

# **State of Health Estimation for Second-Use Electric Vehicle Batteries in Grid Applications**

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## **Abstract**

Escalating demand for sustainable energy solutions necessitates the efficient utilization of energy storage systems (ESSs). This thesis explores the critical need for efficient energy storage systems in the face of increasing demand and intermittent renewable energy sources and addresses the need for advanced energy storage technologies, focusing on second life batteries as a potential solution. A literature review highlights the significance of second life batteries in addressing the challenges of energy storage, emphasizing their potential for cost-effective and eco-friendly alternatives by repurposing retired electric vehicle batteries. These batteries, with decreased capacity for automotive use, still retain energy storage capabilities, making them ideal candidates for secondary applications. Furthermore, the study delves into the development of a State of Health (SoH) model, crucial for assessing battery performance and longevity. The proposed SoH model aims to predict the SoH of batteries and enables the identification of optimal storage and cycling conditions. Through analysis and simulation, this research aims to determine the effective operating parameters, ensuring enhanced efficiency and prolonged lifespan of second life batteries in energy storage applications.

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# **Chapter 1 The Need for Energy Storage Systems (ESSs)**

## **1.1 Introduction**

Technologies have become more prevalent in the field of contemporary energy management as a result of the need to have a reliable and efficient energy system. Energy Storage Systems (ESSs) are at the core of current advancement where Battery Energy Storage Systems (BESSs) are one type of ESSs and have emerged as a dynamic and adaptable technology. The use of Second Life Battery Energy Storage Systems (SLBESS) will become more crucial as energy storage systems grow.

This chapter reveals the need for ESS, BESS, and the idea of giving batteries a second chance for increased utility. Additionally, this chapter mentions some barriers of using Second Life Batterie (SLB).

## **1.2 Energy Storage System (EES)**

Although Renewable Energy (RE) is quickly becoming the primary generation source in the main grid, fossil fuels possess two primary characteristics. They serve as energy reserves and are easily transportable. This implies that the fuels can be kept in storage until they are needed and then transferred via pipeline, road, or rail to the location where they will be consumed. However, due to the detrimental effects of intensive use of fuels and other finite resources for smoothing out the distribution of energy, the need for a more sustainable energy supply has emerged. In contrast to conventional power generation, most renewable energy sources (with the exception of biomass and water) cannot be stored or delivered to the location of usage without first being converted into electricity [1].

Most renewable energy sources vary in their generation from minute to minute, leading to a notable challenge in maintaining a steady energy production and balancing the power grid's reliability and stability. Extensive endeavors have been dedicated to identifying viable solutions, such as Energy Storage systems (ESSs), load shedding based on demand management, and establishing links with external networks. Among these options, ESS has emerged as one of the most favorable methods [2].

ESS technology encompasses the transformation of energy into a storable form which is subsequently stored through various methodologies. This accumulated energy can be later reconverted into electrical energy as required. ESS serves several roles that contribute to network operation and load balance, including:

- Addressing peak electrical load demands,
- Facilitating dynamic energy management,
- Mitigating the intermittency inherent in renewable power generation,
- Enhancing power quality and reliability,
- Enabling the development of smart grids,
- Assisting in distributed and standby power generation management,
- Reducing electricity imports during peak demand periods,
- Yielding cost savings,
- Minimizing environmental impact through energy sector decarbonization and reducing emissions [1, 2].

Various categorization methods can be employed to classify different ESS technologies. These methods include organizing them based on their functions, response times, and suitable storage durations. One commonly used classification approach,

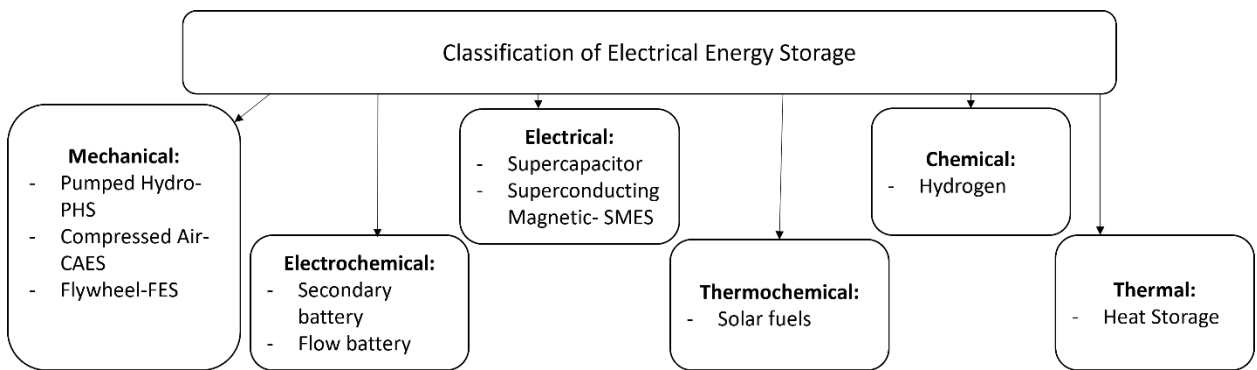
illustrated in Figure. 1.1, is based on the types of energy stored within the system. These energy storage categories encompass:

