a lot of old batteries once their use in EV is over), and partly because retired EV batteries retain almost 80% of their original capacity – which, though not useful for traction use, can serve perfectly for other energy storage system (ESS) applications: such as in the utility sector. The end of EV battery life is defined by the US Advanced Battery Consortium (USABC) as a 20% drop of cell capacity from the rated value, or a 20% drop from rated power density at 80% depth of discharge (DOD) [2], [3]. This definition defined the narrative in most of the literature [4]–[8]. However, though the retirement of EV batteries with around 80% energy capacity is the narration stated in many literatures, Saxena *et al.* opposed this popular belief in [9]. Their simulation study that worked on a vehicle modeled after the Nissan Leaf showed that the driving needs of American drivers could be met with battery capacity as low as 30%. Wood *et al.* also posited that the USABC threshold of 80% is less significant for plug-in hybrid electric vehicles (PHEV), where an internal combustion engine (ICE) is present to share the load with the electric drivetrain; thus enabling the batteries to degrade to 80% of rated capacity and still be able to continue traction service [4]. Nevertheless, battery degradation mechanisms were not considered in this study, and the mentioned work was also a simulation rather than physical test. Therefore, even though it provides an interesting insight in the scope of enhancing useful battery lifetime in EVs, there remains the need for more substantial studies to accurately define the retiring period of these batteries. This also indicates the vast space left in this field of study to explore. Moreover, psychological factors such as ''range anxiety'' [10] can also be a prominent factor behind the discarding of EV batteries when they lose 20% of initial capacity. The prominence of EV batteries for second-life use will become apparent as this paper progresses due to the fact that most of the literature reviewed in the process of constructing this review considered augmented use of retired EV batteries. And as the first generation of retired EV batteries are starting to enter the market to join up with the existing ones generated from consumer electronics, this is the ideal time to summarize the existing works in this area to aid in future research – for which there is a vast area to explore.

The use of batteries after they have reached the end of their useful life is termed as ''second-life'', and this term is used throughout this paper to mention batteries that are to be used after their first intended lifetime is over. To delve into this area of study, there is the necessity to discuss the current second-life battery (SLB) scenario to properly demonstrate the current state of this field. Using SLBs to create viable

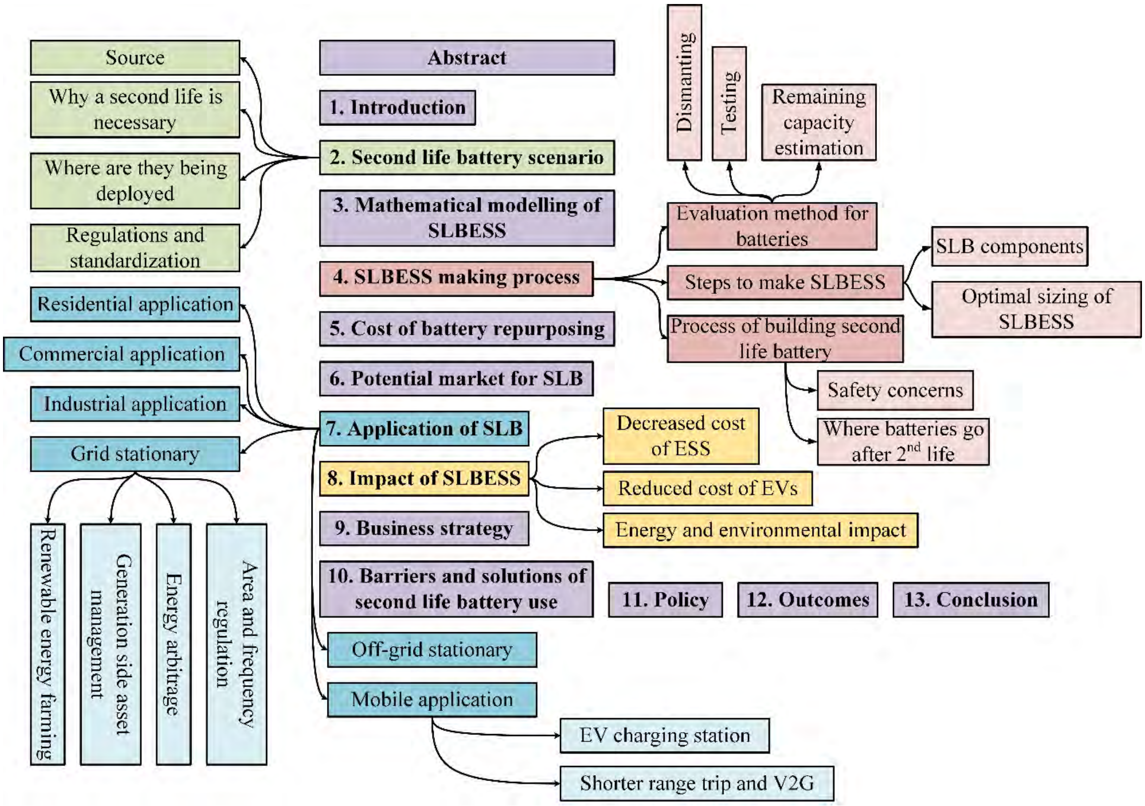


FIGURE 1. Flow of information in this paper. Each aspect of second-life batteries are discussed in gradual progression.

products demands significant discussion as well, and the associated cost and safety concerns need to be emphasized. The proper disposal of batteries after the end of second-life must also be considered so that it can be done in a way that is most beneficial to the environment and economy. The sectors where SLBs can be employed must be discussed in detail to show the wide area this technology can serve, and how that impacts in terms of energy, economy, and environmental concerns. The business strategies and policies to sustain SLB businesses also require attention, and the present barriers to such initiatives and their potential solutions also require delineation. This paper's contribution is to carry out all these tasks to present a complete picture of the SLB landscape, and to suggest ways of action in various sectors. The information flow in this paper is shown in Fig. 1.

The rest of the paper is organized as follows. Section 2 presents the SLB background. Section 3 shows the modeling techniques of SLBs. Section 4 discusses the manufacturing process of SLB energy storage systems (SLBESS) in detail along with related cost and safety concerns. The corresponding cost related to battery repurposing is discussed in section 5. Potential markets for SLBs and their applications are presented in section 6 and 7 respectively. The impact of second life battery energy storage system (SLBESS) for ESS, EVs, and environment are discussed in section 8. The business strategies for SLBs are discussed in section 9. Different impediments in implementing SLBs and their possible solutions are presented in section 10. Different policies and regulations regarding batteries, SLBs, and EVs are discussed in section 11. Major findings of this paper is summarized in section 12. Finally, the conclusions are drawn in section 13.

II. SECOND-LIFE BATTERY SCENARIO

A. SOURCE

The use of batteries has been ubiquitous for a long time because of consumer electronics. Cellphone and laptop batteries, when discarded, raised the concern for a possible second use, as the recycling facilities were inadequate. Though recycling of lead-acid (Pb-acid) batteries is comparative mature, the currently dominant lithium-ion (Li-ion) technology does not share this privilege. However, the use of Li-ion is increasing without any sign of declining, and in high-capacity applications such as electric vehicles, their use is only to proliferate. This can be easily perceived from the increase in EV sales over the past years, demonstrated in Fig. 2. Richa *et al.* categorized second-life EV batteries into two primary types: type 1 being those that reach the end of their first life through the general process of capacity loss, and type 2 - whose vehicles' service life ends before the batteries reach the end of first life [11]. These EV batteries, along with the ones from consumer electronics, are providing the provisions for

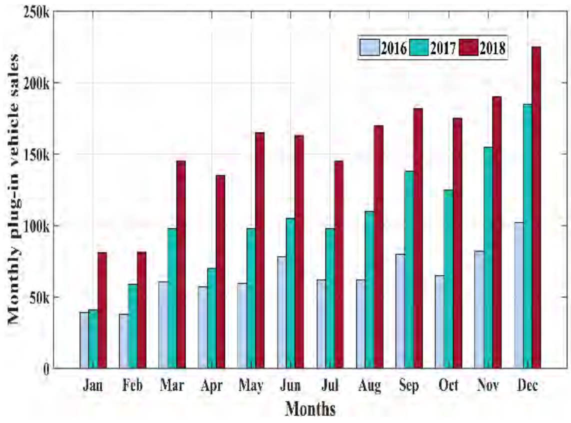


FIGURE 2. Electric vehicle sales over the past years was ever-increasing, which translates into the increase of Li-ion batteries in the market [20].

second-life use. Skarvelis-Kazakos *et al.* estimated that by the year of 2030, even considering massive recession, around 3.6 GWh will be available from second-life EV batteries; for the best-case scenario, they calculated it to be around 17.6 GWh [12]. According to Neubauer *et al.*, the worst-case scenario will be 5 GWh, and according to their speculation, it will reach 32.3 GWh by 2063; and if the conditions are the best-favoured, it will be 1010 GWh [13]. Sathre *et al.*'s base-case assumption marks the amount of energy served by SLBs after 2050 as 15 TWh [14]. However disparate these assumptions may be, it cannot be denied that SLBs will become a major energy-source in the coming years, and it is imperative to use them in the best possible way. Generally, it is conceived that when the primary use of the batteries is over, then they can be employed for second-life usage. The duration of the first-life can be determined by the expected lifetimes declared by the device manufacturers; for example, most mainstream EV manufacturers now provide a warranty of 8 years for their battery packs [15]–[18]. The capacity of different EV batteries available in the market is shown in Table 1 [19]. Calculating the average capacity of available EV batteries in the market form Table 1 (34. 21 KWh), determining the number of EV batteries of 2018 from Fig. 1 (165,410), and considering the second life of a battery starts when its DOD is 80% of its original capacity, it can be calculated that around 4526.94 MWh will be available from second-life batteries by 2026. Venkatapathy *et al.* tried to figure out which factors contribute in deciding the end of first-life of such traction batteries, and the point in these batteries lifetime when they enter the second-life. According to their study, cost, environment, and aging are these factors – while cost is the most prominent one (which indicates the lower cost of second-life batteries as compared to new ones) [21]. Their evaluation model showing the construction of these factors is showed in Fig. 3.

B. WHY A SECOND LIFE IS NECESSARY

Discarding the energy potential of SLBs as waste will be a huge mistake both economically and environmentally. The amount of work hours and financial investments that went into these batteries will not be used to their full capacity, while dumping the batteries directly in landfills will pose serious threats to the environment. The materials used in Li-ion batteries are not cheap, and their prices have increased significantly over the past years as the demand sky-rocketed. Retiring these batteries after only the first use thus spells into economic waste, especially when a second life can add so much value to the use of the batteries. Fig. 4 shows a sample case of the different stages of EV battery usage, including the second life – which extends the battery usage before the end-of-life stage comes to terminate the use of

TABLE 1. List of available batteries in the market and their corresponding capacity [19].

EV make	Battery	Range km (mi)	Wh/km (mi)	Energy cost/km (mi)
BMW i3	22kWh	135km (85)	165 (260)	$0.033 ($0.052)
GM Spark	21kWh	120km (75)	175 (280)	$0.035 ($0.056
Fiat 500e	24kWh	135km (85)	180 (290)	$0.036 ($0.058)
Honda Fit	20kWh	112km (70)	180 (290)	$0.036 ($0.058)
Nissan Leaf	30kWh	160km (100)	190 (300)	$0.038 ($0.06)
Mitsubishi MiEV	16kWh	85km (55)	190 (300)	$0.038 ($0.06)
Ford Focus	23kWh	110km (75)	200 (320)	$0.04 ($0.066)
Smart ED	16.5kWh	90km (55)	200 (320)	$0.04 ($0.066)
Mercedes B	28kWh	136km (85)	205 (330)	$0.04 ($0.066)
Tesla S 60	60kWh	275km (170)	220 (350)	$0.044 ($0.07)
Tesla S 85	90kWh	360km (225)	240 (380)	$0.048 ($0.076)
Chevy Bolt	60kWh	383km (238)	255 (411)	$0.031 ($0.05)

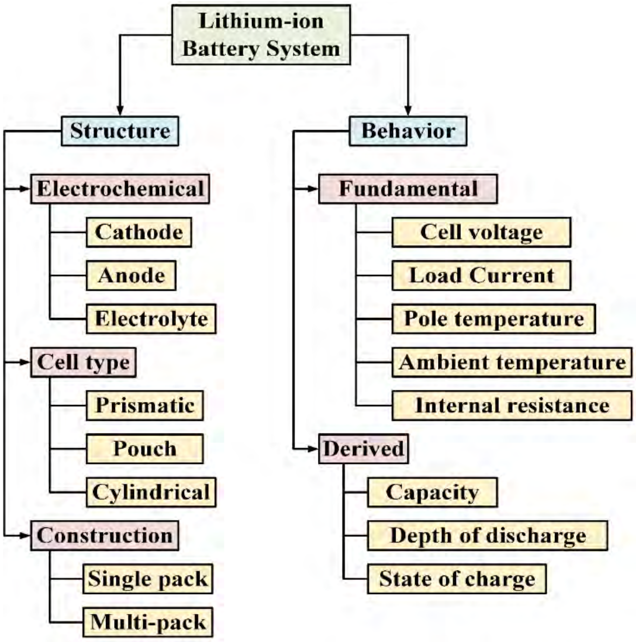


FIGURE 3. Evaluation model of batteries entering their second life [21]: both structural and operational integrity need to be tested for determining validity.

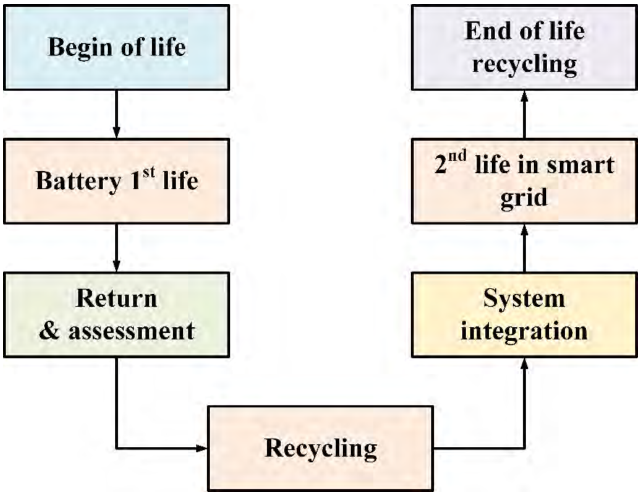


FIGURE 4. Visualization of EV second life battery use (adapted from [23]). The battery useful life is extended through a second use in smart grid and finally recycled.

the battery. Richa *et al.* conducted a comprehensive study to determine the amount of valuable material generated from used EV batteries that can end up as wastes considering extreme and baseline scenarios in [11], and according to their study, 3.4 million kg of Li-ion EV battery cells can enter the waste-stream by 2040 even by baseline assumptions. These battery cells will contain some materials that do not hold any recycle value currently (such as graphite), and some materials that require a lot of energy to be acquired from their natural sources and are thus valuable (such as lithium, nickel, aluminum, and cobalt). Straight-up recycling after the first-life also presents the issues of being not viable because of issues such as complexity, and producing little material at a much higher cost than new material. According to [22], lithium batteries only contain lithium of 2-7% of their total weight, and obtaining them through recycling is five times more expensive than obtaining new lithium from natural sources. The only material worth recycling can be cobalt, but battery technologies are trying to be developed which reduce or omit the use of this material by more stable and cheaper substances – posing a possibility of future batteries not having any cobalt to recycle [22]. A second-life thus can help in better usage of economic resources, and unnecessary pollution of environment from materials that are of no use after recycling [11]. As used batteries are now being generated more than ever, proper investigation and employment of second-life batteries are now more important than ever. To visualize the amount of power that remains in a used EV battery, and a probable application of that, a 24 kWh Nissan Leaf battery can be considered. At the end of its traction use it will retain 80% of its initial energy, which translates into 19.2 kWh, which, considering 80% depth of discharge (DOD), will provide about 15 kWh. This can cater low C-rate applications for years [24]. According to [25], 548 GWh of battery capacity from used EV batteries is going to be available in the world by 2028, around 240 GWh of which will be at China.

C. WHERE THEY ARE BEING DEPLOYED CURRENTLY

Though the discussions of second-life battery mostly reside in the conceptual realm, some notable projects have already been carried out to validate them in real-life. Most of such projects encountered during this study are research projects rather than commercial ones, which indicate that second-life battery systems are in mere infancy currently. The University of California, Davis employed a second-life energy storage system, sourced from Nissan Leaf EVs, in their "RMI Winery Microgrid Project" [26]. Research projects on second-life battery were also conducted at the Rochester Institute of Technology [27], and the University of California, San Diego [28]. Research and development (R&D) projects are also conducted by industrial entities. These efforts include a collaborative work between BMW, Vattenfall, and Bosch, which constructed a 2 MW, 2800 kWh second-life battery energy storage system (SLBESS) at Hamburg, Germany for grid support. The batteries used here were collected from more than a hundred vehicles [29], [30]. A somewhat similar, albeit much smaller prototype was demonstrated by ABB and General Motors (GM) back in 2013, which employed used batteries from the Chevrolet Volt EV hybrid EV to build a 25 kW, 25 kWh energy storage system at San Francisco, California, USA [31]. As of 2016 in Germany, other than the above-mentioned BMW project, Daimler had pilot projects going on at Hannover (15 MWh) and Lünen (13 MWh), while Volkswagen had one in Berlin (10 kWh) [32]. Nissan switched to commercial SLBESS in 2015, following its previous pilot projects [33], [34], and most recently it has undertaken stand-alone solar lighting projects using second-life batteries from the Leaf EVs [35]. In 2015, Toyota built a stand-alone 85 kWh SLBESS using 208 used nickel metal hybrid (NiMH) batteries from their Camry hybrid EVs (HEV) at the Lamar Buffalo Ranch at the Yellowstone National Park, USA. This storage system supported a 40 kW photovoltaic (PV) system. This system made use of the existing EV battery casings with just the battery connections changed, and features tolerance to entire system shutdown in case of a single battery pack failure as well as easy replacement of packs by hand [36]. Along with these projects, [37] listed some other collaborative projects that included efforts from Renault at the UK, and from Mitsubishi at Paris. Notable second-life battery projects are listed in Table 2. On a different front, individuals are also constructing SLBESSs built from used consumer electronics batteries such as laptops batteries. Their systems are primarily employed at homes to store energy generated from home solar systems, and are claimed to have capacities as high as 40 kWh, surpassing even the commercially available residential energy storage systems such as the Tesla Powerwall [38], [39].

D. REGULATIONS AND STANDARDIZATIONS FOR SLB

As second-life battery usage is still to become mainstream, it currently does not have any governing standards. Even the EV industry is yet to standardize a lot of its components universally, such as charging technologies. There are

TABLE 2. Notable second-life battery projects [37].

Joint Ventures	Description	Location
Daimler GETEC/ the mobility house remondis / EnBW	Battery storage unit with a total capacity of 13 MWh using degraded EV batteries from Daimler EV models	Luenen, Germany
BMW/PG&E	18-month pilot project to demonstrate EV smart charging and optimization grid efficiency with participation of 100 BMW i3 owners	San Francisco, USA
Nissan Sumitoto (4R Energy)/Green charge network	System (600 kWh/400 kWh): 16 Nissan Leaf LIBs regulate energy from a solar plant	Osaka, Japan
BMW/Vattenfall/Bosch	2,600 battery modules from 100 electric cars, and provides 2MW of output and 2.8 MWh of capacity	Hamburg, Germany
Renault/Connected Energy Ltd	"E-STOR": on-grid providing energy storage that prevents power grid overload and balances supply and demand	United Kingdom, Europe
Mitsubishi/PSA EDF/ Forsee Power/ MMC	Bi-directional battery energy consumption optimization from retired batteries	Paris, France
General Motors/ ABB	5 Chevrolet Volt LIBs, 74 kW solar array & two 2 kW wind turbines to power a General Motors office building site	USA

a number of cell chemistries and types adopted by different manufacturers, due to the absence of any cell standard. Mixing and matching of these chemistries and cell architectures make second-life applications challenging [24]. It can be safe to assume that standards governing the second-life battery technology may take quite some time to materialize. One standard for battery reuse that is currently being developed is the SAE J2997, which states battery state-of-health (SoH), labeling, and transportation as the evaluating criteria for determining the safety of reuse [40]. The inception of such standards will of course depend on the market penetration rate of this technology, and it is sure to be governed by the dominant system in existence. Considering these, Nissan may play an important role when this standardization phase begins, as it has already demonstrated significant second-life battery commitment. Therefore, at this stage, it is only possible to speculate what kinds of standards may arise to regulate this sector in future. In [22], standardization of vehicle control system, communication interfaces, and base voltage for battery units are identified as requirements to proliferate a battery second-use market. Though these are stated to be vehicle standards, the batteries conforming to them will bear their influence during the second use, and thus create some standards. Currently available standards for automotive Li-ion batteries, such as ISO 12405-2:2012 [41] and IEC 62660-2 [42], can prove effective to construct the new standards for second-life batteries. Nonetheless, safety can be assumed to be a major concern in standards, as it must be ensured for proper operation of batteries in the second life.