- Mechanical storage, encompassing technologies like pumped hydroelectric storage, compressed air energy storage, and flywheels.
- Electrochemical storage, involving both traditional rechargeable batteries and flow batteries.
- Electrical storage, which includes capacitors, supercapacitors, and superconducting magnetic energy storage.
- Thermochemical storage, specifically related to solar fuels.
- Chemical storage, such as hydrogen storage coupled with fuel cells.
- Thermal energy storage, covering sensible heat storage and latent heat storage [2].

In the conventional electrical supply system, energy storage serves specific purposes, including the following:

1. Grid regulation: Energy storage can address short-term, unpredictable fluctuations in demand, removing the necessity for the primary power generation source to manage frequency control. It also offers quick response to brief power interruptions, reduces harmonic distortions, and mitigates voltage fluctuations.

2. Spinning reserve: Energy storage diminishes the requirement for the main power plant to operate at partial loads, which are maintained to swiftly address unforeseen surges in demand and to manage power emergencies arising from generator or transmission line failures.



**Figure 1.1:** Classifications of Electrical Energy Storage Systems.

3. Peak load reduction: Energy storage helps manage the high-demand periods during the daily load curve, typically occurring in peak hours.

4. Load balancing: Excess electricity generated during off-peak hours or at night can be stored and utilized to meet peak demand during daytime hours [1].

Furthermore, the utilization of energy storage finds categorization into three primary groups: management of bulk energy, balancing of power, and enhancement of power quality and reliability. Table 1.1 outlines eleven distinct applications within these categories [3].

### **1.3 Battery Energy Storage Systems (BESSs)**

Despite the development of various technologies like flywheels, capacitors, and superconducting magnetic storage for large-scale energy storage, many of these technologies face limitations such as being dependent on specific locations, having capacity constraints, or exhibiting slow response times. In comparison, electrochemical energy storage systems, particularly batteries, offer a higher degree of flexibility in terms of capacity and rapid reaction times, catering to a broader array of applications. Batteries have been integrated into grid operations for many years, and although BESSs currently constitute a relatively small percentage of grid-based energy storage, they have undergone significant advancements recently due to their versatility, notable energy density, and efficiency. As battery technology continues to improve its lifespan, BESSs are becoming more suitable for a wider range of grid applications [4].

Battery Energy Storage Systems (BESSs) present a diverse range of storage and power capabilities, responding nearly instantaneously to grid requirements and

**Table 1.1:** Applications of Energy Storage Systems for Power Systems.

<b>Bulk Energy Management</b>	<b>Power Balancing</b>	<b>Power Quality/ Reliability</b>
Energy Arbitrage	Renewable Smoothing	Power Quality
Generation Upgrade Deferral	Load Following	Voltage Support
T&D Upgrade Deferral	Frequency Regulation	UPS
	Inertia Emulation	
	Reserves	

functioning efficiently over extended timeframes. Integrating BESSs into power systems yields several benefits. These systems effectively address challenges posed by increased distribution as well as variable and unpredictable generation from renewable energy sources (RES), making them particularly suitable for aiding distribution system operators (DSO) [4, 5].

Deploying BESSs as storage units within power systems offers a technological solution to meet peak power demand, enhance utilization of generation, increase grid stability, improve power quality, and facilitate balancing tasks such as frequency control. Furthermore, BESS supports the reduction of source intermittency and encourages the internal consumption of locally generated energy, thereby enhancing supply system reliability. Additionally, the development of BESS technologies plays a crucial role in achieving self-sufficiency in energy usage and reducing the necessity for emergency energy reserves. Ultimately, BESS contributes to the enhancement of grid performance, reliability, and power quality [4, 5].

In spite of the benefits that BESSs offer to power systems, their widespread adoption has been limited due to the implementation of BESS faces both technical and economic challenges within the grid context. A significant economic obstacle is the substantial initial cost associated with current BESS installations. On the technical front, the advantages of integrating BESS into the electric power system are heavily influenced by the specific operational environment, consequently constraining the broader adoption of the BESS [5].

## 1.4 Second-Life Battery Energy Storage Systems (SLBESSs)

Despite the gradual decrease in price, lithium-ion batteries remain costly for ESSs. As a result, second-life lithium-ion batteries (SLBs) offer a compelling option as they maintain strong performance capabilities at a more affordable cost, making them a favorable alternative to new lithium-ion batteries [6].

According to the International Renewable Energy Agency (IRENA), renewable sources are projected to account for a significant 86% of global energy production by 2050. This shift is accompanied by an increased reliance on batteries for energy storage to address the intermittent nature of renewable energy sources. Furthermore, advancements in electric vehicle (EV) technology have contributed to a more extensive integration of various types of storage batteries into the market. It is anticipated that a substantial quantity of batteries from both EVs and hybrid EVs (HEVs), experiencing a capacity decline of 20% to 30%, will be discarded and accumulate in large quantities. These batteries pose a significant environmental concern due to their hazardous composition [7].

Looking at the situation from an alternate perspective, retired EV batteries might not lack utility; in fact, they can be repurposed for various stationary applications or managing peak loads. This is possible due to the retained residual capacity, which allows them to have an extended lifespan when used in secondary applications [7].

The usage of second-life batteries for purposes such as domestic energy storage systems, cost-effective energy trading systems, and off-grid applications has been documented and is gaining traction, particularly as the quantity and size of retired

batteries grow. However, due to the adaptable nature of these retired batteries, their integration into a specific application is not a straightforward process [7].

Since used batteries are taken out of service under diverse conditions and varying states of health, the act of categorizing them for a unified application cannot be overlooked. Each battery bank must be treated as an independent source, necessitating distinct interfaces. Managing retired batteries poses greater complexity due to their modified charging and discharging traits, which differ from those of new batteries. Moreover, they exhibit distinct nominal voltages and residual capacities [7].

Retired batteries from various manufactures that have different chemistries and even batteries of the same type can differ in their condition upon reaching the end of their life (EoL). Additionally, the extent of degradation experienced during their initial operational lifespan is variable, contingent upon the overall condition of the battery materials [7].

When dealing with used batteries that exhibit slight variations in their characteristics, various active and passive balancing methods have been extensively explored and analyzed in the literature. Additionally, numerous control algorithms and configurations have addressed the efficient distribution of power from these batteries when utilized in conjunction with other sources such as photovoltaic (PV) and wind energy. However, while a significant portion of the literature has concentrated on integrating batteries into energy systems to improve overall performance, only a limited amount has delved into the considerable variability in characteristics often observed in repurposed batteries, a scenario frequently encountered in the case of second-life batteries [7].

However, there are several barriers that can hinder the prevalent implementation of second-life EV batteries:

- **Degradation and performance:** EV batteries degrade over time and usage, which can lead to reduced capacity and performance. Using these degraded batteries in second-life applications requires careful monitoring and management to ensure they meet safety and performance requirements.
- **Quality and reliability:** Since second-life batteries come from a variety of vehicles with different usage patterns and maintenance practices, their quality and performance can vary significantly. This can make it challenging to predict their behavior and integrate them effectively into energy storage systems.
- **Safety concerns:** Battery safety is a paramount concern, especially in applications such as energy storage where a large number of batteries are connected together. Second-life batteries may have undergone stresses that increase the risk of thermal runaway or other safety issues.
- **Economic viability:** Assessing the economic viability of second-life batteries involves evaluating the costs of repurposing, testing, and maintaining these batteries against the benefits of extended use. If the costs are too high or the benefits are not substantial, the business case might not be attractive [8].

Chapter 2 is dedicated to a review of the literature regarding Second-Life Batteries (SLBs), encompassing their fundamental ideas and practical uses. This chapter will also delve into an analysis of the obstacles that have the potential to impede the widespread adoption of SLBs. Chapter 3 will delve into the derivation of the mathematical SoH model used to predict battery lifespan. In Chapter 4, it will discuss the good operational and

storage conditions for batteries. Finally, Chapter 5 will include a summary, conclusions, and a preview of future work.