III. SLBESS MODELING

The primary way of modeling a battery is to create an equivalent circuit with parameters that represent the internal voltage, internal and lead resistances, and cell capacitances. The governing equations of a battery model must reflect its relations with temperature, state of health (SOH), state of charge (SOC), and current flow, while replicating the non-linear behavior of the battery. Relation of a battery to these factors depends on the cell-chemistry, and thus need to be determined by experimentation on that cell-type. An aged battery shows the signs of degradation by gradual loss in reserve capacity, and increase in internal resistance, which further reduces the terminal voltage [43]. Modeling of a second-life battery thus requires determining how the battery parameters change in value, and which are the factors that affect these changes.

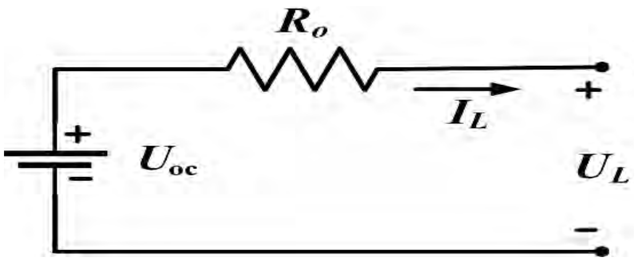


FIGURE 5. Equivalent circuit of battery according to the Rint model. It is a simplistic one with a resistance connected in series to a voltage source.

For general battery modeling, various equivalent circuits have been presented previously, which are discussed in [44]. The simplest of them is the Rint model, as shown in Fig. 5 [44]. U_{oc} is the open circuit voltage, U_L the terminal voltage, R_o is the battery resistance, and I_L is the load current - which flows to the terminals while discharging. The terminal voltage is expressed as:

$$U_L = U_{oc} - I_L R_o \qquad (1)$$

The RC model, as the name suggests, is completely constructed by resistors and capacitors (Fig. 6) [44]. C_b represents the batteries chemical energy storage capacity, and C_c stands for the surface effects. R_e is termed the end resistor, R_t represents the terminal resistance, and R_c represents the resistance of the capacitor. U_L is the terminal voltage.

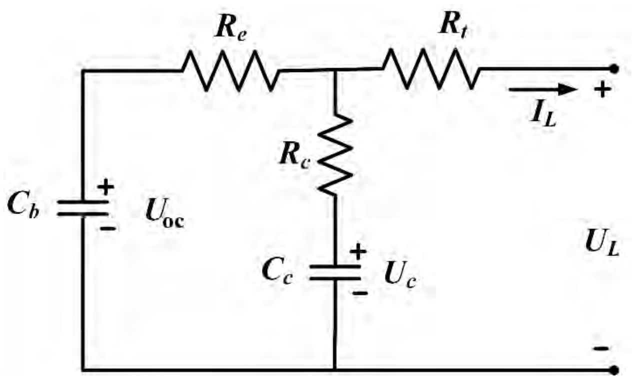


FIGURE 6. Equivalent circuit of battery according to the RC model. Resistances are added in series and parallel with two sources for detailed representation of a battery system.

U_b determines the SOC. Equations of this circuit are [44]:

$$\begin{bmatrix} \dot{U}_b \\ \dot{U}_c \end{bmatrix} = \begin{bmatrix} \frac{-1}{C_b(R_e+R_c)} & \frac{1}{C_b(R_e+R_c)} \\ \frac{1}{C_c(R_e+R_c)} & \frac{-1}{C_c(R_e+R_c)} \end{bmatrix} \begin{bmatrix} U_b \\ U_c \end{bmatrix} + \begin{bmatrix} \frac{-R_c}{C_b(R_e+R_c)} \\ \frac{-R_e}{C_c(R_e+R_c)} \end{bmatrix} [I_L] \tag{2}$$

$$[U_L] = \begin{bmatrix} \frac{R_c}{(R_e+R_c)} & \frac{R_e}{(R_e+R_c)} \end{bmatrix} \begin{bmatrix} U_b \\ U_c \end{bmatrix} + \begin{bmatrix} -R_t - \frac{R_c R_e}{(R_e+R_c)} \end{bmatrix} [I_L] \tag{3}$$

The Thevenin equivalent model introduces a polarizing resistance R_{Th} in parallel with an equivalent capacitance C_{Th} (Fig. 7), this capacitor accounts for the transient characteristics observed during charge-discharge. U_{oc} is the open circuit voltage, U_{Th} is the Thevenin equivalent voltage, R_o is the internal resistance, and U_L is the battery terminal voltage [44]. The voltage equations are:

$$\begin{cases} \dot{U}_{Th} = -\frac{U_{Th}}{R_{Th}C_{Th}} + \frac{I_L}{C_{Th}} \\ U_L = U_{oc} - U_{Th} - I_L R_o \end{cases} \tag{4}$$

The Partnership for a New Generation of Vehicles (PNGV) [45] model adds an additional series capacitor to the Thevenin model shown in Fig. 7 to produce the circuit shown in Fig. 8. This added capacitor helps to explain changes in the open circuit voltage when load current accumulates [44]. Equation (5) expresses the PNGV circuit behavior. Here, C_{PN} is the capacitance of the PNGV model. U_{PN} is the voltage across the capacitance C_{PN}.

$$\begin{cases} \dot{U}_d = U_{oc} I_L \\ \dot{U}_{PN} = -\frac{U_{PN}}{R_{Th}C_{PN}} + \frac{I_L}{C_{PN}} \\ U_L = U_{oc} - U_d - U_{PN} - I_L R_o \end{cases} \tag{5}$$

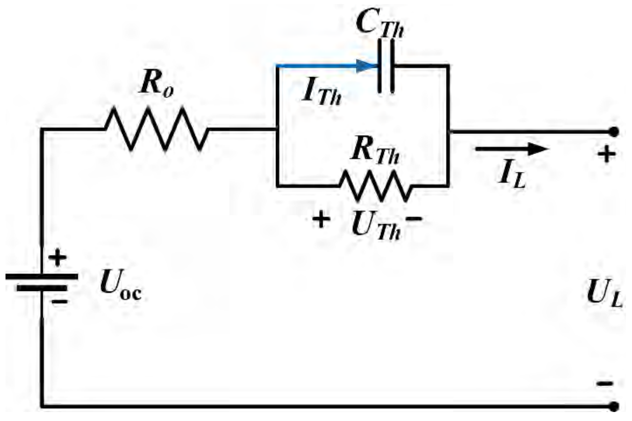


FIGURE 7. Equivalent circuit of battery according to the Thevenin model. An RC parallel circuit is added with the basic Rint model.

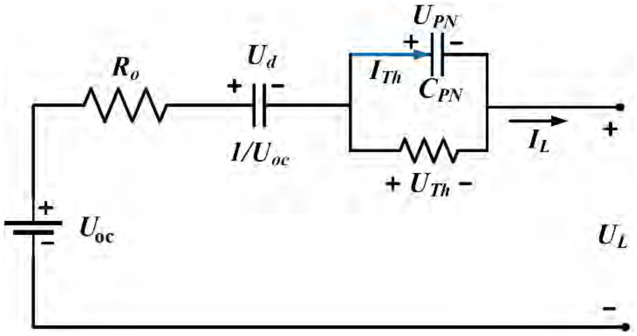


FIGURE 8. Equivalent circuit of battery according to Partnership for a New Generation of Vehicles (PNGV) model. A capacitor is added in addition to the Thevenin model Fig. 7.

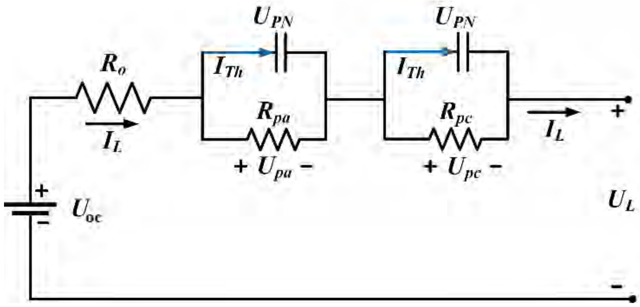


FIGURE 9. Equivalent circuit of battery according to dual polarization (DP) model. This model is capable of representing both concentration polarization and electrochemical polarization – which the Thevenin model is incapable of.

The polarization effects of Li-ion battery, concentration polarization and electrochemical polarization, can only be simulated to limited extents with the Thevenin model – often leading to inaccurate simulations at the ends of charge and discharge cycles. The dual polarization (DP) model is made to overcome this issue–which can simulate both the polarizations separately. It is shown in Fig. 9. Here, ohmic resistance R_o, and effective resistances for the polarizations

(R_{pa} for electrochemical polarization, R_{pc} for concentration polarization) represent the internal resistance of battery. The polarization capacitances C_{pa} (for electrochemical polarization) and C_{pc} (for concentration polarization) can be used to model the transient responses during charge-discharge, as affected by each of the polarizations. U_{pa} and U_{pc} are the voltages across C_{pa} and C_{pc}, respectively. The currents and voltages through and across each circuit component are also shown in the figure, considering all of which gives the following equations that governs this battery model [44]:

$$\begin{cases} \dot{U}_{pa} = -\dfrac{U_{pa}}{R_{pa}C_{pa}} + \dfrac{I_L}{C_{pa}} \\ \dot{U}_{pc} = -\dfrac{U_{pc}}{R_{pc}C_{pc}} + \dfrac{I_L}{C_{pc}} \\ U_L = U_{oc} - U_{pa} - U_{pc} - I_L R_o \end{cases} \tag{6}$$

For any battery, the SOC can be determined from the following equation [46]:

$$SOC(\%) = \frac{\text{Remaining Charge}(A.h)}{\text{Nominal Capacity of Battery}(A.h)} \times 100\% \tag{7}$$

In the models shown above, resistances are used in different quantities and purposes to emulate certain behaviors of batteries. In addition to the above models, battery equivalent circuit resistances can be used to account for capacitances, charge transfer resistance, and electrolyte resistance [47]. For any battery model, combination of all these resistances represents the internal resistance of that battery. If formulated in terms of open circuit voltage (OCV), battery terminal voltage, and discharge current, the internal resistance (R_{int}) can be expressed as [46]:

$$R_{int} = \frac{\text{Open Circuit Voltage - Battery Terminal Voltage}}{\text{Discharge Current}} \tag{8}$$

The resistance for self-discharging $R_{self-discharge}$ can also be determined from the parameters mentioned so far [46]:

$$R_{self-discharge} = \frac{\text{Open Circuit Voltage} \times SOC}{\text{Discharge Current}} \tag{9}$$

The depth of discharge (DOD) can be defined as:

$$\begin{aligned} DOD(\%) &= \frac{\text{Used Up Charge}(A.h)}{\text{Nominal Capacity of Battery}(A.h)} \times 100\% \\ &= \frac{\text{Nominal Capacity of Battery}(Ah) - \text{Remainig Charge}(Ah)}{\text{Nominal Capacity of Battery}(Ah)} \\ &\quad \times 100\% \end{aligned} \tag{10}$$

Therefore,

$$DOD(\%) = 1 - SOC(\%) \tag{11}$$

The state of health (SOH) of a battery can be defined in terms of its nominal and actual capacities as following [48]:

$$SOH(\%) = \frac{\text{Actual Battery Capacity}}{\text{Nominal Battery Capacity}} \times 100\% \tag{12}$$

Considerations made in several pervious works to determine SOH can be found in [8].

Now, for modeling second-life batteries, the aging model has to be defined and then, with the help of it, general battery models can be modified to reflect the characteristics a battery has when it has reached the end of its first-life and ready to enter the second one. To understand what value EV SLB based systems might have, it is essential to understand what the possible degradation looks like in terms of capacity fade, impedance growth, and efficiency fade. Also necessary are conclusions related to how long such a system can perform its second life task. A review of the available literature reveals that this topic, as it pertains specifically to EVs, is poorly understood. This is due in part to the impact that location and use profile contribute significantly to aging as well as the fact that aging mechanisms in general are complicated and interdependent.

In an electrochemical cell, the anode, cathode, electrolyte, and current collectors are all subject to degradation. The specific mechanisms as they pertain to Li-ion cells are visualized in Fig. 10. This section will discuss the most common mechanisms that affect the performance of the Li-ion class of cells.

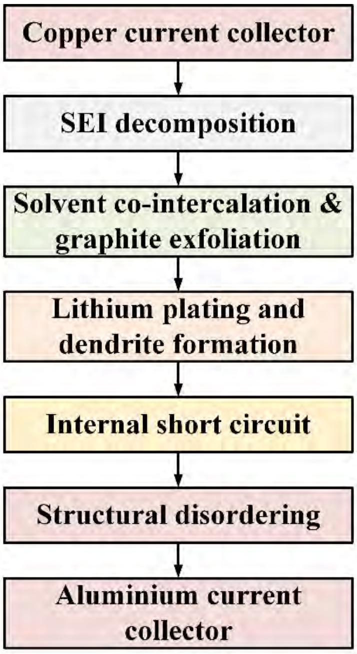


FIGURE 10. Degradation mechanisms in Li-ion cells (adapted from [49]), which gets initiated by solid electrolyte interphase (SEI) composition.

The majority of research in this area is related to the study of anode degradation with the greatest concern given to the formation and development of the solid electrolyte interphase (SEI) [50]. The SEI is essentially a protective barrier that mitigates the effects of the reactions that would normally occur between the electrode and electrolyte. Specifically, it slows the effects of corrosion on the electrode and reduction in the electrolyte [50]. In Li-ion batteries, the SEI is actually formed in multiple steps with the first occurring at voltages greater than 0.25 V compared to the Li+/Li reduction potential [51]. During the initial stage, the electrolyte begins to decompose through a series of reduction reactions, where insoluble compounds such as Li2O, LiF, and Li2CO3 are formed [51]. At voltages of 0.25 V and above, lithiation of the cathode has not yet begun to occur and the SEI, just beginning to form at this point, can be characterized as loose with high impedance and is composed of insoluble decomposition products [51]. At voltages between 0.04 V and 0.25 V, lithium is actively intercalated into the anode, allowing the SEI to form a tightly knit and highly conductive layer capable of protecting both the electrode and electrolyte [51]. Examining the coulombic efficiencies during the 1st delithiation cycle, it is seen that loss of lithium inventory is significant, ranging from 23-8.8% depending on battery chemistry [51], [52]. During storage and operation, the SEI can both grow and degrade. Under high temperature storage and operation conditions the SEI layer may dissolve and form salts that are less permeable to Li+ ions [50]. At low temperatures, the diffusion rates of Li+ ions may limit intercalation resulting in plating of metallic lithium, increased resistance, and further losses of cyclable lithium [50]. In cases of extreme cold or under stressful operating conditions, the platting of metallic lithium can be so severe that dendrites are formed [53]. If dendrite growth becomes too severe, a short between the electrodes will be produced leading to a thermal event and catastrophic failure [53].

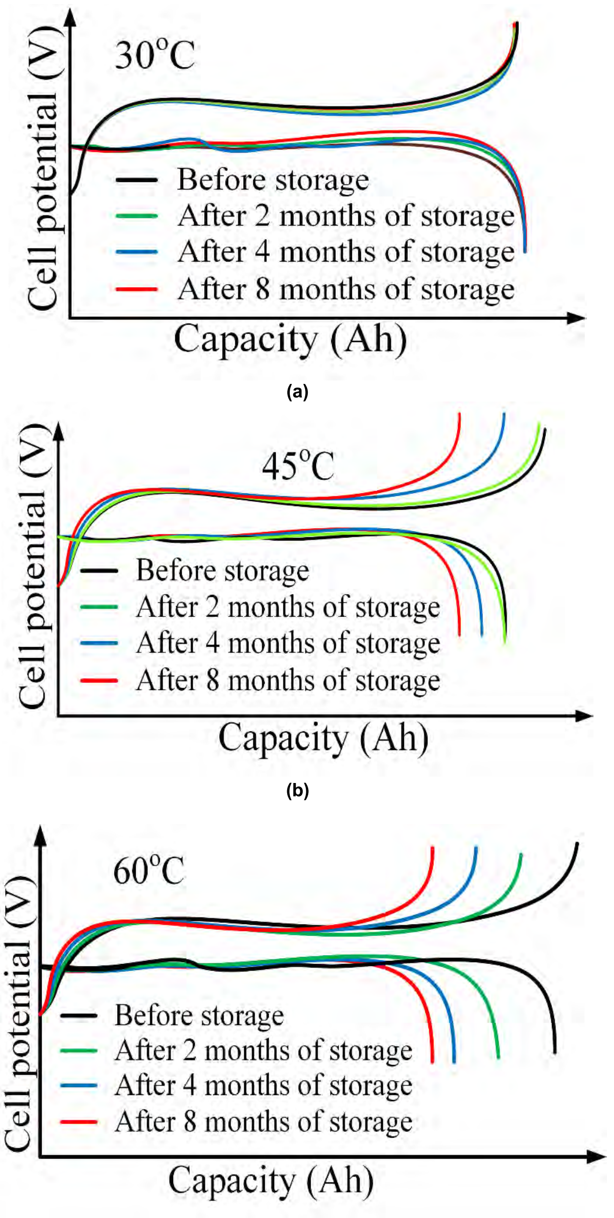
The SEI layer is permeable to lithium ions, charged elements, and solvents [51]. Solvent that diffuses through the SEI can interact with the graphite electrode causing exfoliation and gas evolution capable of damaging the SEI. Cracks in the SEI provide space for its continued growth, which results in increased impedance and further loss of lithium inventory [49]. This sort of degradation occurs over a long period and can be mitigated by storing batteries at lower voltages [49], [50]. Research has shown that if prolonged storage is required, cells and packs should have an initial state of charge not exceeding 80% [50]. While the majority of research focuses on the anode, as it is primarily responsible for the performance of the cell, the health of the cathode is starting to receive some attention as well [54]. Initially it was thought that no SEI layer would form on the cathode but this has been found to be incorrect [50]. The cathode layer is difficult to detect but is formed due to the high voltage seen at this electrode. The formation of this layer causes wear of active mass, electrolyte degradation, electrolyte oxidation and formation of an SEI [54]. There is also interaction between the active mass of the anode and the active mass of the cathode as both electrodes degrade and particulate separates into the electrolyte [54].

The current collectors and electrolyte are also susceptible to degradation. Lithium-ion cells rely on copper current collectors at the anode and aluminum current collectors at the cathode [50], [54]. Current collectors at both electrodes may suffer from separation as the bonding material connecting them to the electrode fails, resulting in increased impedance [55], [56]. While both copper and aluminum current collectors can be subject to corrosion, the aluminum current collector is much more likely to experience this phenomenon and will corrode at a much greater rate [55]. This again will lead to increased impedance and uneven current distribution across the material [56]. Electrolyte decomposition occurs rapidly during the production of the initial SEI and then slowly over the lifespan of the cell and is exasperated by extreme temperatures in both directions as well as high state of charge (SOC) storage [50], [55], [56]. Electrolyte decomposition results in loss of active lithium and increased impedance.

Overall, the degradation mechanisms can be separated broadly into three categories. These are loss of lithium inventory, loss of anode active mass, and loss of cathode active mass [50]. The effects of these mechanisms have been theorized and simulated with respect to open circuit voltage (OCV) mapping but it was not until recently that they were experimentally confirmed [50]. It is impossible to diagnose the true extent of failure mechanisms without dismantling the cell and subjecting individual components to intense scrutiny. Failure analysis is complicated and specific mechanisms are difficult to identify and attribute as the processes are complicated and interdependent [50], [56]–[58]. As such, in the commercial realm, testing is focused on the overall impacts on the cell. Namely, those interested in commercial applications are focused on power fade studies and impedance growth studies.

The capacity of Li-ion cells has been shown to fade with both time and use [50], [59]–[61]. The effects of time and storage are known as calendar aging effects and the effects of use are known as cycle aging effects. Aging effects are defined as capacity fade and impedance growth. This section will explore the ageing effects on capacity fade. Calendar aging is primarily impacted by storage temperature [50], [56], [59]. High temperatures mean increased side reactions and greater losses of cyclable lithium which equates to capacity losses [50]. Low temperature storage reduces the rate of side reactions but also slows the rate of diffusion of Li-ions in the electrolyte. This can lead to the plating of metallic lithium on the anode, which results in a loss of cyclable lithium and therefor capacity loss [50]. This phenomenon is illustrated in Fig. 11 with work completed by Kassem *et al.* [60].

SOC is a secondary factor. Consider that SOC is a theoretical representation of the number of ions present on the electrodes and in the electrolyte. A high SOC means that there is a significant imbalance in the dispersion of Li-ions in the cell. The difference in ionic concentration between electrode and electrolyte promotes side reactions that result in loss of cyclable lithium and increased capacity fade [60]. Wu and Lee demonstrated the impact of this effect by storing batteries at 0%, 25%, 50%, 75% and 100% depth of discharge (DOD) in a temperature controlled environment and testing their capacity every month [62]. DOD is the inverse of SOC



(a)

(b)

(c)

FIGURE 11. Impact of temperature on capacity fade in calendar aging study (a) 30°C, (b) 45°C, and (c) 60°C [60]. Higher temperature promotes faster fading.

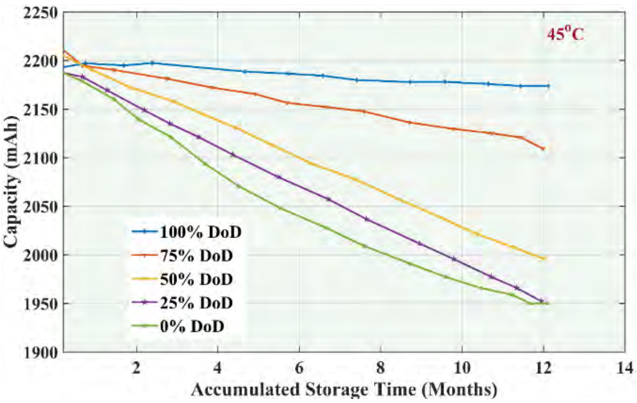


FIGURE 12. Effect of SOC/DOD on calendar aging showing that high SOC during storage results in increased capacity fade [62].

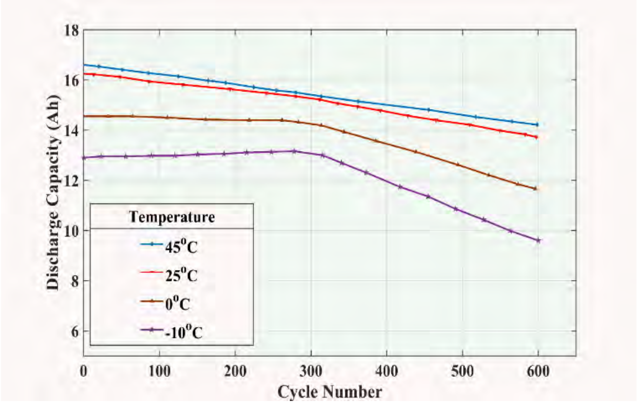


FIGURE 13. Effect of temperature on cycle aging showing that capacity fade increases at lower temperatures [63].

meaning that 0% DOD corresponds to 100% SOC. Their findings can be seen in Fig. 12.

Cycle aging is also affected significantly by operating temperature with the greatest increases in capacity fade being measured at low temperature [63]. This is illustrated in the work by Zhang *et al.* in which, capacity determination studies were undertaken on cells kept at 45°, 25°, 0°, and −10° [63]. Their results showed that after 600 cycles power fade was 14.3% for the cells at 45° and 25.8% for the cells at −10° [63]. The graphical results of this experiment can be seen in Fig. 13. The cause of this is hypothesized to be related to lithium plating caused by decreased diffusion [63]. During charge and discharge cycles there are also many exothermic reactions taking place that result in internal heating [50]. While the effects of ambient temperature on capacity fade are well understood, the effect of internal cell temperature is not.

A healthy charge cycle is defined as one where initial charging occurs at a constant current until a cut-off voltage is reached followed by a constant voltage charge until charging current has reduced to approximately 20 mA [64]. If the voltage increases above the rated constant voltage cut-off level, the cell will experience significant capacity fade and reduced cycle life [64]. Choi and Lim demonstrated this phenomenon by examining the capacity fade in cells, where the constant voltage level was raised above the manufacturers recommended cut-off. The results of this experiment can be seen in Fig. 14. It is hypothesized that the degradation in this case comes from increased oxidation reactions that occur due to the increased potential at the cathode [64]. In the same work, Choi and Lim conducted experiments to evaluate the effect of charge and discharge current on capacity fade. With 1C defined as the nominal charging rate, charging tests were undertaken at 1C, 1.2C, and 1.4C; discharge tests were performed at 1C, 1.1C, 1.3C, 1.5C, and 2.0C [64]. The results of these experiments can be seen in Fig. 15. It was determined that while elevated current rates in both charge and discharge

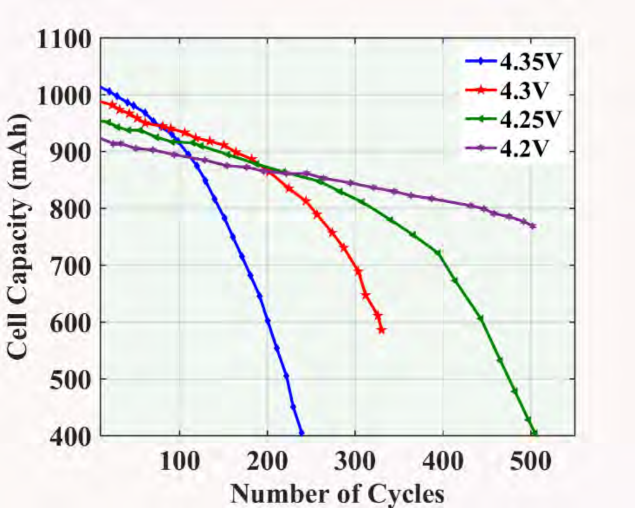
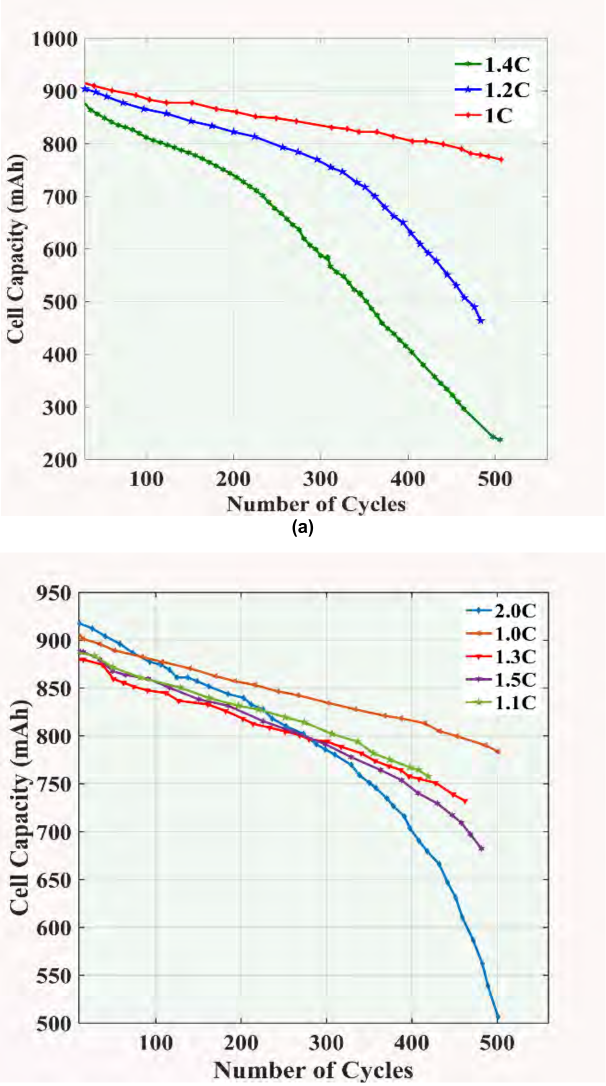


FIGURE 14. Effect of constant voltage float magnitude on capacity fade and cycle life with 4.2 V defined as optimal by the cell manufacturer [64].



(a)

(b)

FIGURE 15. Impact of elevated constant current charge on capacity fade and cycle life during both charge and discharge periods. (a) Charge cycles, (b) Discharge cycles [64].

cycles resulted in increased capacity fade, the effects were much more pronounced when the abnormality occurred during charging [64]. Ecker *et al.* performed a cycle life study to examine the effects of DOD on capacity fade. Cell temperature was maintained at 35° and were cycled at a rate of 1C to normalize for temperature and rate effects [61]. The results, depicted in Fig. 16, show that cells cycled over a wider SOC range displayed high levels of capacity fade [61].

Similar to capacity fade, impedance growth occurs naturally over the lifetime of a cell and can be studied through both calendar and cycle aging studies. During operation, impedance growth manifests as power fade, and this section will focus on studies related to both phenomena. Bloom *et al.* focused on the effects of SOC and the change in SOC for power fade and impedance growth using both calendar and cycle studies [59]. With end of useful life defined as 20% power fade, high levels of SOC during storage (over 60% SOC) negatively impacted power fade characteristics during calendar testing [59]. It was hypothesized that this change was due to SEI growth at the cathode. During cycle testing they focused on the effects of change in SOC of either 3% or 6% at various starting SOC conditions [59]. It was found that a change of 6% in SOC over a discharge period resulted in significantly increased power fade with end of useful life reduced from 38.72 weeks to 1.94 weeks at a starting level of 80% SOC [59]. The calendar aging phenomenon is illustrated in Fig. 17 and the cycle aging results are seen in Fig. 18.

Impedance growth is also dependent on temperature as demonstrated by Zhang *et al.* Using electrochemical impedance spectroscopy (EIS) they measured the internal resistance of LiFePO4 cells under a range of temperatures at 0, 300, and 600 cycles. The results, displayed in Fig. 19, shows that the impedance growth increased at lower temperatures [63]. This is hypothesized to be related to SEI growth at the anode as metallic lithium is plated due to lower diffusion rates [63]. Kassem *et al.* evaluated the relationship between impedance growth and temperature in a calendar aging study but only experimented with cells at high temperatures. Their results showed that impedance growth effects were limited to less than 70% and deemed minimal. Work by Ecker *et al.* seems to cast doubt on this finding as they conducted similar studies and found that high temperatures did have an impact on impedance growth during calendar aging but that effect began to be more pronounced after 200 days [61]. Kassem *et al.* may have missed this result as they ran their calendar test for only 240 days total [60]. This finding was later confirmed by Schmitt *et al.* [65]. It is hypothesized that the effects would be more pronounced at low temperature due to SEI growth and lithium plating at the anode [60]. High current discharge rates are also shown to increase the impedance growth in cycle aging studies [66], [67]. Ning *et al.* studied the impact of 1C, 2C, and 3C cycling

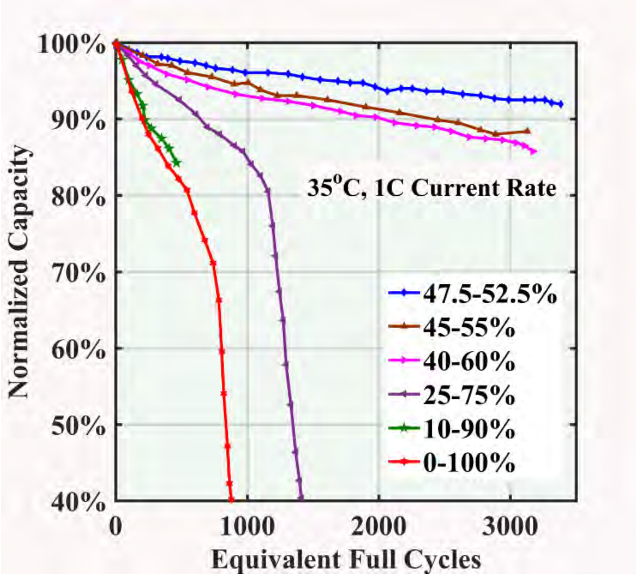


FIGURE 16. **Experimental results from Eckers *et al.* showing that increased cycle span can reduce the lifetime and increases capacity fade [61].**

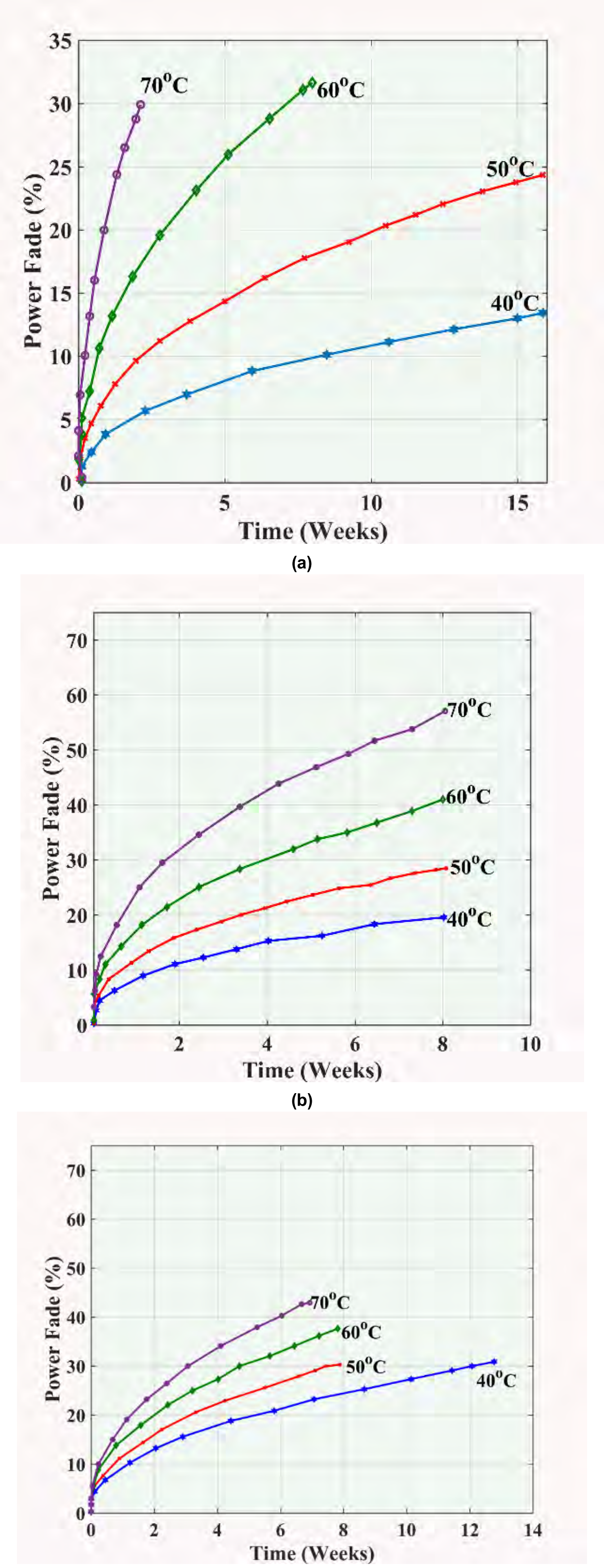
compared to nominal. After 300 cycles, the cell exposed to 3C discharge conditions displayed DC resistance measurements 27.7% higher than those found in the cell operated at manufacturers specifications. The results of this study can be seen in Fig. 20. It is hypothesized that the growth in impedance is due to gasification at the anode that promotes cracking of the SEI layer resulting in SEI expansion [67].

Modeling these aging effects mathematically is a complicated task, as the aging mechanisms are different for each battery chemistry and use-case [22], [68]. In [69], the stress-factors to model calendar-aging of batteries are identified as the temperature and the SOC. The electrochemical equations that can predict calendar aging are the Arrhenius equation (equation (12)), and the Tafel equation (equation (13)). The Arrhenius equation gives the reaction rate evolution (A(T)) with respect to the temperature (T), whereas the Tafel equation shows the relation between electrochemical reaction rate ($^{i}/_{i_o}$) and over-potential (ΔV) [69].

$$A(T) = a \times \exp(\frac{b}{T}) \tag{13}$$

$$\Delta V = A \times \ln(\frac{i}{i_0}) \tag{14}$$

Ahmadian *et al.* conducted a detailed study of plug-in EV (PEV) battery degradation models, and identified calendar aging and cycle aging as the two major causes of degradation [70]. According to their findings, temperature, SOC, and time generally affect the calendar aging; whereas charge rate, cycle number, and DOD determine the cycling aging. A test matrix for battery aging model development,

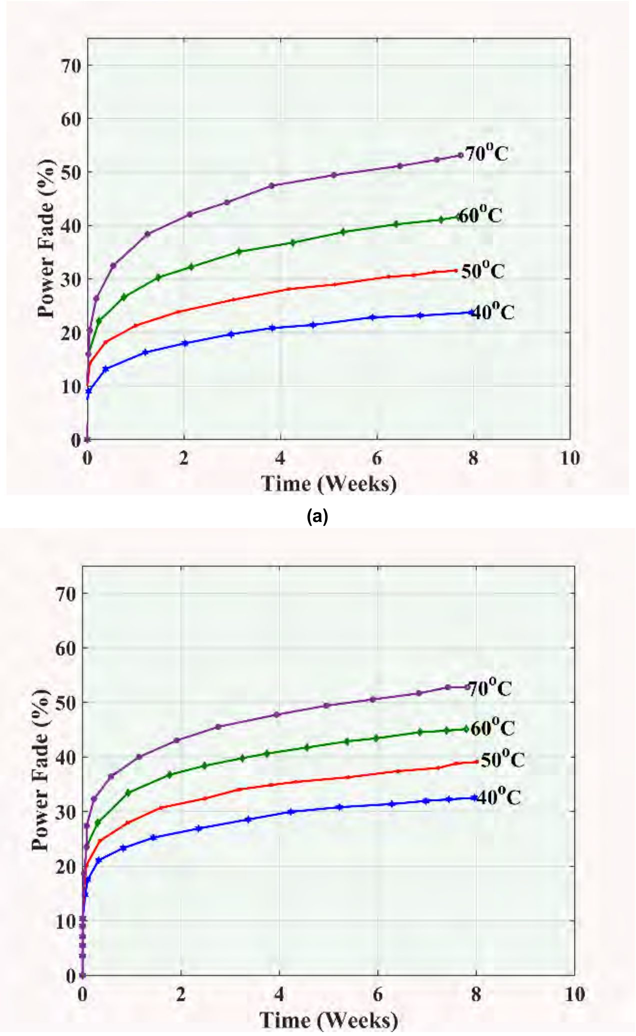


(a)

(b)

(c)

FIGURE 17. **Impact of SOC on power fade in calendar aging (a) 40% SOC, (b) 60% SOC, and (c) 80% SOC. Rapid power fade is exhibited above 60% SOC [59].**



(a)

(b)

FIGURE 18. Impact of change in SOC on power fade in cycle aging with change in SOC of 3% in (a) on the left and 6% in (b) on the right [59].

and the characterization tests required for that, are provided in [68]. Reference [68] also indicated that with current rates lower than C/2, cycling aging does not depend on DOD and current flow. For higher C-rates, the capacity fade (Q_{loss}) follows an empirical equation defined as [70]:

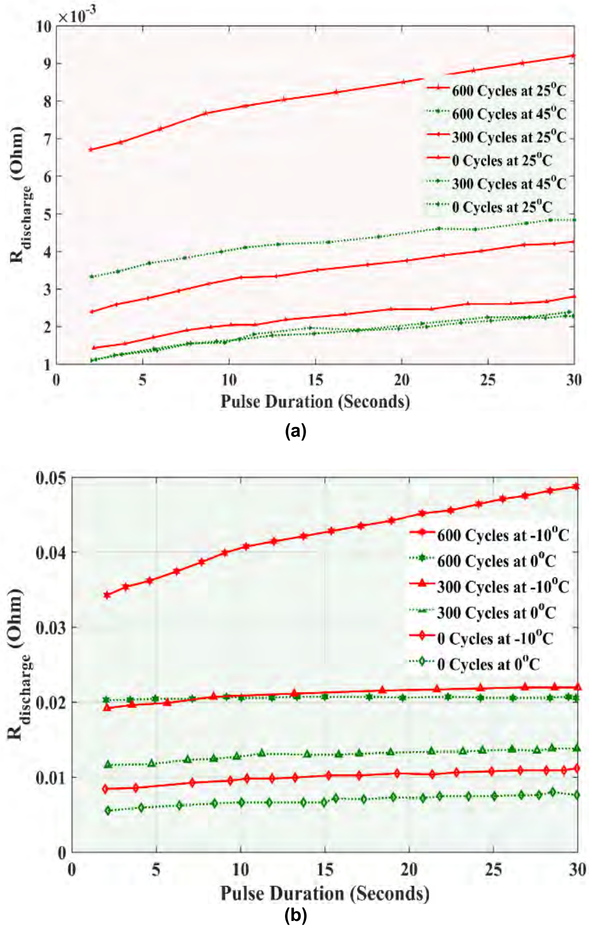
$$Q_{loss} = B \times \exp(\frac{C + A \times C_{rate}}{\Re T}) \times A_h^n \tag{15}$$

Here, B's value depends on the C-rate, and A_h represents the DOD. Empirical calendar aging and capacity fade models can also be found in [71], [72]. Comparison of different parameters of new and second-life batteries can be found in Table 3, which can aid in visualizing the differences of battery behavior and application in these two stages.