## Chapter 2 Second Life Batteries (SLBs) Literature Review

### 2.1 Battery

Modern life is powered by battery technology, which powers everything from mobile devices to large-scale energy storage systems and transportation. Battery consumption is still rising on a global scale. By 2019, the battery market had doubled to \$120 billion from its 2014 value of \$62 billion. Over the following ten years, it is predicted that global battery consumption would increase fivefold [9].

Batteries can be divided into two categories: primary (single-use, such lithium metal and alkaline batteries) and secondary (rechargeable, like Li-ion Batteries, Lead-Acid Batteries, nickel metal hydride Batteries, etc.). Additionally, they can be divided into categories based on their intended usage, such as consumer, office supply, and industrial batteries. Batteries are categorized in the commercial world according to their chemistry, which includes lithium-ion batteries [9].

Lithium-ion batteries (LIBs) find application in a wide range of uses. Among them is a variant of LIBs known as lithium-ion polymer batteries, which utilize a polymer electrolyte instead of a liquid one. This is particularly advantageous in situations where factors like weight and safety are of paramount importance [9].

The LIB battery chemistry is the one that is expanding the quickest in the field of consumer energy storage. LIBs have a long shelf life, few maintenance needs, quick charging and discharging capabilities, scalability, suitability for installation close to energy consumption locations, ease of manufacture, and rapid deployment, among other benefits [9].

Despite their advantages, LIBs have certain drawbacks. These include the need for protection circuits and disconnect devices to prevent issues such as overcharging or thermal runaway, degradation when exposed to high temperatures or stored at elevated voltages, reduced charging efficiency in freezing temperatures, the potential for fires, and transportation constraints due to safety and waste regulations, especially when dealing with large quantities [9].

LIBs contain four primary components: the cathode, anode, separator, and electrolyte. These essential elements work together to facilitate the storage and release of energy in LIBs [10].

1. Cathode: The cathode is one of the two electrodes in the battery. It is responsible for storing lithium ions ( $\text{Li}^+$ ) when the battery is discharging process and releasing them during charging process. Cathode materials are crucial for determining the battery's performance characteristics.
2. Anode: The second electrode, the anode, complements the cathode in its function. In the reverse direction, it likewise stores and releases lithium ions. Lithium ions are drawn out of the anode during discharging and are drawn back in during charging.
3. Separator: In order to prohibit direct contact between the cathode and anode, a separator is a physical barrier positioned between them. It permits the movement of lithium ions ( $\text{Li}^+$ ) while preventing internal short-circuits. The separator's nanopores allow for the regulated passage of  $\text{Li}^+$  ions [10].
4. Electrolyte: The electrolyte is a critical component responsible for facilitating the movement of ions, including lithium ions ( $\text{Li}^+$ ), allowing them to shuttle between the

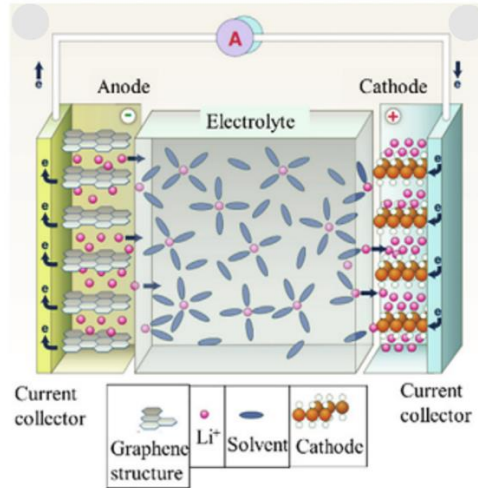
cathode and anode. In conventional LIBs, the electrolyte typically consists of a liquid or gel-like substance [10].