IV. SLBESS MAKING PROCESS

A. EVALUATION METHODS FOR BATTERIES ELIGIBLE FOR SECOND LIFE USE

As previously mentioned, recycling as a mean of exploiting the remaining capacity of rejected EV batteries is fast losing its appeal among investors. This is primarily due to the anticipated dominance of LiFePO4-cathode batteries in the market for its many advantages [1]. The upshot of this would be the decline of LiCoO2 batteries, which are more attractive



(a)

(b)

FIGURE 19. Effect of temperature on internal impedance over cycle time (a) at 45°C and 25°C, and (b) at 0°C and -10°C. It is evident that impedance increases at lower temperature [63].

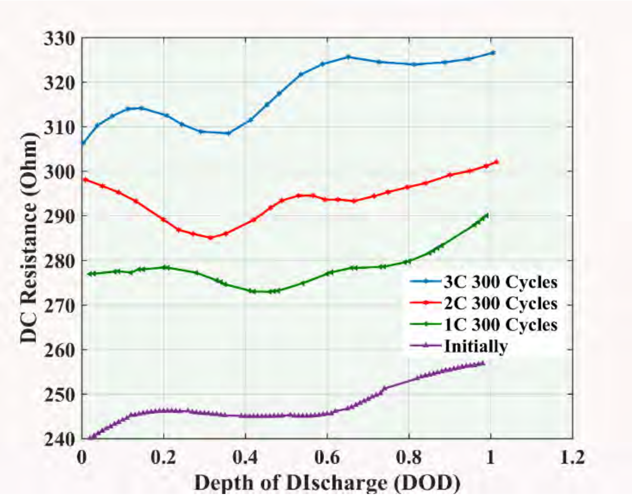


FIGURE 20. Increase in impedance growth of Li-ion cells as a function of discharge rate [66].

TABLE 3. Comparison of new and second-life batteries [23].

Category	New batteries	2nd life batteries
Nominal voltage level	~ 400 V	~ 800 V – 1000 V
Operating hours for 10a	~ 16 800 h (on)	max. 87 600 h (on)
Ambient temperatures	-40 -60 o C (in operation)	10 -35 o C (in operation)
C-rates	Continuous 2-3 C Peak > 5C	Continuous < 0.5 C Peak 0.5 -2C
Thermal management concept	Active (air or liquid)	Passive (active air or liquid only for specific use cases with critical temperatures)
Vibrations	Typical for vehicles in motion	None
SoH (Capacity begin of life)	100%	70-90 %
Control technique	EV Battery management system: depends on driving mode. Has regenerative braking etc.	ESS control: will depend on application: frequency regulation, voltage regulation, peak shaving etc.
Maintenance	Almost maintenance-free	Requires more frequent and careful maintenance
Size	EV rated sizes	ESS sizes
Capacity fade		~20%
Impedance		Increased impedance
Application	EV	Stationary use

to the recycling industry owing mainly to the high salvage value of recycled cobalt. Moreover, the recycling process itself is energy-intensive, which further discourages potential investors to absorb the risk associated with first-movers [24]. Hence, a further incentive is provided to push for the nascent ESS remanufacturing industry, which is solely predicated on leveraging the staggering 80% capacity of rejected batteries and requires only a modest initial investment.

However, the remanufacturing process is not going to be without its inherent complications. The prime issue with refurbishing old batteries is the lack of a universal cell standard. Every cell manufacturer follows a different cell type, which requires a unique module type. These different modules are mutually exclusive in terms of compatibility [24]. Therefore, even if we choose to ignore the different cell chemistries employed, the mix-and-match process that follows disassembly of used battery packs is rather arbitrary. To circumvent this issue, a sophisticated flowchart of procedures has to be maintained. The flowchart is shown in Fig. 21. Gladwin *et al.* classified this evaluation steps as the assessments of physical state, output voltage, battery pack impedance and capacity, and the battery management system (BMS) data – in that order [73].

1) DISMANTLING

The first stage to creating SLB energy storage systems is to dismantle the used battery packs [74]. In the major sources of second-life batteries such as EVs, battery packs consist of numerous individual cells; and thus, dismantling is a key step to produce second-life battery systems. As different manufacturers use different cell-types having disparate packaging [75], the dismantled components can be categorized based on that for easier component selection for SLBESSs. Fig. 22 shows the components of a battery pack made with prismatic cells; for other cell-types such as cylindrical cells and pouch cells [76], similar setups can be expected. Fig. 23 shows these different battery cell types, the battery modules, and the battery packs made from them. Reference [1] suggests that dismantling of battery packs needs to be done in a controlled environment with no atmospheric air to avoid oxidation at the cathodes. It is also noted in that work that removing the solid electrolyte interface (SEI) – which develops on the battery electrodes because of the chemical reactions that occur in the cells – after the dismantling can dramatically restore the battery performance. In [1], laser is noted as a potential SEI removal process for

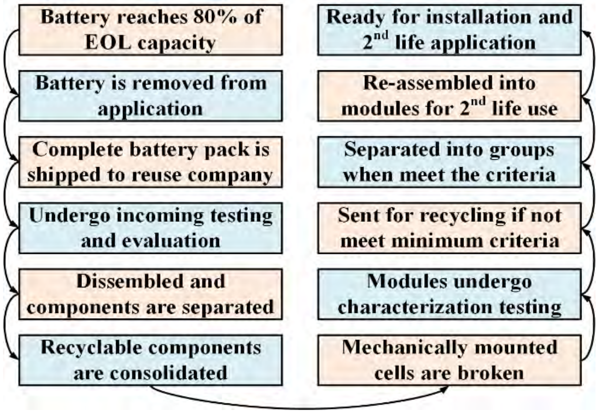


FIGURE 21. Detailed process of preparing batteries for second-life application: all these steps must be followed in proper sequence to create properly functioning SLB systems (adapted from [24]).

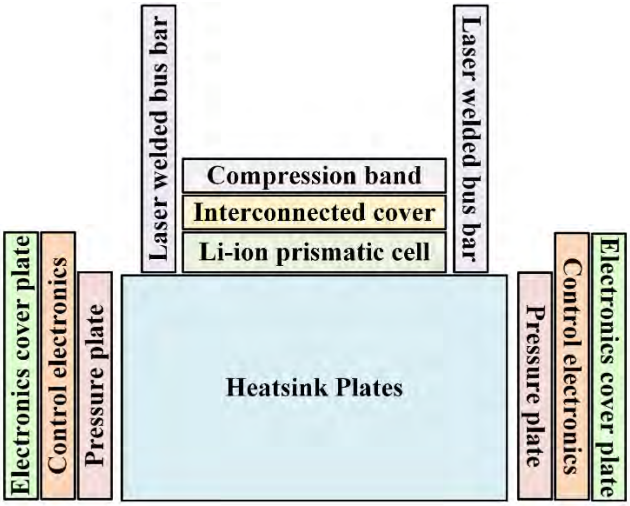


FIGURE 22. Components of an EV battery pack that need to be disassembled as the first step of making second-life battery energy storage systems. This system shows the components of a system made with lithium prismatic cells.

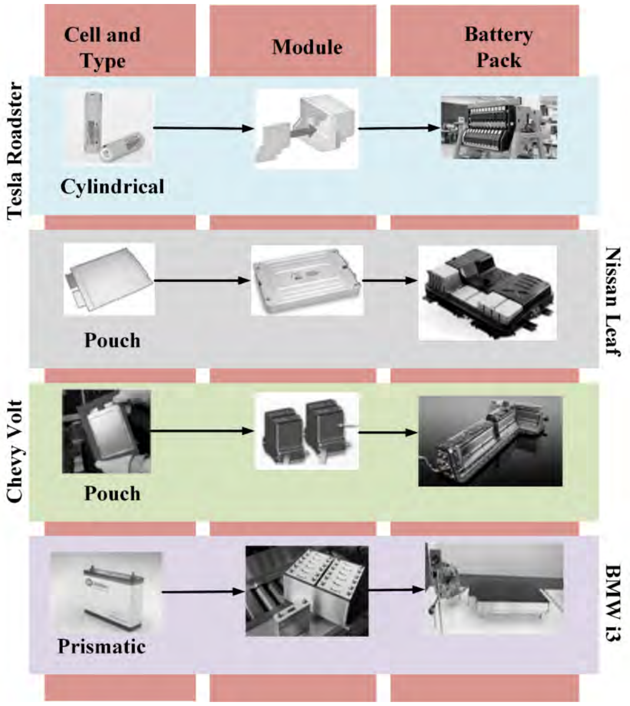


FIGURE 23. Different EV battery cell types and their stages of assembly (adapted from [22]). Different cell types are used by different manufacturers, and they have arranged in packs as per the vehicle designs.

pouch type LiFeO4 battery cells. This laser-driven process to remove SEI needs to be investigated for other cell-types to be deployed in the SLB production line.

2) TESTING

The battery cells obtained after dismantling used EV batteries need to be tested for determining their fitness for second-life applications. Also, a battery pack's power and capacity are determined by the performance of the cell with the least capacity; and thus it is essential to properly characterize cells in terms of voltage, capacity, and SOH, and classify cells with similar characteristics to have a homogenous cell-selection for each second-life battery pack [24]. A three-stage evaluation procedure was presented in [74] for sifting through a large number of batteries to determine the ones eligible for second use. The first stage was visual inspection, which would reveal the cells or modules with evident physical damages and those could be promptly discarded. The second stage was to verify the voltages of the batteries remaining after the first stage, and the ones proved to be fit in this step were then subjected to SOH assessment. Visual inspection was also listed as the initiating test in [77], where any battery demonstrating bulge, and/or leakage was send to recycling. A common form of battery testing is the cycling study, where battery cells are charged and discharged under pre-defined laboratory cycles, and the cell capacity, voltage, SOH, physical properties, etc. are observed along the way. In such a study, 19 used EV battery modules having 40-90 Ah, 3.4-3.6 V were divided into two groups to be cycled with a high power cycle (250 kW, 200 Wh) and a low power cycle (95 kW, 250 Wh) in [78]. The high-power cycle reduced the capacity of the cells subjected to it by 68% after 75 cycles, efficiency also dropped 12%, with discernable physical deformation. The low power cycle, on the other hand, did not have any patent detrimental effect on the cells exposed to it. This indicated the batteries under observation in this study were suitable for low power application in the second life. In [79], the tests conducted to observe battery characteristics during cycling studies are listed as pulse power characterization test, capacity test, quasi-OCV vs SOC test, short impedance parameter identification test (IPIT), and hybrid pulse power characterization test (HPPC). In the paper of Martinez-Laserna *et al.*, these tests were noted to be conducted for both cells and battery modules or stacks, where stacks were made with cells having both similar SOH (homogenous stack) and different SOHs (heterogeneous stack). Similar tests were also reported in [74], with the addition of electrochemical impedance spectroscopy (EIS) measurement, with necessary discussions and illustrations. Other than determining the battery status, tests also help to quantify the battery model parameter. For example, extended hybrid pulse power characterization test can provide time-domain parameters [74]. Table 4 lays out the different tests and the reference papers that adopted them in their respective research.

3) REMAINING CAPACITY ESTIMATION

If remanufacturing of batteries is to contribute to the second life-cycle in any meaningful way, then the remaining capacity of batteries is a crucial factor. But estimation of remaining capacity is open to arbitration. Different researchers approached the topic from different vantage points. For example, Sen *et al.* [80] have predicated their SLB second-life estimation based on a few fixed parameters, namely, a total lifespan of 20 years and a fixed DOD of 60%. Based on these a priori assumptions, the lifespan of the second life was determined to be 20 years minus the first life. But there are other notable works that do not leverage such fixed parameters but base their estimation on usage data. The most prominent of these is [81]. In this experiment, over 100 EVs were leased to members of the public or fleet operators for a minimum period of 12 months, with data collected over a 27-month period. Each EV was equipped with a GPS tracker and a data logger, which recorded the usage and charging pattern of individual commuters. At the end of the first life, the battery packs were extracted and disassembled for second life estimation. It was found that once the "First Life" is over, the lifespan of second life will be different, depending on the usage pattern. Table 5 points out the different estimations corresponding to different usages i.e. ancillary service, network deferral or energy management.

Furthermore, other researchers have conducted aging experiments i.e. the fading of battery capacity due to aging. In [82], the battery that was employed for experimentation was Samsung GS4 with a capacity of 2600 mAh and

TABLE 4. Different battery characterization tests adopted in literature.

Authors	**Laboratory**	**Battery used**	**First life application**	**Second life application**	**Tests conducted**					
					Visual inspection	**SOH assessment**	**Capacity test**	**Quasi-OCV vs SOC test**	**EIS**	**OCV**
Abdel-Monem *et al.* [74]	Vrije Universiteit Brussel (2017)	Lithium iron phosphate batteries (LFP)	Laboratory ageing	Stationary grid	*	*	*	X	X	X
Martinez-Laserna *et al.* [79]	Energy Storage and Management. Arrasate-Mondragón, Spain (2016)	20 Ah NMC/graphite based Li-ion cell	EV	Residential demand management and power smoothing renewable integration application	X	*	*	*	X	X
Strickland *et al.* [146]	Aston University, Birmingham, (2014)	Honda "Insight" battery (NiMH)	EV	Ancillary service, network deferral, and energy management	X	*	X	X	*	*
Kootstra *et al.* [147]	UC Davis (2015)	Lithium battery pack	EV	Grid integration with residential PV system	X	*	X	X	*	*
Zhu *et al.* [148]	Harbin Institute of Technology (2017)	Lithium-iron phosphate battery (LFP)	PECV, PEPC	Backup power for communication base stattion	X	*	*	X	X	*
Kim *et al.* [149]	Korea Electronics Technology Institute (2013)	LiFePO4	Laboratory ageing	Stationary energy storage	X	X	*	X	*	X
Neubauer *et al.* [150]	National Renewable Energy Laboratory, USA (2015)	Li-Ion	PEV	Daily peak shaving	X	*	*	X	X	*
Hegazy *et al.* [90]	Vrije Universiteit Brussel (2015)	Li-Ion	EV	Fast DC-Charging Systems	X	*	*	X	X	X
Mukherjee *et al.* [151]	Aston University, Birmingham (2014)	Li-Ion, lead-acid, and NiMH	EV/HEV	Smart grid	X	*	*	*	*	*
Casals *et al.* [75]	Universitat Politècnica de Catalunya, Spain (2016)	Li-Ion	EV	Load levelling, peak shaving, and frequency regulations	X	*	X	X	*	X
Burke *et al.* [152]	UC Davis (2013)	Lithium titanate oxide (LTO), lithium manganese oxide (LMO)	Laboratory aging	High energy density, but relatively low power capability applications	X	*	*	X	*	X
Tong et al. [153]	UC Davis (2013)	Lithium ion phosphate	EV/PHEV	Off-grid PV vehicle charging system	X	*	*	*	X	*
Gladwin *et al.* [73]	The University of Sheffield	Honda Civic NiMH battery	EV	Back up power application and vehicle recharging station	X	*	*	X	X	X
Einhorn *et al.* [85]	Austrian Institute of Technology	Li-Ion	EV, HEV	Stationary storage applications	X	*	*	*	X	*
Eklas *et al.*	Oregon Institute of Technology	Li-Ion, lead acid, lithium manganese oxide (LMO)	EV, Automotive vehicles	Utility based energy storage, smart grid, peak shaving	*	*	*	*	X	*

TABLE 5. Remaining lifespan summary [81].

Usage	Second life cycle	Estimated remaining life
Ancillary service	1500 cycles at 10% p.a.	6 years
Network deferral	50% per day for 4 months	15 years
Network deferral and ancillary service	Combination of A and B	4 years
Energy management	50% per day 5 days per week	7 years
Energy management and ancillary service	Combination of A and C	3 years

TABLE 6. Parameters for process step based refurbishment [22].

Process Information	Description
Level at which reprocessing occurs	Designate cell/module/pack level process, this allows process steps to be shared between repurposing scenarios and pack designs, as repurposing costs will scale with vehicle pack design or reprocessing scenario.
Process type	PROCESS: Normal process such as cleaning, testing, inspection, etc. Does not alter the properties of the battery. DISPOSAL: Disposes of any packs or modules (depending on process level) that are outside of the defined limits. SORT: Sorts packs or modules according to sorting criteria.
Time required for the process step	Information is generally available through service concept development and planning. And is a standard metric needed for production resource planning.
Frequency in which the process step occurs	100% correlates to a process done on every pack or module, and anything less than 100% correlates with a repair type process which may not be performed on all packs or modules. This parameter can come from warranty data when appropriate.
Number of hours requiring specialist (or higher qualified labor) and standard labor	Due to the high voltage many process steps require higher trained professions. Breaking out the hours needed between standard and specialized labor is needed for headcount planning and process optimization.
Description of additional parts required and part cost	Additional or replacement parts needed.
Associated fixed cost, including equipment and tools	Fixed or capital equipment costs can be specified here or in entity-based repurposing.
Recycling cost of disposed parts	Disposal of unusable battery modules or components.

a nominal voltage of 4.35 volts. The batteries were exposed to several bouts of charging and discharging with a 10-minute interval in-between each process. It was discovered that as the battery ages, the time-to-charge and time to-discharge decreased and hence the total time of a charge-rest-discharge-rest cycle decreased. This decrease in time-to-charge and time-to-discharge is attributed to capacity fade. The upshot of all these experimentations is that battery second life is not a fixed value but depends on both previous and future usage. The battery cells evaluated through such testing can be classified by their capacities and then color coded for easy selection of packs to create SLBESSs having cells with similar capacities; for example, cells still in the first life region (above 80% capacity) can be colored green, the second-life cells can be given a unique color based on different capacities: blue for 80%, violet for 60%, yellow for 40%, and red for below 20% (totally unusable).

B. STEPS TO MAKE SLBESS

The entire process of refurbishment can be broken down into a number of discrete steps. Depending on the functionality chosen, the steps can be categorized in terms of associated labor and costs; or in terms of the entities/stakeholders involved. Either way, discretization offers convenience and facilitates interaction between parties in a co-evolving industry. It also smoothens the work flow. The process based refurbishment according to [22] is represented in Table 6.

1) SLBESS COMPONENTS

The batteries determined in the evaluation phase to be suitable for second-life application are to be used for making SLB energy storage systems (SLBESS). The components of these SLB systems are similar to the general ESS, the only difference is these use SLBs rather than the new batteries used in the general ESSs. The components of SLBESS thus mainly comprise of the SLB packs, and associated power electronics systems including the battery management system (BMS). The BMS in the SLB case has to carry out the task of battery-balancing in addition to the regular BMS duties, as the SLBs are expected to be slightly imbalanced even after rigorous testing and classification in the evaluation phase. Tong *et al.* achieved this by employing an extended Kalman filter to estimate the storage SOC, and considered high shunting currents in [83]. Their SLBESS system consisted of 135 prismatic SLBs in series-parallel configuration, and a DC-AC bidirectional converter in addition to the BMS. Mukherjee *et al.* added some significant advancements in this area by considering different battery chemistries in a single SLBESS, including NiMH, lithium titanate, and lead-acid batteries as low-voltage and high-voltage batteries, then considered their disparities to design a BMS employing distributed control [84]. Einhorn *et al.* contested that cell with different capacities as well as chemistries can be connected in series to get significant energy increase from SLB packs [85]. Additionally, the communication between the batteries when they were in EVs, and how that could be modified while being used as SLBESS in smart grids, are analyzed in [86]. There are multiple options to choose from for the power converter topologies; Mukherjee *et al.* investigated these configurations based on reliability and cost, and decided the single inverter with modular cascaded dc-side the best choice [87]. A similar investigation was conducted for SLBESS application in frequency response use in the grid in [88]. Modular approach was also favored in [89],

TABLE 7. Converter topologies proposed in the reviewed literature.

Reference	Author	Year	Converter used
[83]	Tong et al.	2015	DC-AC bidirectional converter
[84]	Mukherjee et al.	2016	Modular DC-DC converter
[85]	Einhorn et al.	2011	DC-DC converter
[90]	Hegazy et al.	2015	Multi-port interleaved converter

where modular design of cascaded multilevel converter was proposed for SLB application. Hegazy *et al.* developed an multi-port interleaved converter system for using SLBESS in DC fast-charging stations [90]. Choosing a proper converter is crucial as the performance of the energy storage system (ESS) depends on it [91]. Table 7 presents the converter topologies proposed in the reviewed literature.

Even though the construction of both the stationary and vehicle battery system are essentially similar, there exists some disparities [22]. In the aforementioned storage systems, the cells are connected in series and parallel and are grouped in to modules, which ensures easy assemble and maintenance. These modules include, voltage and temperature sensors, control electronics for data communication, and thermal management system. In the vehicle battery system, these modules are configured into a battery pack containing relays, crash sensors, isolation sensors thermal management system, and electrical and mechanical interface with the vehicle. On the other hand, in the stationary battery system, a battery string is created by connecting the modules in series. This string includes rack level current and voltage sensors, relays, fuses, and BMS control electronics. The battery racks are connected in parallel to a single power control system to create a battery cabinet. This includes control electronics for BMS with the exclusion of inverter. Multiple battery racks are collected to construct integrated energy storage system, which includes safety system, thermal management system, and system controller. The system architecture of vehicle and stationary battery system are represented in Fig. 24.

2) OPTIMAL SIZING OF THE SLBESS

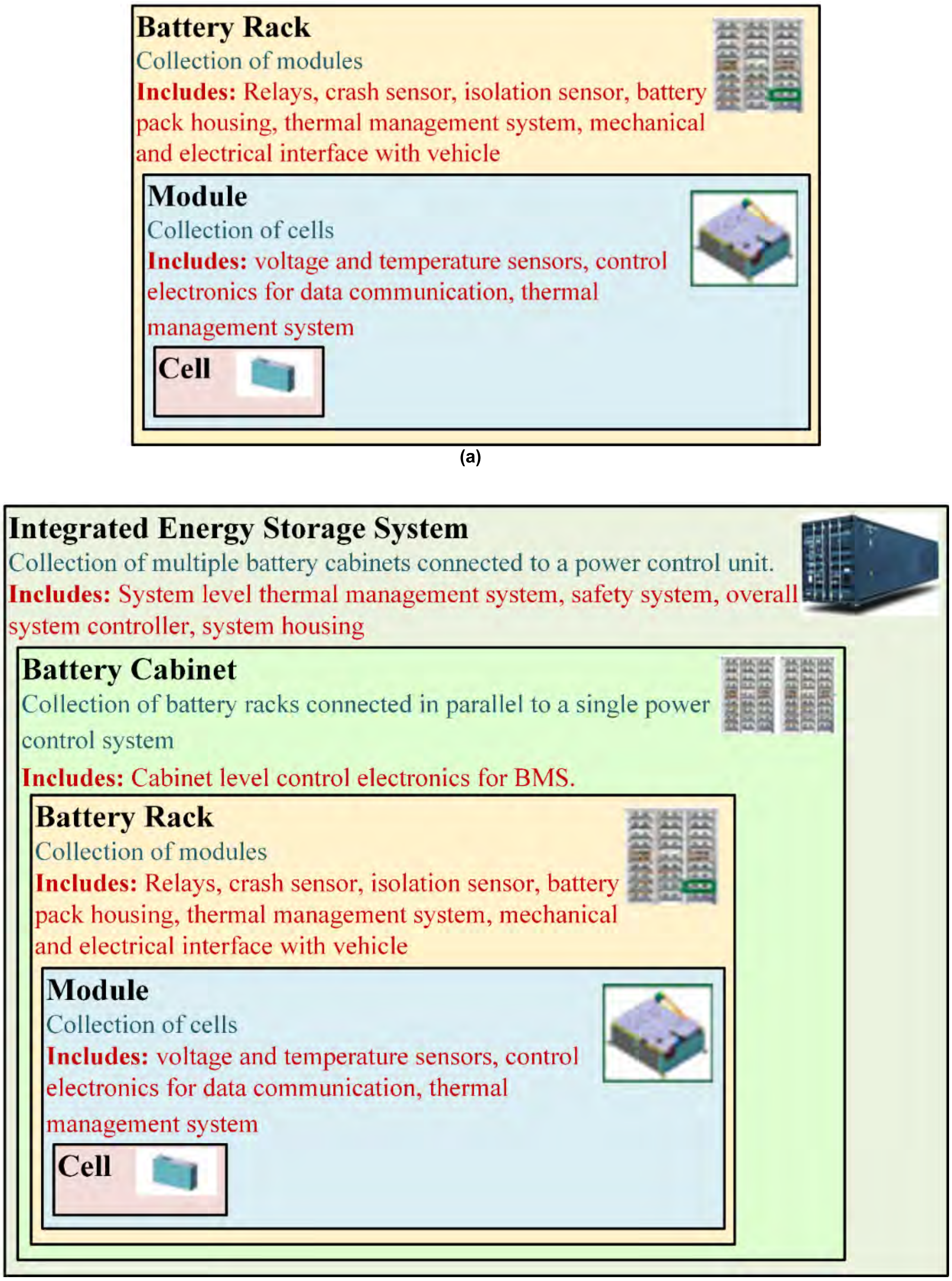
A significant amount of study was directed towards the optimum sizing of SLBESS in the past. Saez-de-Ibarra *et al.* approached this objective for solar photovoltaic power plants through a two-stage strategy: calculating the required storage for a single day first, and then calculating the required capacity throughout a year [92]. Their strategy was tested for a PV plant in Spain. A similar approach determined the SLBESS rating for maximized profit in the demand-response service in residential applications [93]. Koch-Ciobotaru *et al.* also used data from the energy market in Spain to develop their optimal SLBESS rating [94]. All these studies stated a battery operational algorithm used in each of their analysis, as the sizing process is closely related with it [94]. The general sizing strategy used in these works are visualized in Fig. 25: the SLBESS ratings are optimized for the use-case of interest, and the modeling as well as algorithm selection were done with that specific application in mind. An alternative approach of sizing SLBESS can be a modular design, where modules with identical ratings are built first, and then cascaded according to the needs of different applications. Such a strategy is presented by Mosely *et al.* in [95]. In a more general sense, the sizing analysis can be done based on four parameters: system size requirement, control algorithm, aging, and cost. The size can be chosen to fit the system, or can be made bigger for reliability and longer life; the control algorithm can be chosen to operate at the safety bound, or can be designed for the lifecycle of the system; the ESS aging rate can also be selected to have fast or slow aging process – which is determined by the sizing and operational choices made for the first two parameters; and finally, all these choices, which determine the cost of the system: an SLBESS with the minimum size, operating at the safety bounds with a fast aging rate will have higher operational cost than the one with more reliability – which will have a higher capital cost [22]. These tradeoffs are visualized in Fig. 26.

C. PROCESS OF BUILDING SECOND LIFE BATTERY SYSTEMS

After the SLBESS components are chosen, assembling them is the last step to produce these storage systems. Therefore, this stage will require connecting the batteries in required configuration, installing the battery management system and required converter circuitry. Fig. 27 shows the total process of SLBESS construction. Fig. 28 shows the components of a completed SLBESS.

1) SAFETY CONCERNS

Batteries being both electrical and chemical devices, the safety practices required during SLBESS manufacturing must abide by the guidelines encompassing these two sectors. SLBs are especially tricky to handle as their earlier conditions (whereabouts, storage condition, and remaining capacity) are generally unknown. Old batteries are expected to swell and even explode or catch fire during the evaluation period, and precautions must be put in place to contain the chemical spills and fumes as well as to protect the personnel. The damaged batteries (swelled, exploded, or caught fire) must be disposed immediately without making any attempt to extract materials through recycling, according to the best knowledge of the authors. Therefore, safety practices must be upheld in every stage of this process: from evaluation to assembly. One good choice can be to conduct the initial testing in a small chamber maintaining a controlled environment. Disassembling batteries in glove-boxes with Argon gas is a general approach to avoid cathode-oxidation [1], [96]. Proper personal protective equipment (PPE) must be used, while handling batteries meant for second-life application. The PPEs are categorized in four main classes by the occupational safety and health



(a)

(b)

FIGURE 24. System architecture of (a) vehicle battery system, (b) stationary battery system [22]. Both system share identical basic components, indicating the relative ease of used EV battery application in stationary energy storage systems.

administration (OSHA) based on their application, which is shown in Table 8 along with the national fire protection association (NFPA) [97] equivalents. Selection of the PPE levels has to be done according to the situation (battery chemistry and electrical rating). For example, Li-Ion batteries can emit harmful gasses during testing, and appropriate safety equipment must be deployed for that. Hill *et al*. presented a gas sensor to detect such events during SLBESS evaluation in [98]. Notable OSHA safety standards for SLBESS related works are listed in Table 9.

2) WHERE BATTERIES GO AFTER 2ND LIFE

One important aspect of the SLBESS life-cycle that demand significant attention is the disposal of SLBESS after the expiration of the second-life. As SLB application came into consideration for preventing usable resources ending up into

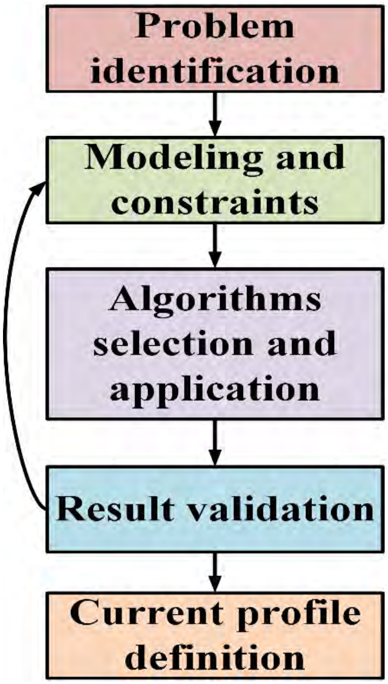


FIGURE 25. SLBESS sizing strategy [93]. The ratings are optimized for the use-case of interest, and the modeling as well as algorithm selection were done with that specific application in mind.

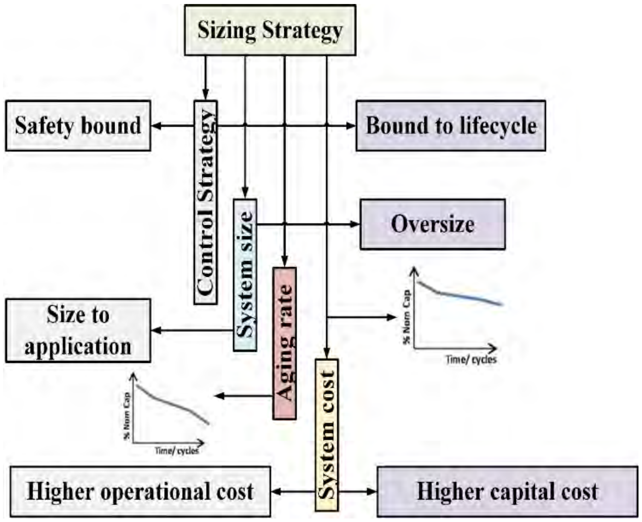


FIGURE 26. General sizing considerations of SLBESS [22].

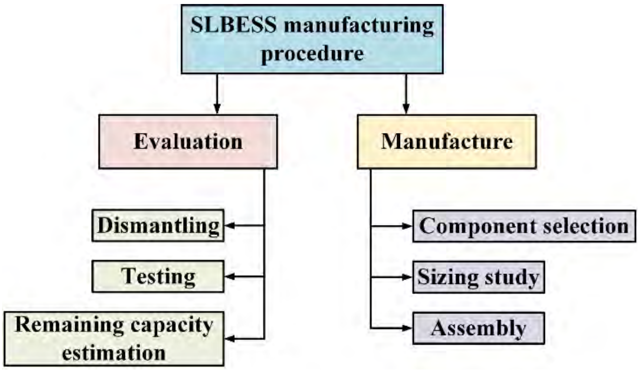


FIGURE 27. Manufacturing procedure of SLBESS. The available used batteries are to be evaluated first, and then the ones suitable for second-life use will be introduced to the manufacturing process.

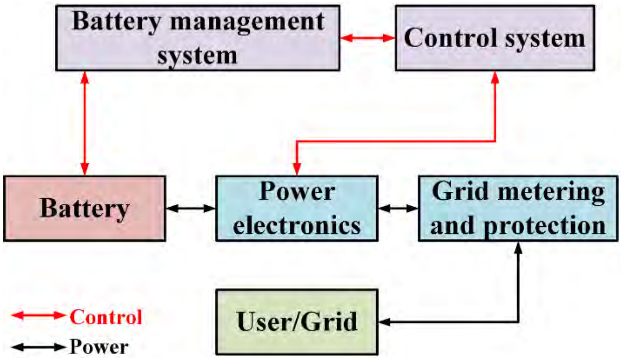


FIGURE 28. Different components of a completed SLBESS: a battery management system with required control and protection mechanisms create the final product when mated with the battery cell arrangement.

landfills, and also to curb some environmental pollution in that process, its disposal must also stay true to those objectives. Recycling the reused batteries is a good way to achieve that, based on the principles of circular economy [1], [104]. This way the batteries can be used to the maximum of their energy storage capabilities, and then recyclable useful materials can be recovered (e.g. electrodes) to minimize the amount of resources being dumped in landfills. Ahmadi *et al.* listed Pyrometallurgy and Hydrometallurgy as the recycling processes, which represent the applications of aqueous chemical treatment, and high heat for material extraction respectively [105]. A similar and more detailed recycling process outline for used Li-ion batteries was presented in [24], which is visualized in Fig. 29. This method can be applied for other battery chemistries as well. The concept of recycling used SLBESSs are supported by other works too [37]. Based on these studies, recycling and then disposing of the leftovers appear to be the process of choice, but before going down that path, a few considerations have to be made. First of all, the economic feasibility of the recycling process has to be validated first in order for this approach to thrive, and related business models has to be investigated. The existence of required amount of used batteries to sustain such approaches need to be considered as well. This process thus can succeed in regions where there will remain sufficient supply of used batteries, and the demand for the recycled material as well as the environmental benefits resulting from such approaches. Considering these factors, such recycling approaches can be adopted in developed regions with environmental concerns such as the United States, Canada, the European Union, Korea, Japan etc. Developing regions such as India, Mexico can show inclination to such initiatives as well; whereas there is little possibility of profiting from such businesses in underdeveloped areas unless an export market for recycled materials is secured. Secondly, the proper disposal of the leftovers remaining after recycling has to be determined considering

TABLE 8. Personal protective equipment (PPE) classification (adapted from [99]–[101]).

Level of PPE (OSHA)	Use-case	Apparatus	NFPA 1994 equivalent category
Level A	Maximum eye, skin, mucous membrane, and respiratory protection	• Self-contained breathing apparatus (SCBA) • Chemical protection suit (fully encapsulated) • Chemical resistant outer gloves • Chemical resistant inner gloves • Chemical resistant boots with steel shank and toe	None
Level B	Maximum respiratory protection with less emphasis on eye and skin protection	• Self-contained breathing apparatus (SCBA) • Chemical resisting apparel • Chemical resistant outer gloves • Chemical resistant inner gloves • Chemical resistant boots with steel shank and toe	Class 2
Level C	Known airborne substance with known concentration with no chance of eye and skin exposure	• Air purifying respirator (half or full mask) • Chemical resisting apparel • Chemical resistant outer gloves • Chemical resistant inner gloves • Chemical resistant boots with steel shank and toe	Class 3
Level D	Work uniform	• Safety boots • Overall	Class 4

the least environmental pollution. Burying these materials with proper insulation can be an option. Fig. 30 sums up the battery life-cycle with second-life use.

According to [104], the Li-Ion battery (LIB) waste stream consists of 25% battery-electric vehicle (BEV), 36% long-range plug-in hybrid electric vehicle (PHEV), and 39% short-range PHEV LIB packs. In the year 2018, an estimated 100000 metric ton (MT) LIBs were recycled globally [106]. The proposed mass flow hierarchy of LIB batteries according to [104] is shown in Fig. 31. The batteries will cycle through multiple systems at different time in future. The cycles are denoted as C1, C2, and C3, which are separated by a time lag of n, n+4.5, and n+9.5 years respectively.

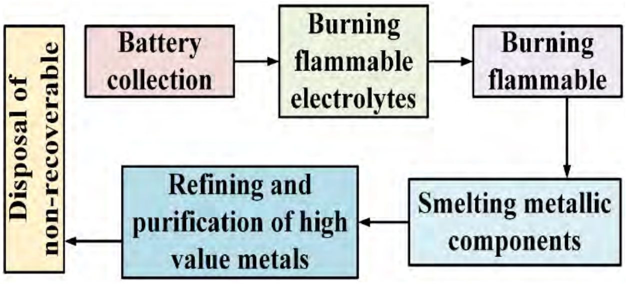


FIGURE 29. Process of handling SLBESSs after second-life [24], flammable materials are burnt first, and the rest of non-recoverable items are discarded after extracting the high-value metals.

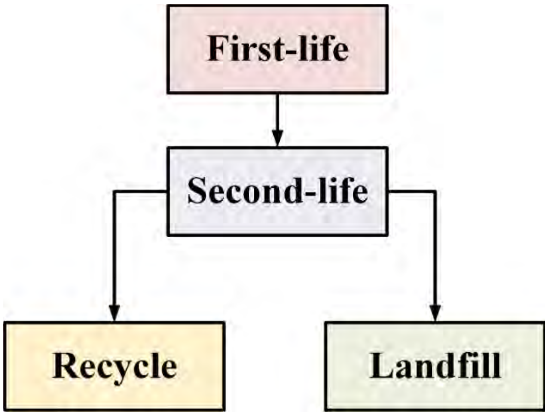


FIGURE 30. Battery lifecycle with second life use. The second life extends the service period by employing used batteries in useful applications.

V. COST OF BATTERY REPURPOSING

Similar to any product, the SLBESS cost is to be determined by the production costs and required service margins. In a report published by the Sandia National Laboratory the sectors contributing to this cost are discussed in detail, where the money required for obtaining SLBs, expenses in labor, general & administrative costs, and packaging materials were identified as the major contributors [107]. All the factors contributing to SLB price those were identified in this study are shown in Fig. 32. The expenses in different sectors in SLBESS manufacturing is presented in Fig. 33. Additional cost estimations can be viewed from [13]. Neubauer *et al.* investigated the effect of SLBESS module size on cost in [108]. They have considered different cell-level fault rates and determined cost for purchasing used batteries and making SLBESSs for module sizes with up to 24 kWh capacities. The purchasing cost was understandably the lowest with the highest fault rate of 1%, but the production cost of SLBESS with such faulty cells were naturally found to be the highest as more effort was required in the testing phase. And with the lowest fault rate of 0.01% gave the lowest cost (~30 $/kWh)

TABLE 9. OSHA standards related to SLBESS manufacturing (adapted from [102], [103]).