The operational process of a typical LIB is as follows:

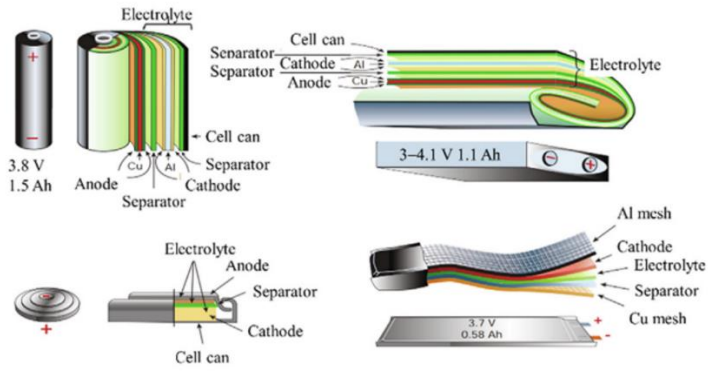
- During the charging process, lithium ions ( $\text{Li}^+$ ) migrate into the electrolyte, de-intercalate from the cathode materials, and subsequently pass through the nanopores of the separator before intercalating into the anode material. Simultaneously, electrons flow in the reverse direction through the external circuit to ensure electro-neutrality is maintained.
- During the discharge phase, lithium ions ( $\text{Li}^+$ ) return from the anode to the cathode, thus completing the electrochemical cycle. This process releases electrical energy that can be harnessed to power electronic devices or perform various other operations, as illustrated in Figure. 2.1 [10].

The ability of lithium ions to move between the cathode and anode is the fundamental mechanism that underlies the energy storage and release capabilities of lithium-ion batteries. This characteristic makes them a widely adopted and efficient choice for a diverse range of applications [10].

Figure. 2.2 illustrates the four primary cell types commonly utilized in lithium-ion batteries (LIBs): cylindrical, prismatic, coin, and pouch cells. Cylindrical cells are available in both high-capacity and low-capacity variants, but low-capacity cylindrical cells are more commonly used due to the high impedance of high-capacity ones. Prismatic cells are preferred in many applications as they reduce the number of cells needed to create a battery pack with the desired capacity, enhancing overall system stability. Coin cells are



**Figure 2.1:** The working mechanism of typical LIBs [10].



**Figure 2.2:** Cell types of LIBs [10].

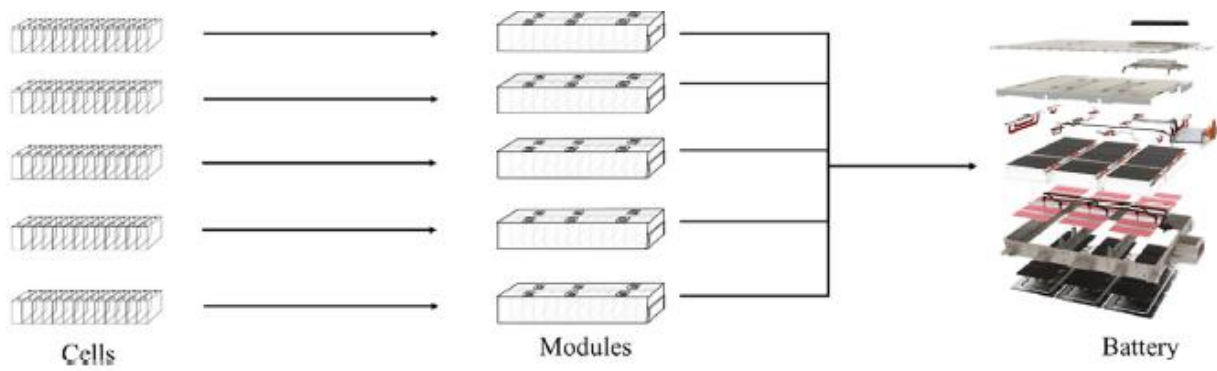
frequently employed for laboratory testing purposes. Pouch cells, on the other hand, offer flexibility in shaping the cell to fit specific device designs. Currently, pouch cells dominate the market because of this advantage [10].

To attain a specific voltage and capacity, it is common practice to connect hundreds to thousands of cells in parallel and series configurations within a single battery pack, as illustrated in Figure. 2.3 [10].

## 2.2 Battery Conventions

This section delves into various technical conventions regularly utilized within the battery sector, which encompass the following:

- **Cell Balancing:** A technique employed in battery packs to ensure that individual cells maintain a similar state of charge and capacity.
- **Charging:** a process that transforms electrical energy, which is normally provided as a current, into chemical energy that is then stored inside the battery.
- **Degradation:** The gradual loss of a battery's capacity and performance over time due to chemical and physical processes
- **Depth of Discharge (DOD):** A battery's energy consumption is frequently stated as a proportion of its overall capacity. A 40% depth of discharge, for instance, means that 40% of the battery's rated energy has been used and it has 60% of its usable energy.
- **Discharging:** The process of converting the chemical energy stored in the battery into electric energy for use.