Area	Standard	Topic
29 CFR 1910: General Industry – Personal Protective Equipment	1910.132	General requirements
	1910.133	Eye and face protection
	1910.134	Respiratory protection
	1910.135	Head protection
	1910.136	Foot protection
	1910.138	Hand protection
29 CFR 1910: General Industry – Toxic and Hazardous Substances	1910.1025	Lead
	1910.1200	Hazard communication
e-CFR 1926: Safety and Health Regulations for Construction – Electrical	1926.441	Batteries and battery charging

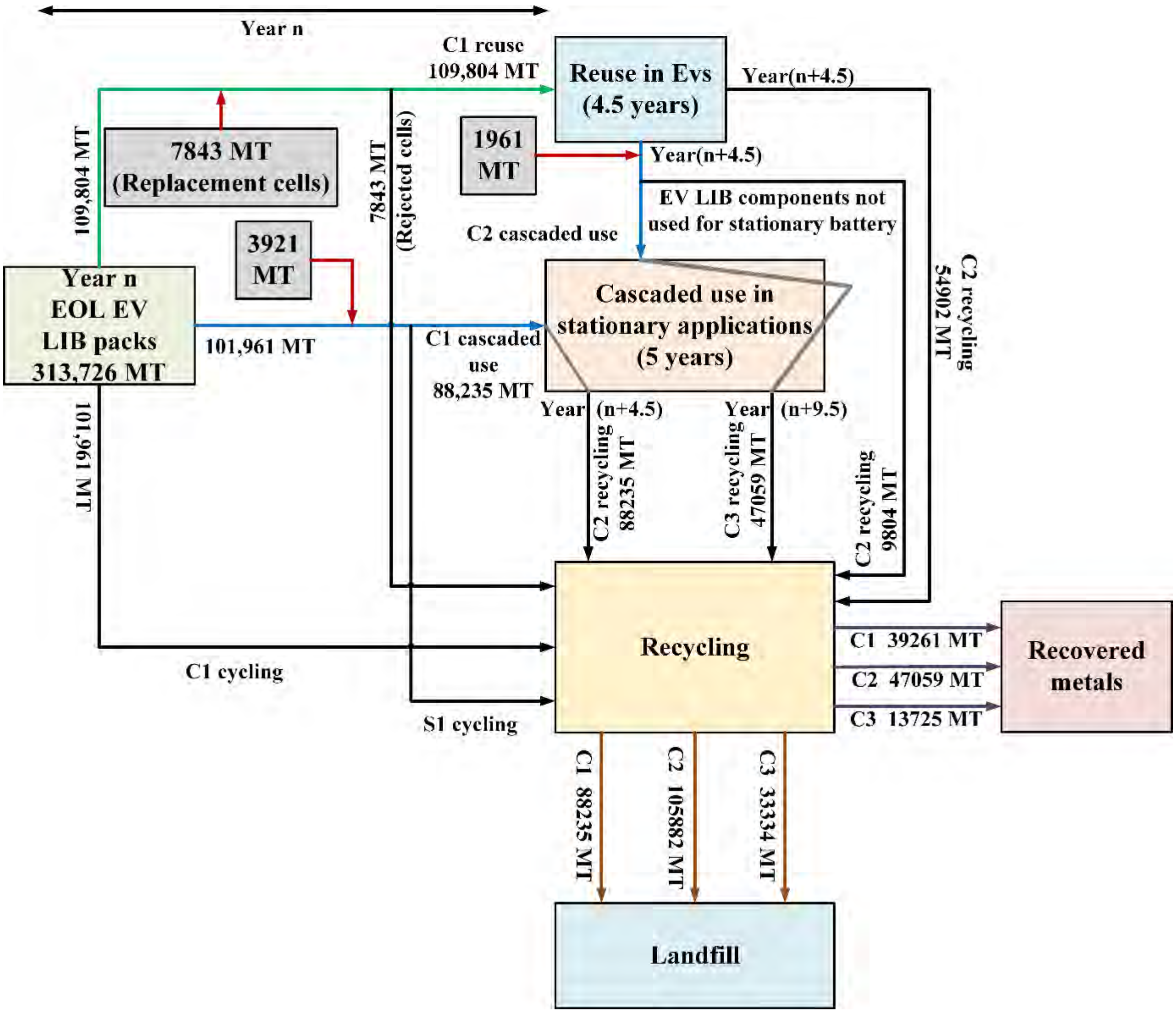
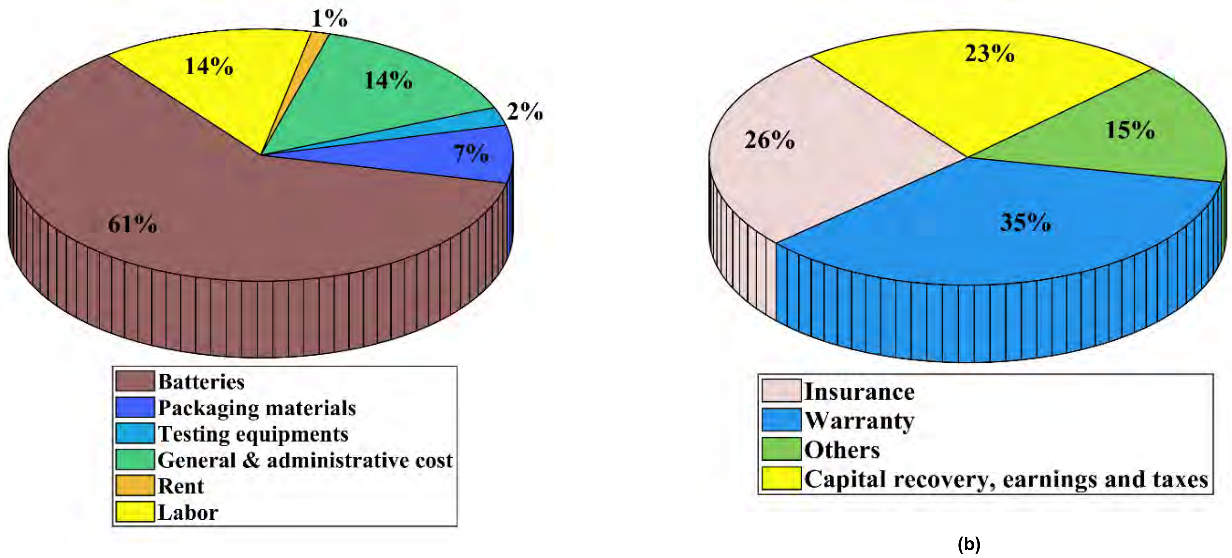


FIGURE 31. Diagrammatic flows of EOL EV LIBs across different waste management routes [104]. The amount of materials flowing in different directions are shown in terms of metric tons (MT).

for almost all module sizes ranging from 8-24 kWh. However, discrepancies remain among different cost studies, which was presented in [22], and is shown in Table 10. This trend of dissimilarity in cost estimation was continued in [109], where transportation cost was considered the second most prominent expense after purchasing used batteries, contrasting the previously mentioned literature, where this sector was not mentioned directly. This study by McLoughlin *et al.* also demonstrated costs for SLBESSs for different applications such as residential, commercial, and industrial uses where



(a)

(b)

FIGURE 32. SLB cost breakdown (a) direct cost, (b) indirect cost [107]. The most obvious costs are from purchasing the raw materials (used batteries), and providing essential services such as warranty.

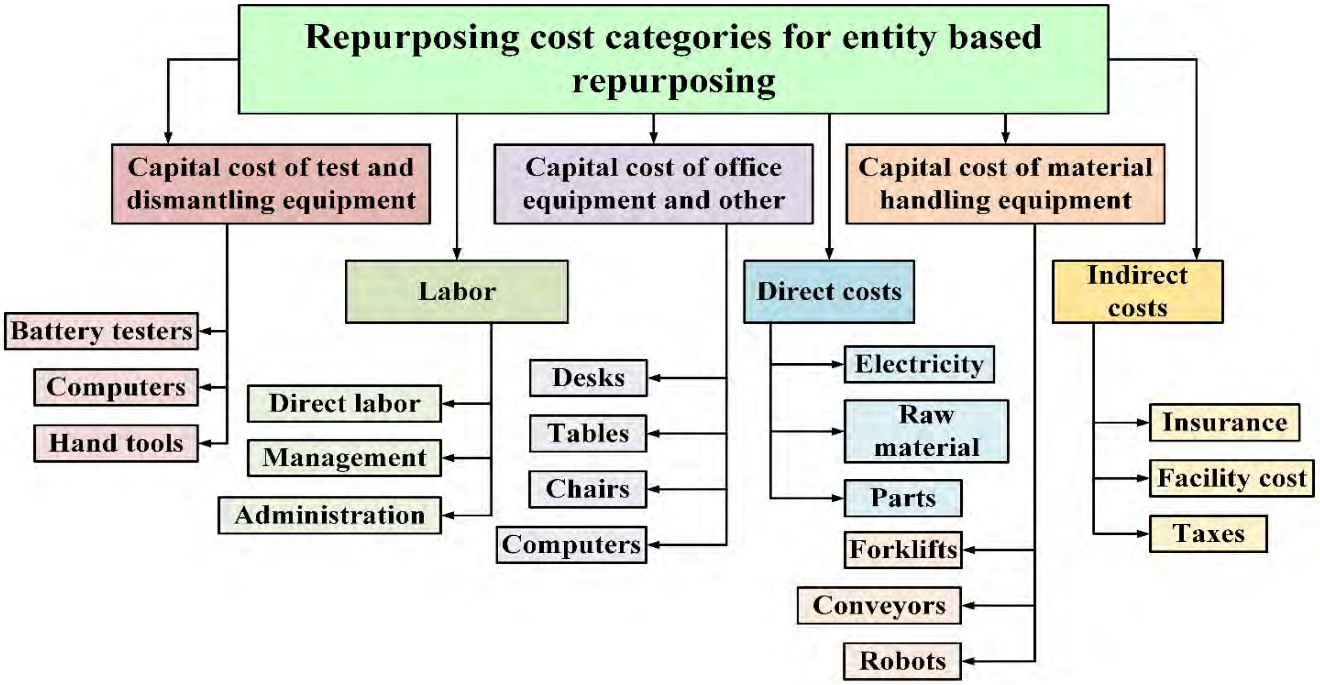


FIGURE 33. Estimated expenses in SLBESS manufacturing [22].

TABLE 10. Discrepancy in different cost studies of battery repurposing [22].

	Cready	Narula High	Narula Low	Williams	Neubauer High	Neubauer Low
Repurposing(€/kWh)	55.38 €	1.94 €	1.29 €	48.08 €	24.62 €	13.85 €
Repurposing(€/module)	149.54 €	5.23 €	3.49 €	129.81 €	66.46 €	37.38 €

the costs for residential setups were the lowest and industrial applications had the highest costs – as can be expected from their scales.

VI. POTENTIAL MARKETS FOR SLB

From an economic point of view, the second-life battery applications can be categorized into two business options.

TABLE 11. **Markets for repurposed Li-Ion batteries [110].**

Market application	Number of repurposed packs	Estimated market size	Cycle frequency	Potential for application	Limitations for application
Residential	1-2	> 3 Million'	Daily	- Large market - Small, easy-to-handle units - Market can be incrementally developed	-Regulated pricing minimizes savings for user - Risk and maintenance must be addressed
Telecommunication towers	5-10	100,000 s	Daily and back-up	- Motivated for onsite energy storage, and back-up currently has many sites	- High reliability demanded by application, and would be difficult to achieve
Light commercial	10-15	10,000-100,000	Daily	- Greater savings due to unregulated electricity pricing - Availability of expertise, location, and personnel to support the technology	- Safety regulations for storing batteries on site must be determined - More packs are required
Office building	30-40	100,000	Daily	- Greater savings due to unregulated electrical pricing - Can complement generator use	- Larger application requires significant storage investment - Urban locations may create greater risks
Fresh food distribution centers	30-40	10,000-100,000	Daily	- Greater savings due to unregulated electrical pricing - Large electrical demand with highly controllable equipment will work well with technology - Possibility of attracting early adopters if business case can be demonstrated - Have the expertise, location and personnel to support the technology	- Larger application requires significant storage investment - Payback must be clearly demonstrated
Stranded power (renewables)	900	Uncertain (< 10)	10-20/Month	- Intermittent nature of renewable energy justifies energy storage - Availability of expertise, location and personnel to support the technology - Motivated early adopters allow for greater market penetration of wind and solar	- Size of application may use up supply or the supply will not be available - Increased risk of fire - Complexity of controlling packs of varying states of health
Transmission support	1000 s	Uncertain (<10)	1/Months	- Large energy needs create larger market for batteries - Currently users of auxiliary electricity services and thus have some comfort with the application	- Size of application may use up supply or the supply will not be available - Increased risk of fire
				- Motivating early adopters to help ease transmission congestion. - Benefits can be achieved even if worked with smaller market and customers base.	- Complexity of controlling packs of varying states of health

The first option corresponds to using the batteries for large applications such as providing support to renewable energy sources (RES) such as wind or solar, etc. and transmission. The second option is the smaller energy applications, which include residential consumers, commercial consumers such as telecommunication companies, food distribution centers, and light commercial buildings. Due to the intermittent nature of the renewable energy sources, the use of SLBs as energy storage device can be justified. The large energy need can create a large market for the batteries. Furthermore, this technology has the necessary expertise and personnel support, required for safe and efficient operation, thus motivating the early adopters and facilitating greater penetration of wind and solar. However, these kinds of application require a prodigiously large array of battery packs.

The need for onsite energy storage opens up the possibility of employing SLBESSs in telecommunication energy management. However, it requires high reliability, which is an arduous task to achieve. SLB enables the commercial consumers, offices, and fresh food distribution centers to have access to unregulated electricity pricing, and thus greater savings can be achievable. Furthermore, the aforementioned

TABLE 12. Different applications opportunities of SLB and their corresponding capacities [109].

Storage	Applications	Capacity
Residential	Load following	- One deep discharge and several shallow discharges per day - Typical discharge rate of C/3
	Back-up systems	- Up to 25 kWh for off-grid - Daily, moderately deep discharges (>50% DoD)
Commercial	Load following	- 75 to 100 kWh - Typical discharge rate of C/3 - One deep discharge and several shallow discharges per day
	Back-up systems	- Standby power - C/5 discharge, infrequent
	Peak shaving	- 3,000 to 4,000 kWh - C/2 to C discharge, daily
Industrial	Load levelling	- 100,000 kWh
	Renewables firming	- 1,000 to 10,000 kWh - C/5 discharge, frequent
	Spinning reserve/area regulation	- 5,000 to 7,500 kWh - C/2 to C discharge, infrequent
	Peak shaving	- 3,000 to 4,000 kWh - C/2 to C discharge, daily
	Transmission stabilization	- 140 kWh, 500,000 kW - 5 to 10 pulses per second, once/month

markets also have expertise, location, and personnel to support this technology. Nevertheless, this kind of application requires a considerable amount of safety regulations and greater storage investment. Therefore, implementing this technology in urban areas will be difficult and will have a greater risk due to the proximity of residence and community members. Different markets for repurposed lithium-ion batteries, the number of packs, and their potential and limitations for application for each of these markets according to [110] are shown in Table 11.

VII. APPLICATION OF SLB

Second-life batteries can be employed for a wide range of applications. This section presents an overview of those with necessary elaborations.

A. BASED ON APPLICATION AREA

1) RESIDENTIAL APPLICATION

Most of the electricity demand in residential applications correspond to powering the electrical appliances for space and water heating. This demand for electricity varies for different parts of the day. With RES integration with the grid such as PV, the electricity need can be met during the daytime. During the evening, however, when there is no PV generation, the peak demand occurs and thus necessitates using energy storage systems such as batteries. Considering the cost, SLBESS is a viable solution for this problem [109]. Using SLB as storage enables the PV generated energy to be stored so that it can be used later. For load following in residential applications, a storage capacity of 3 to 4 kWh is required with one deep discharge and several shallow discharges per day. Furthermore, the discharge rate of SLB is considered to be C/3. During back up application, the SLB has a capacity of 25 kWh and DOD greater than 50%. The residential opportunities of SLB are presented in Table 12. The schematic diagram of residential application SLBESS according to [93], is represented in Fig. 34.

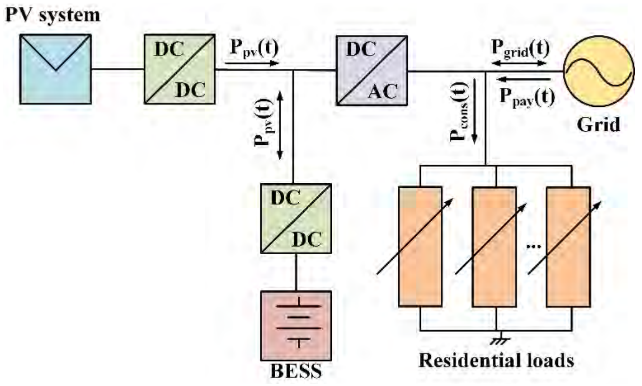


FIGURE 34. Schematic diagram of residential application of SLBESS [93]. SLBs can be used in the BESS instead of new batteries for reduced cost.

2) COMMERCIAL APPLICATION

The commercial demand for electricity on average is much higher than the residential demand. The peak demand for the commercial sector occurs closer to midday in contrast to the residential sector, and thus the need to shift demand from the evening is not the main concern here. However, the PV generation being dependent on climate conditions such as rain and cloud prevalence necessitates the need for storage systems. The average commercial load being higher, load following and peak sharing applications may be more appropriate. Peak shaving applications have a demand of 3000 to 4000 kWh, which necessitates the need for higher storage capacity [109]. Therefore, a large pack of SLB is required for this kind of application. According to [109], for residential storage, a battery having 70% of its original capacity is considered a reconditioned battery. Reconditioned Nissan Leaf batteries having 70 % of their original capacity is used for peak shaving application in [109]. 178 to 238 batteries were used in to accomplish this task. This requirement for a high number of batteries is the reason why it is unlikely to use reconditioned batteries for peak shaving applications for commercial use. However, engaging in demand side management (DSM) schemes enables the reconditioned batteries in smaller packs to assist in peak reduction. On the other hand, the load flowing application for commercial use has a demand of 75 to 100 kWh, which is significantly less than the peak shaving application. Therefore, it is more realistic to use the reconditioned batteries for load following application. Only 4 to 6 reconditioned batteries combined together is required for load following applications [109]. Furthermore, the C-rate of Li-Ion batteries is more than enough to meet the demands of the load following application. There will be one deep discharge and several shallow discharges per day, therefore to avoid excessive DOD's, this application will only be suitable in locations with high solar irradiance. The battery backup application in remote areas requiring small power equipment is also a well-suited application for the reconditioned batteries. The commercial opportunities of SLB are presented in table 12.

3) INDUSTRIAL APPLICATIONS

The demand for industrial consumers is very much higher than the residential and commercial consumers. For the industrial sector, the peak demand occurs during midday and the PV generation is also the highest during this time. Therefore, using a storage system can provide back up during low solar irradiance. The difference between the maximum and minimum electricity use between morning and midday is large and thus the demand has to be shifted from the peak to other times of the day. This done by utility load leveling by using storage devices such as batteries. The load leveling in this case, requires a huge amount of storage capacity (100,000 kWh) because the load demand of the industrial consumers is very high. According to [134], approximately 6000 reconditioned batteries with size similar to the Nissan Leaf combined together is required for load leveling for a typical industrial customer. Thus it is not very practical to use reconditioned batteries for such applications. On the other hand, significantly less storage capacity is required for renewable farming for industrial applications. The load demand is in between 1000 kWh to 10000 kWh, which corresponds to needing 60 to 595 reconditioned Nissan Leaf batteries for providing necessary backup [109]. The peak shaving application for industrial sector requires a similar amount of capacity like the commercial sector discussed earlier. Transmission stabilization is another application in which very short bursts of power is required to stabilize the voltage and frequency variations. However, the reconditioned EV batteries cannot be used in this purpose as their C-rate capabilities will exceed [109]. The industrial opportunities of SLB is presented in Table 12.

B. BASED ON USAGE

1) GRID STATIONERY

With the increase of EV penetration in the market, it can be estimated that the number of batteries on their second life will also be increasing. These large number of SLBs can be used to create a large array of packs having power in MWh range, and thus; can be applicable in stationary grids [94]. The utilization of SLBs in utility grids can effectively reduce the peak load. Furthermore, it will enable the consumers, both small industries and domestic, to optimize their energy demand patterns according to the market conditions, and thus; ensuring optimized use of energy. The application of SLBs in the stationary grid operations can be categorized by the following subsections.

a: RENEWABLE ENERGY FARMING

The integration of renewable energy sources (RES) with the grid has both environmental and economic advantages [94]. However, the intermittent nature of the RESs raises a major concern on the grid's stability and integrity. Using a large battery energy storage system may be a potential solution for this problem, however, due to high cost, it cannot be considered a viable solution. Therefore, to reduce the cost, SLBs can be utilized in the renewable energy system to not only store the excess energy but also reduce the effects of the intermittent characteristics of the RESs; and thus contributing significantly to enhance the stability of the grid. In [94], method for determining the optimal size and rating of the SLBESS for facilitating RES integration in the grid was proposed. Furthermore, the cyclic patterns for testing real Li-Ion batteries and their aging effects on the specific application were also studied [94]. How the storage system reduces the intermittency of RES is shown in Fig. 35. Whenever the renewable energy (RE) generation ramps up, the energy provided by the storage system ramps down. Similarly, when the RE generation ramps down the energy provided by the storage system ramps up. Therefore, by charging or discharging the active power, the BES contributes in reducing the intermittency caused by the RESs. The output power of a solar farm with and without BES is shown is Fig. 36.

b: GENERATION-SIDE ASSET MANAGEMENT

The longevity of the generation side assets, such as the plant equipment and the generating units depends on regular and well-planned maintenance. However, the necessity for continuous electricity supply and high demand makes it difficult for scheduling the maintenance periods. Furthermore, forced outrage and temporary maintenance of the thermal units are quotidian in the power plants. Therefore, alternative sources are needed to provide necessary backup during abeyance of generation. Using renewable energy sources is a potential solution for this case. However, the intermittent nature of these sources requires incorporation of additional storage devices. Using conventional storage devices such as batteries are more feasible, but costly at the same time.

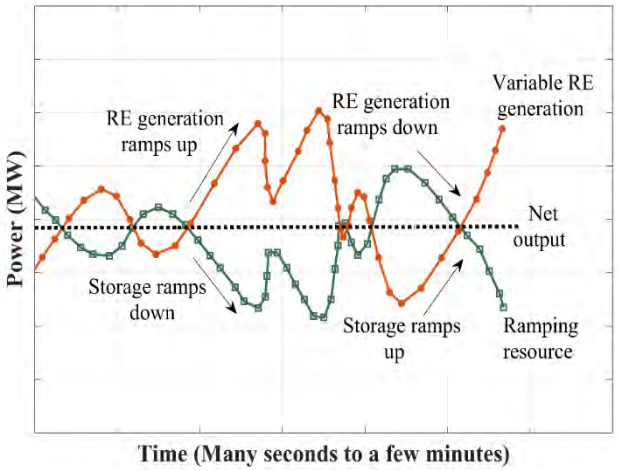


FIGURE 35. Representation of the ESS mitigating the intermittency of RESs by using storage ramping.

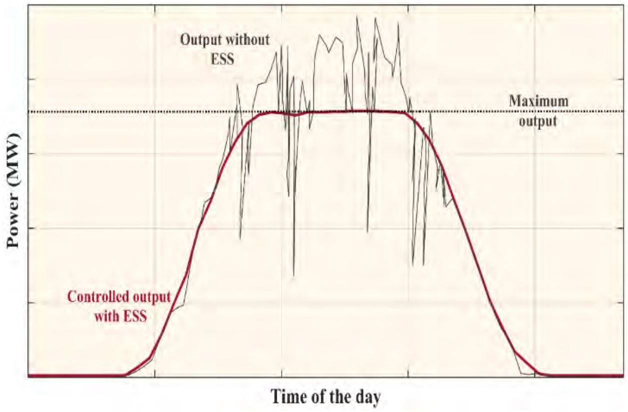


FIGURE 36. The output of renewable energy sources with and without energy storage system. Storage helps to smoothen the output.

Therefore, considering the overall stability, reliability, and economic aspects, the second life batteries is the most feasible solution for generation assessment management [111]. The flow chart for the generation-side asset management using energy storage system is shown in Fig. 37. When the power generation is temporarily suspended due to maintenance or forced outrage the ESS is activated. On the contrary, when the maintenance is completed or the outrage is cleared the ESS is deactivated.

c: ENERGY ARBITRAGE

The energy storage plant can be implemented for energy arbitrage applications [112]. Energy arbitrage corresponds to storing electricity during the off-peak periods and using the stored energy during the peak periods which also includes peak shaving and load leveling applications. According to [113], the timetable for peak and off-peak periods are shown in Table 13.

However, the major drawback associated with BESS is its cost. According to [114], for optimal economic operation, reasonably priced storage components are required.

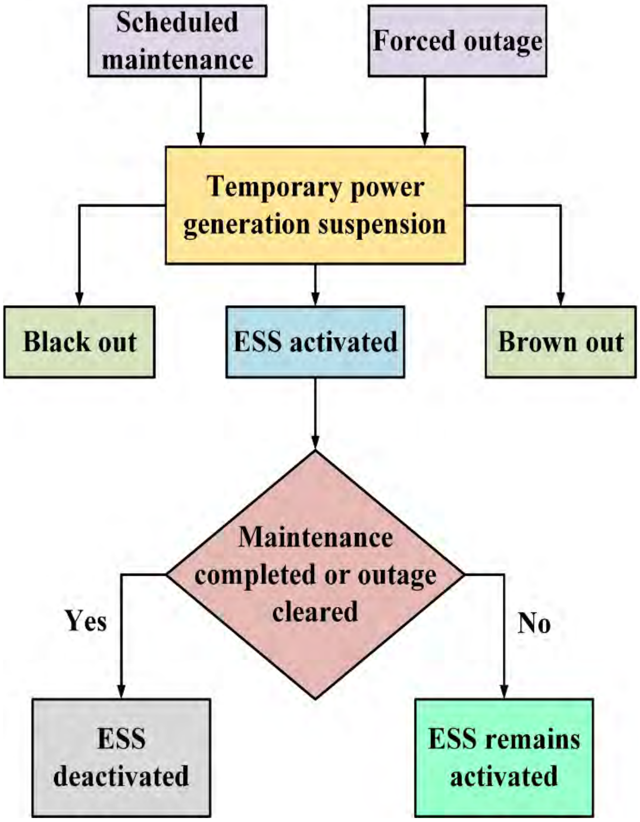


FIGURE 37. Flow chart of how the ESS is used for generation-side asset management. ESS is activated when primary power supply is disrupted.

TABLE 13. Peak and off-peak period schedule [113].

Summer (May - October)		
Peak	12 noon — 6 pm	Monday - Friday (Except Holidays)
Partial-peak	8:30 am to 12 noon 6 pm to 9:30 pm	Monday - Friday (Except Holidays)
Off-peak	9:30 pm to 8:30 pm All days	Monday - Friday (Except Holidays) Saturday, Sunday and Holidays
Winter (November — April)		
Partial-Peak	8:30 am to 9:30 pm	Monday - Friday (Except Holidays)
Off-peak	9:30 pm to 8:30 am All days	Monday - Friday (Except Holidays)

The second life batteries having a capacity of 70% of their maximum capacity can be used for this kind of application due to their low cost. As the cost corresponding to the energy consumption is higher during the peak periods than the off-peak periods, energy arbitrage is a promising solution for

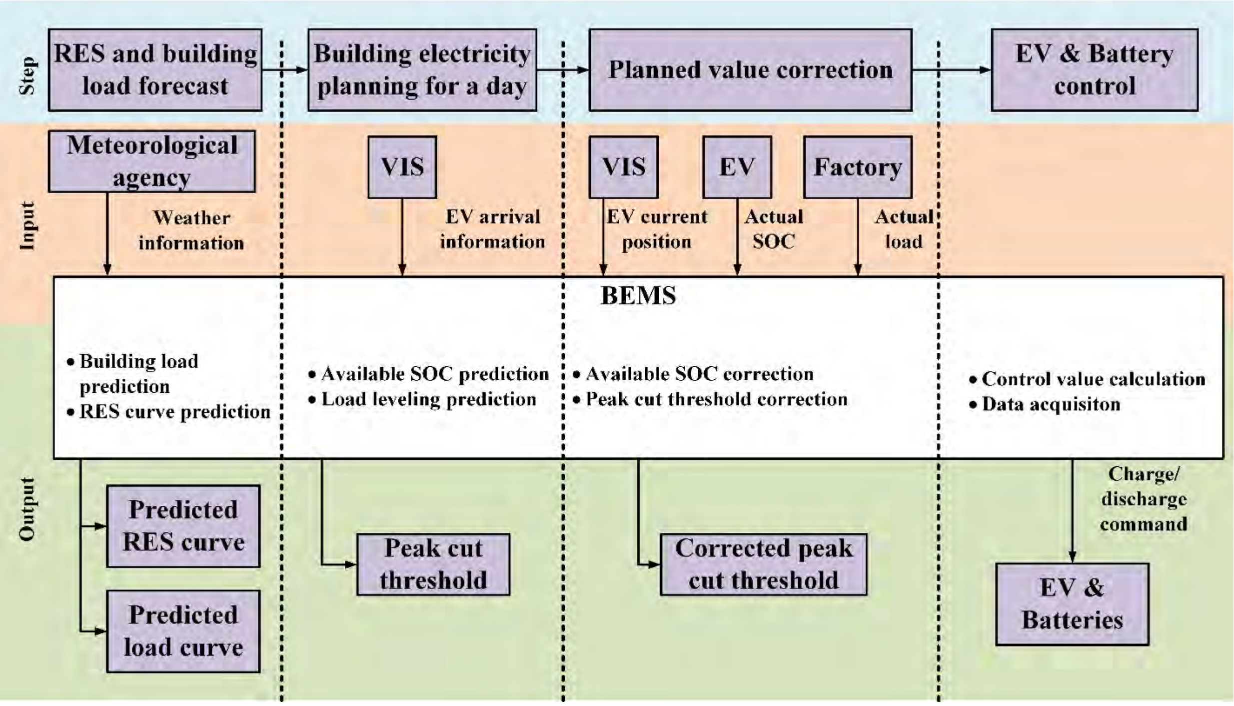


FIGURE 38. Schematic representation of the load leveling concept using EVs and SLBs [116]. Based on the inputs and control scheme, storages can be asked charge or discharge for energy arbitrage.

mitigating energy consumption cost. Storage devices such as batteries are used to store the electricity during the off-peak period, when the consumption cost is low. This stored energy is then used during the peak hours during which the prices are highest, significantly reducing the energy consumption cost. Moreover, during the peak hours, the power quality is not very consistent, which results in losses. By using the storage devices for energy arbitrage, these kinds of losses can be eliminated and the power quality can also be improved [115]. Furthermore, energy arbitrage can also help in meeting the peak demand and thus lessening the need for high capacity generators. The concept of peak shaving of the energy arbitrage applications using battery energy management system according to [116], is represented in Fig. 38. The RES generation and forecasted load was first taken into account. Weather forecasting was into consideration for forecasting the RES generation. The difference between the actual and planned load and generation per day were compensated using EV and battery control. This resulted in significant peak shaving and less usage of energy during the peak periods.

d: AREA AND FREQUENCY REGULATION

To ensure stability, every single generator in the power grid must spin at the same rate. This means that the grid frequency should remain within a specific range of the nominal frequency. However, due to load variation, mismatch occurs between the generation and the load demand, which causes the variation of frequency. Thus frequency regulation is required to ensure that the frequency does not go out of range. Furthermore, to maintain the stability of the power system, real and reactive power injected to the grid must be controlled using area regulation to balance the generation and load demand. Energy storage devices such as batteries can be used for area and frequency regulation applications, which requires them to operate on zero or partial loading [107]. However, due to the high price of Li-Ion batteries, using them for such purpose is not very economical. On the other hand, second-life batteries have enough functional capacity to be used for ancillary services such as area and frequency regulations at a much lower cost [117]. Gas turbine generators, which is often used for area and frequency regulation services due to their fast response can take the help of low cost second-life batteries to have higher participation in the electricity regulation market [117]. Fig. 39 shows that the frequency control can be categorized into three steps- primary, secondary, and tertiary. Batteries can supply real power to the system very fast, therefore it can work along the generators for primary and secondary frequency control.

2) OFF-GRID STATIONERY

Isolated grids such as microgrids are self-sufficient cells, which is used to generate electricity in reliable and economical manner and can work in standalone mode or interconnected with the conventional network and plays a very important role for providing power to remote areas. The integration of RES to isolated systems has become very popular due to the environmental and economic advantages [94], [118]. However, due the intermittent nature of the RESs,

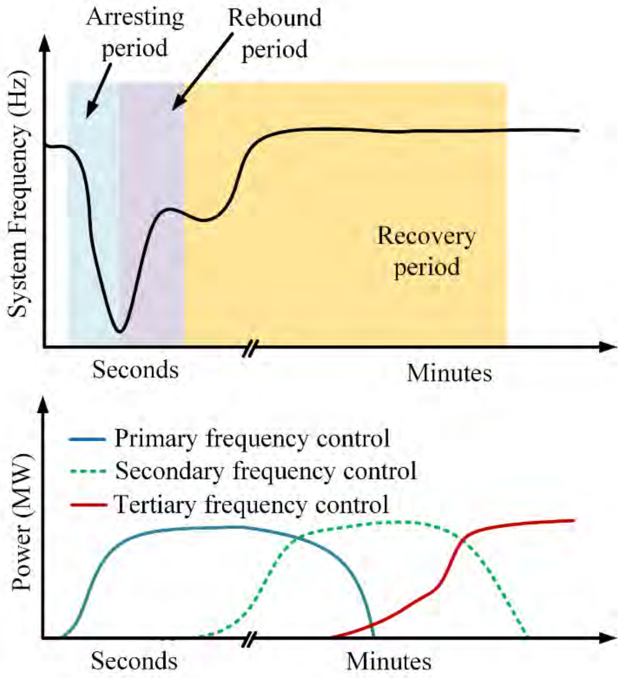


FIGURE 39. Frequency control schemes: primary, secondary, and tertiary frequency control. Each of these work at different operational stages.

energy storage devices such as batteries are used to ensure the stability and integrity of the power system as well as providing backup power to the system. Furthermore, storage systems play a crucial role in maintaining instantaneous power balance between generation and consumption. But the high cost of Li-Ion batteries makes this option restrictive. SLBs have potential applications as energy storage in such sectors, and can offer services at a lower cost. Furthermore, they can also be implemented in commercial and domestic applications which in turns provides support for efficient operation of smart grid [94]. In Fig. 40, the life cycle of repurposed batteries for implementation is stationary setups is shown.

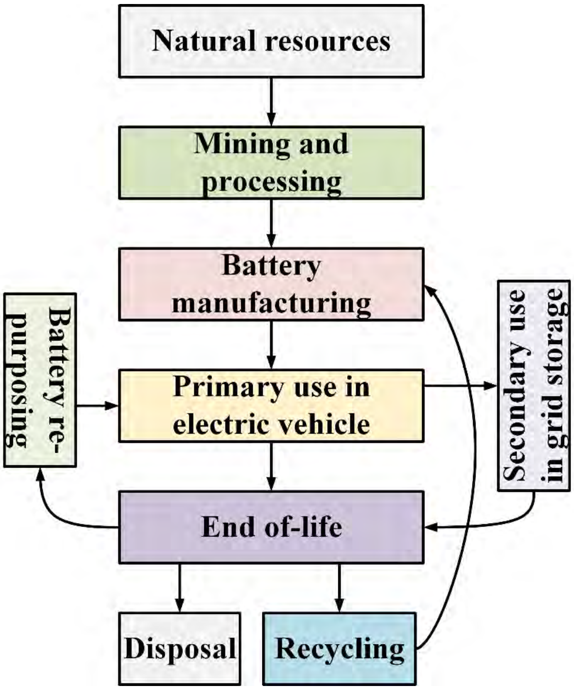


FIGURE 40. Life cycle of repurposed batteries for implementation in off-grid stationary applications [94].

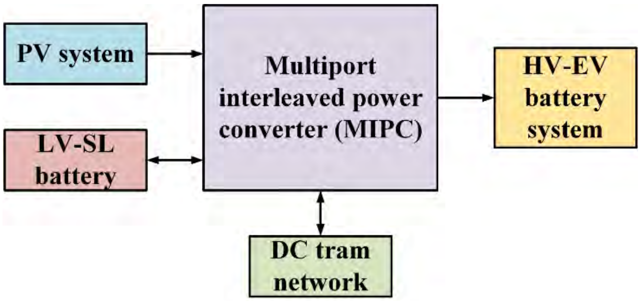


FIGURE 41. DC fast charging system using hybrid PV-SLB-tram network [90]. Second-life batteries support the PV system by complementing the intermittencies.

3) MOBILE APPLICATIONS

a: EV CHARGING STATION

In recent times, due the economic and environmental benefits, there has been significant increase of EVs as replacement of conventional internal combustion engine (ICE) vehicles. However, the scarcity of charging infrastructure is a major concern for more EV penetration in the market. The EVs are recharged from the utility via battery charging system; and thus establishes a connection between the utility sector and transport sector [119]. Li-Ion batteries can be used in fast-charging stations but are not economically feasible due to their high price. The price of SLB on the other hand, is much less and therefore, can be used for providing interim storage and power buffering for fast charge stations. Hegazy *et al.* [90] suggested a hybrid PV-SLB-tram network (TN) topology based DC fast charging system for EVs, which is illustrated in Fig. 41. The multiport interleaved power converter (MIPC) is used to control power flow directions. This proposed system can also function as the storage system for the tram network (TN). The circuit of the hybrid PV-SLB-tram network topology based DC fast charging system is presented in Fig. 42. The direction of power flow is from PV to the DC link and from DC link to PV, therefore, both PV and EV are connected to the DC link via unidirectional interleaved converter ports. However, the SLB and the TN both are connected the DC link via bidirectional interleaved ports, because in this cases the power flow is also bidirectional. The different operating modes of the charging infrastructure is represented in Fig. 43.

b: SHORTER RANGE TRIP AND VEHICLE-TO-GRID (V2G)

According to [9], EV batteries, which are retired from its first life and have 60 % of their original capacity can continue to meet the daily travel of over 75% of drivers. Therefore, the used EV batteries have the potential to be deployed in short range EVs. The utility and recreational EVs operate in shorter

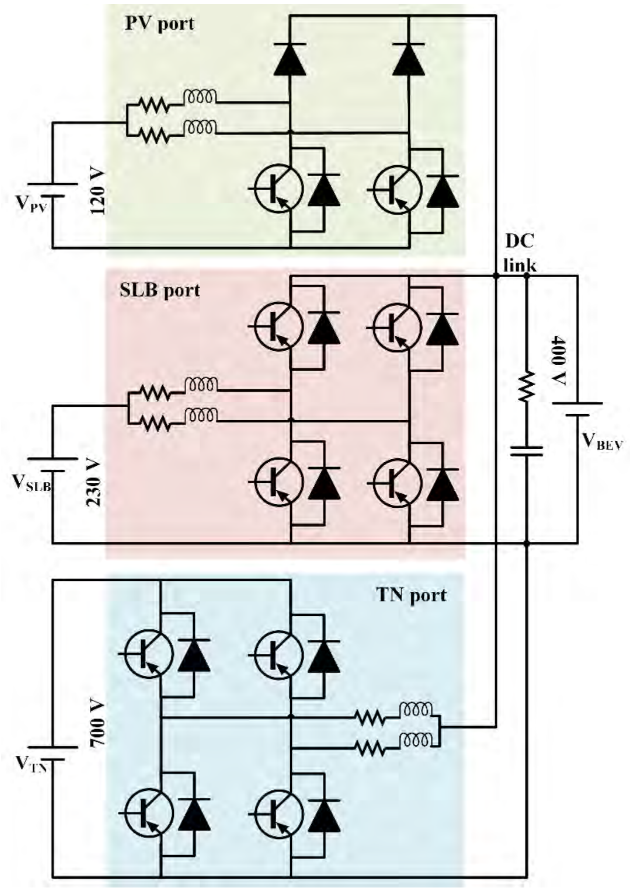


FIGURE 42. Circuit representation of the DC fast charging system using the hybrid PV-SLB-tram network [90].

range, therefore, it will be more cost effective to use SLBs for this purpose. Furthermore, used EVs having batteries past their first life can be sold in the used car markets to drivers requiring a vehicle for only local travel or commuting. The high penetration of EVs result in substantial increase in the demand of electricity, required for charging. Matching this increasing demand with the power generation is a very arduous task. Furthermore, the demand varies for different parts of the day and the peak demand lasts for only a few hours for the daily cycle. The generation and the transmission systems have to be designed to meet with this peak demand, which results in the network being under-loaded for most time of the operation cycle [115]. These problems can be mitigated by using the idle EVs at charging stations for vehicle-to-grid (V2G) services [120]. The EVs during their idle time can supply energy to the grid, making a significant contribution to counter peak power demand. The EVs containing SLBs, which are used for short range trip can also be used for V2G services. As the SLB batteries has more capacity than needed to meet the needs of short range trips [9], the SLB EVs dedicated for short range trips, can make a significant contribution to the V2G technology during their idle time. The schematic diagram of V2G application of EVs is shown in Fig 44.

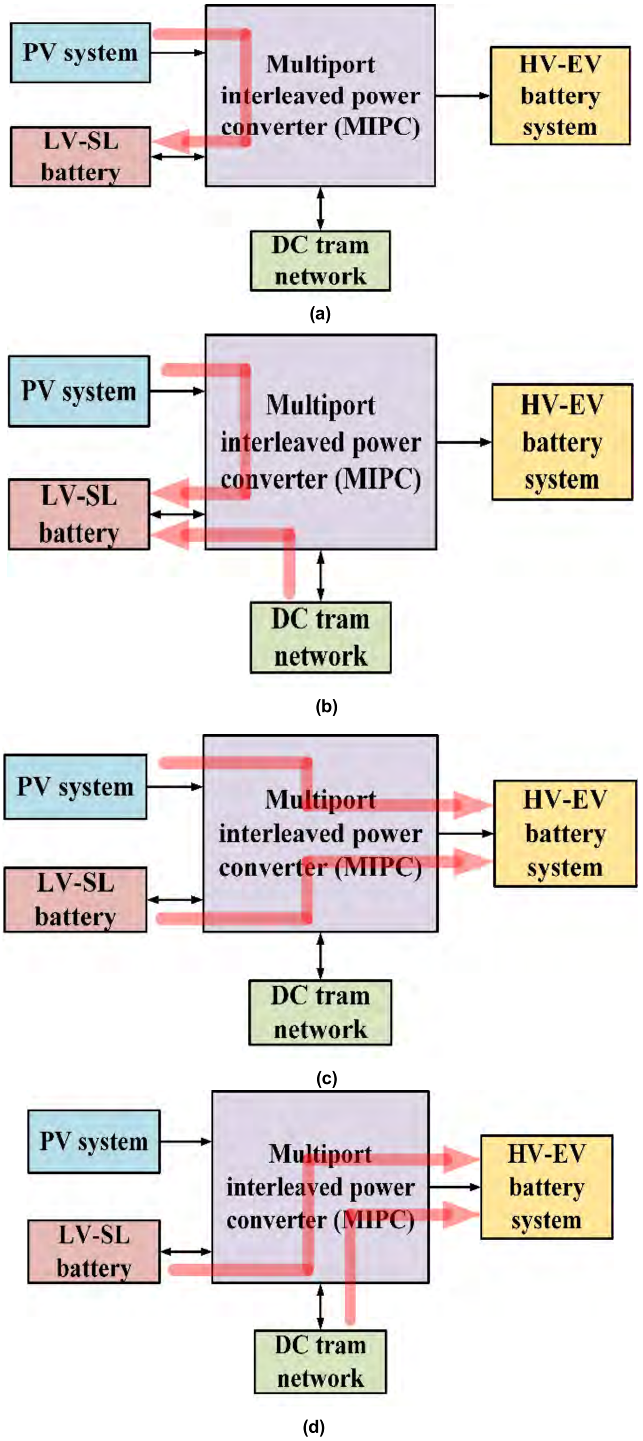


FIGURE 43. Different operating modes of the DC fast charging system (a) Charging of the SLB from PV, (b) Charging of the SLB from PV and tram network (TN), (c) Fast charging of the EV battery from PV and SLB, and (d) Fast charging of the EV battery from SLB and TN [90]. The battery can be get charged from different sources, and can deliver power when required, depending on the operating mode.

Table 14 shows the applications of ESS using first life and second life of battery along with their usage pattern and potential.

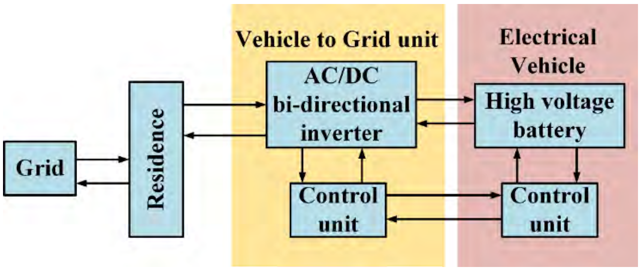


FIGURE 44. Schematic diagram of V2G application of EVs. This system is capable of supplying stored energy of EVs to the grid, which has an array of benefits.

TABLE 14. Applications of ESS using first life and second life of battery.

Applications of ESS		1st life usage	2nd life usage
On-grid stationary	Renewable Farming	***	***
	Peak reduction	***	*
	Load levelling	***	**
	Area & frequency regulation	***	***
	Generation-side asset management	***	**
	Voltage or reactive power support	**	*
Off-grid stationary	Microgrid	***	***
	Smart grid	***	***
	Power quality & reliability	***	*
	Load following	***	**
	Spinning reserve	***	*
Mobile applications	EV charging station	***	**
	V2G for fast charging	***	*
	EV for long range trips	***	X
	EV for short range trips	***	**

*** Frequent, ** Occasional, * Rare, ^{X} Infeasible

VIII. IMPACTS OF SLBESS

A. DECREASED COST OF ESS

In this age of ever-increasing use of renewable energy sources (RES), ESSs are becoming an essential part to complement RES-intermittencies, and also to provide a number of ancillary services to the grid. In such cases, the high cost of ESS become a serious concern. SLBESSs are expected to cost less than new ESSs, and still be capable to serve the grid-duties perfectly; and thus will provide a very attractive solution for such use-cases. This is especially significant as it will enable further penetration of RES in the energy generation sector while opening up affordable options for operators to provide reliable services. A 2012 study made by Shokrzadeh *et al.* showed that SLBESS could cost 31.71% of new ESSs, based on their estimations [121].

B. REDUCED COST OF EVS

The price of batteries contributes significantly to the comparatively high price of EVs [1]. If additional value for used EV batteries are created because of the SLBESS industry, then such vehicles will retain more resale values; and if there is a battery takeback or leasing system available from the automobile manufacturers, then the price of the EVs itself can come down. Such a system was adopted by Nissan for its Leaf EV [122], [123]. This practice is expected to increase EV penetration and contribute to a greener transportation sector. Considering the second-life value, [124] determined the total value of the Leaf battery to be around \$15,000, where \$3040 was considered as SLB value. However, SLB usage is not going to benefit the first-generation EV owners, whose batteries are assumed to end their first life in 2019, as the cost of new batteries can be decreased by as much as 70% – according to a study published by Neubauer *et al.* in 2011 [6].

TABLE 15. Economic and associated environmental impacts of SLB.

Economic Impact	Aftermath	Environmental Impact
Reduced cost of ESS	Increased RES penetration	Less pollution from energy generation
Reduced cost of EV	Increased EV penetration	Less pollution from transportation

C. ENERGY AND ENVIRONMENTAL IMPACTS

The most prominent impacts of SLBESS, and almost the whole point of such an approach, are the gains it facilitates in terms of energy and environmental benefits. 80% energy of traction batteries, and significant amount of energy left in used batteries generated from other sources, will be wasted if they are not reused. Reference [27] showed that from 2015 to 2040, 63% of the EV batteries could end up in waste stream. This will be a huge waste of the energy, time, and effort spent on collecting the raw materials, and manufacturing the batteries. And if these batteries are not reused, they will end up in landfills that will pollute the environment. A second-life use thus significantly dials down such wastes, and presents an opportunity to make good use of the energy spent in producing the batteries in an environment friendly way. Reference [125] stated that 15-70% reduction in gross energy demand and global warming possibility can be achieved by expanding battery-life through SLB application. Reference [126] also showed there existed scopes to improve the use of batteries thorough better reuse and recycle process, and reduce ecological impacts through that. Sathre *et al.* showed that the renewable penetration supported by SLB from PHEVs can provide around 15 TWh energy per year in 2050 in California, while reducing 7 million metric tons CO_2 in equivalent emission [14]. Ahmadi *et al.* showed that SLB application of vehicle batteries could be compared to converting conventional vehicles into electric ones, and thus; such extended use of vehicle batteries essentially doubles the GHG emission reduction of electric vehicles [127]. The economic impacts of SLB usage and associated environmental effects are shown in Table 15.

TABLE 16. Barriers and potential solutions of SLB usage.

Barrier	Degree of impact	Potential solution
Shortage of raw materials	Low	Proper waste management/collection of used batteries
Shortage of supply	High	Implementing proper production methodologies
Shortage of demand	Low	Investing in market development
Shortage of public interest	Medium	Organizing education, training, seminar, symposium, pilot projects.
Shortage of technology	Low	Investing in research and development (R&D)
Creating market structure	Medium	Investing in market development
Creating business policy and framework	Medium	Developing organizational, state, and federal policies. Ensuring availability of battery data.
Securing supply and distributing chain	Medium	Market and supply analysis
Maintaining reasonable price and performance	Low (possibility of increase in future)	Market analysis and technology development

IX. BUSINESS STRATEGY

For the second-life battery idea to survive as a business, the SLBESS must have cost lower than the new ESS available at that time, and the SLBESS price must be justified by the services it will provide. Recycling after the reuse phase is a key component to reap the most of economic and environmental benefits of the SLB concept, and the recycled materials also should have lower price than new materials [24]. Reference [32] showed that the price of new batteries can be halved by 2020 as compared to 2015, and SLB businesses must be designed keeping such things in mind. Avoiding such scenarios can be comparatively easier for corporations in ESS or EV business if they start SLB ventures as well, as they have easy access to the SLB supply line, and already available expertise and equipment to produce SLBESS. Nissan has already shown the feasibility of such an approach through its joint venture with Sumitomo Corp.: the 4R Energy Corp. [128]. Such an approach can also be feasible for entities those have both EV and ESS businesses, such as Tesla. Reference [22] predicted that such original equipment manufacturers (OEM) can play a major role in the SLB market, at least in medium and short terms. The viability of a business depends on matrices such as net present value, internal rate of return, and return of investment. SLB businesses must be able to score satisfactorily in these matrices to show their competence to come out strong, and the business models for this industry have to be developed considering that. And there are strong evidences that it is possible. Reference [129] listed four such cases, who created values from SLB use in various ways: ESS, EV charging, recycling, and financial leasing; the Nissan-4R Energy was one of the cases studied in this work. SLB businesses can also receive, or can ask to receive monetary awards for the additional services they generate, for example, reduces costs of waste management. References [124], [130] showed the numerous ways second-life EV batteries come into use, and the monetary values associated with those. They used PHEV, Chevrolet Volt, and Nissan Leaf as study cases. Reference [131] showed that 35% value can be added to EV batteries through a second-use phase. Klör *et al.* noted the market properties necessary for SLB businesses in [132], while likely challenges in such markets were shown in [22]. Challenges and possibilities of the SLB market were studied in [37] as well. The constituents of a business model are stated by Jiao *et al.* in [129], which is visualized in Fig. 45; while additional suggestions for SLBESS business models were provided in [133].

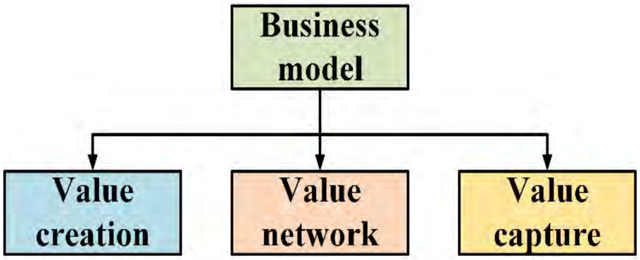


FIGURE 45. Essential parts of business model (adapted from [129]), SLB businesses must satisfy these in order to thrive.

X. BARRIERS AND SOLUTIONS OF SECOND LIFE BATTERY USE

However beneficial and sensible the SLB usage is, there exists several obstacles that has to be considered and overcome for this practice to become mainstream. To survive as a product, it must have secure supply of used batteries, capable and efficient production line, and proper supply chain to deliver the SLBESS to the masses. Also, to create sufficient demand for such a product, general awareness and demand has to be developed [134]. The cost must be kept in check all the time to maintain the demand [135]. Proper policies and necessary incentive as well as business models must also be developed. This also includes the process of determining and providing warranty for the SLBESS [22]. Availability of battery data is crucial for these [32], [134], [136]; one way of achieving this can be keeping track of the batteries since first life by employing some program in the battery management system. However, many of these barriers do not pose much serious a threat to SLBESS deployment. The used

TABLE 17. **Current policies adopted for EV batteries in NA (North America) and EU (European Union) regions.**

Region	Act	Aim	Criteria
EU	Battery Directive 2013/56/EU [139]	Improving the environmental performance of batteries and accumulators	• Proscribe the use of portable batteries having cadmium of more than 0.02 % • No restriction for Li-Ion and mercury battery materials • The recycling efficiency should be 50% and there should be specific rules for calculating the efficiency • The vehicles or appliances should be designed to facilitate battery or other components removal • The transportation of Li-Ion batteries are regulated by U.S. Hazardous Materials Regulations, International Air Transport Association, U.S. Department of Transportation, International Maritime Dangerous Goods, and International Civil Aviation Organization
			Exemptions • The limitation of cadmium for batteries of cordless power tools is no longer effective since, January 1, 2017 • The limitation of cadmium does not include products of the following types (a) Emergency and alarm system, (b) Medical equipment
	The Waste Batteries and Accumulators Regulations, UK, 2015 [140]	Maximizing collection of portable batteries	• Proscribe the sale of batteries containing more than 0.0005% mercury by weight • Proscribe the sale of portable batteries containing more than 0.002% cadmium by weight • Appliances should be designed in such a way so that the batteries may be readily removed.
			Exemptions • The prohibition does not include button cell having a mercury content of no more than 2% by weight • The limitation of mercury does not include portable batteries intended to use for cordless power tool, medical equipment, and emergency alarm system • The limitation of mercury does not include batteries used for vehicle purpose
	ELV: EU end-of-life vehicle directive [141]	To prevent waste from end-of-life vehicles and promote the collection, re-use, and recycling of their components to protect the environment.	• Vehicles should be designed in a way that they can be easily reused, recycled, and recovered. • Prohibit the of use of lead, mercury, cadmium, and hexavalent chromium • Ensuring free of cost delivery of end-of-life vehicles to authorized treatment facilities • Prohibit landfill and incineration
NA	Mercury-Containing and Rechargeable Battery Management Act (the Battery Act) 1996 [142]	Phasing out the use of mercury in batteries and provide for the efficient and cost-effective collection and recycling or proper disposal of used nickel-cadmium batteries	• Universal waste rule to be effective immediately in all 50 states for the collection, storage, and transportation of batteries • Ni-Cd and certain rechargeable batteries must be easily removable from the consumer products • Ni-Cd rechargeable batteries do not require the full array of hazardous waste regulatory requirements • Allows certain companies to transport Ni-Cd rechargeable batteries with a common carrier, instead of a hazardous waste transporter. • Prohibits, or otherwise conditions alkaline-manganese, zinc-carbon, button cell mercuric-oxide, and other mercuric-oxide batteries • The Ni-Cd and SSLA rechargeable batteries may be regulated under RCRA
			Exemptions • Batteries used in households and small businesses like small quantity generators may be exempt from some RCRA regulations
	California Rechargeable Battery Recycling Act 2006 [143]	To establish a system for accepting rechargeable batteries for reuse, recycling, or proper disposal	• Solid waste landfill disposal of household batteries are banned • The retailers must take back rechargeable batteries for recycling at no cost to the customer • The Li-Ion batteries classified as hazardous due to excessive levels of cobalt, copper, and nickel
NA	NYS: NY Rechargeable Battery Recycling Act (2010) [144]	Ensure proper end-of-life management for rechargeable batteries	• Proscribe rechargeable battery disposal from the solid waste stream • Rechargeable batteries should be returned to the retailers that sell them • Battery manufacturer must arrange the return of the used batteries collected by the retailers and recycle them at their own expense.
	MN: Minnesota Rechargeable Batteries and Products law (1994) [145]	Phase out the use of mercury in batteries and provides for the efficient and cost-effective disposal of used batteries, including nickel cadmium (Ni-Cd), used small sealed lead-acid (SSLA) batteries.	• Prohibits rechargeable batteries and products with non-removable rechargeable batteries to be disposed as mixed municipal waste • Retailers and manufacturers must develop a program for used battery collection and recycling
			Exemptions • New type of rechargeable batteries that does not poses unreasonable hazardous material can be disposed as mixed municipal waste

EU: European Union, NA: North America

battery supply is expected only to grow, and the technology to produce SLBESS does not require much improvement. The SLB cost is not expected to rise above the new batteries currently, but it can become prominent in the future if major breakthroughs take place in battery technology. There is the need of market and policy development, though these are not supposed to be much of a challenge considering the opportunities SLB usage provides. Table 16 shows different barriers of SLB use and their potential solutions

XI. POLICY

With the world moving towards more environment-friendly direction to meet with the energy demand there has been a prolific increase in the generation of electricity using RESs. However, these RESs introduces intermittency, which affects the stability and reliability of power. Large scale energy storage devices i.e. batteries can be used to mitigate this intermittency. Furthermore, batteries have a wide range of applications such as peak shaving, area regulations, etc. [109]. However, large scale applications of batteries is very much expensive due to their high price. The used EV batteries, having reached end-of-life cycle, can be a critical and inexpensive solution for this purpose. These batteries can be recycled, repurposed, and reused for different applications. However, there are economic uncertainty and liability concerns about second life batteries, which limits the market opportunities and increases the cost. Therefore, to ensure development of a market for these batteries, specific policies and strategies are required [22]. To encourage the use of second-life batteries federal and state tax credits, rebates, and other financial support should be provided. The reuse and collection of used EV batteries should be specified and the policy makers should ensure that the recycling of a battery only occurs once in the entire useful life of the battery has been utilized. Furthermore, the amount of hazardous material such as cadmium and mercury should be regulated and a proper waste management plan for the battery disposal should be adopted in order to protect the environment. The current policy and mechanisms adopted by NA (North America) and EU (European Union) regions regarding the EV batteries are presented in Table 17.

XII. OUTCOMES

The major findings of this paper can be summarized as follows:

- Extension of battery life time is necessary through a second-use phase.
- Second-life battery energy storage systems (SLBESS) can be produced through a standard production procedure, which involves modeling, testing, and manufacturing.
- Modeling of SLBESS can be done through processes similar to standard battery modeling.
- Used batteries need to be inspected and categorized for determining their eligibility and fitness to be used in SLBESSs.
- Standard safety practices must be upheld in every stage of SLBESS production.
- Cost of SLBESS must be kept competitive.
- SLBESS can be used in an array of applications, especially in stationary uses such as in the utility grid, creating significant values.
- There are significant environmental and economic impacts of SLB usage.
- SLB businesses require proper business models to operate sustainably, and some of such practices already exist while more can be developed.
- SLB usage face several barriers currently, but there exist viable solutions to overcome those.
- In addition to existing state and federal policies, more are required for nurturing SLB technology and market in national and private levels.

XIII. CONCLUSION

The used batteries hold significant potential to be used in a second life, which has been studied in detail in this study. The current SLB scenario has been discussed in detail first to point out the necessity and opportunity of such a practice. The processes of producing SLBESSs to create a deliverable product to establish this practice has been demonstrated afterwards along with related cost and safety analysis. The applications and impacts of SLB have been discussed as well. Business strategies and policies required to make SLB businesses sustainable have been discussed next along with the barriers and related solutions of SLB usage. The future work related to this paper can be on the second-life potentials of upcoming battery technologies such as solid-state batteries.

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