**Figure 2-3:** Single battery pack [10].

- **End-of-Life:** When a product consistently experiences a reduction to less than 80% in its initial discharge capacity (cannot be charged to 80% of its original energy rating), it likely signifies that it has reached the end of its usable life for its primary application.
- **Energy Density:** Watt-hours per liter (Wh/L) is a common unit of measurement for a battery's energy storage capacity.
- **Fast Charging:** Technology that enables rapid battery charging, often at higher power levels.
- **Internal Resistance:** The resistance encountered by the flow of electric current within a cell or battery.
- **Open-Circuit Voltage:** the battery's voltage when it is neither sending nor receiving electricity (no current flow).
- **Oxidation:** A chemical reaction where an electrode's active material releases electrons (e.g., during discharging of an anode or charging of a cathode).
- **Power Density:** Watts per liter (W/L), a volumetric measure of a battery's capacity for power production.
- **Reduction:** A chemical process where an electrode's active material accepts electrons (e.g., during charging of an anode or discharging of a cathode).
- **Self-Discharge:** The loss of capacity resulting from the chemical instability or reactions of an active material within an electrode, occurring when the battery is in an open-circuit state.
- **Specific Energy:** Watt-hours per kilogram (Wh/kg), which is a gravimetric measurement of a battery's energy storage capability.

- **Specific Power:** the gravimetric power density of a battery, measured in Watts per kilogram (W/kg).
- **State of Charge (SOC):** Similar to a car's fuel tank, where 0% signifies empty and 100% denotes full, the proportion of a battery's total energy capacity that is available for discharge.
- **State of Health (SOH):** A measurement of a rechargeable battery's performance quality in relation to its initial state; typically expressed as the proportion of the original capacity that is still useable.
- **Thermal Runaway:** A circumstance in a cell when the internal reactions produce more thermal heat than the cell can expel, possibly resulting in cell venting and early failure [11, 12].

### 2.3 Second Life Batteries (SLBs)

The transportation industry is swiftly embracing electrification as a response to escalating environmental and energy-related concerns. EVs are becoming more and more popular as a competitive alternative to conventional internal combustion engine cars. Within the transportation sector, LIBs are widely utilized due to their notable advantages, such as a high energy capacity (ranging from 200 to 250 Wh/kg), exceptional charge-discharge performance, and the absence of memory effect. It is anticipated that the demand for LIBs will persistently grow in the foreseeable future, particularly with the global expansion of electric vehicle fleets. As these batteries approach the end of their primary utility, the proper management of their disposal and recycling is becoming an increasingly pivotal issue [13, 14].

In the automotive industry, a LIB is typically considered no longer useful when its capacity drops below 80% of its nominal capacity. As a result, a significant number of batteries in EVs are expected to be replaced in the coming years. It is estimated that approximately 250,000 metric tons of LIBs used in EVs will reach their end-of-life (EoL) by 2025. Even the most optimistic projections suggest that a substantial portion of Li-ion EV battery cells will become wasted by 2040. Subsequently, there will be a significant number of retired batteries in the future [14].

In addition, the move away from fossil fuels has resulted in a rise in the production of electricity from renewable resources like solar and wind energy in response to global climate change. Due to these sources' intermittent nature, their generated power is varied, which makes grid integration difficult. Performance, voltage stability, and overall reliability of the grid are all impacted by this unpredictability. Keeping the generated renewable energy in batteries until it can be converted to the necessary grid voltage and frequency using proper power electronic converter topologies is one method [14].

Nonetheless, in the forthcoming years, LIBs will emerge as a significant energy source, emphasizing the necessity to optimize their utilization. The prevailing notion is that once the primary purpose of batteries is fulfilled, they can find a second application [14].

Repurposing retired batteries for a second life, which entails using them beyond their initial usage phase, presents several advantages. From an economic perspective, studies emphasize that battery expenses significantly impact the high prices of Electric Vehicles (EVs). Consequently, car manufacturers are exploring methods to cut EV costs by repurposing used batteries returned by car owners. In addition, repurposing used

batteries delays the recycling process and reduces the cost of manufacturing a new battery. The use of SLB presents considerable financial opportunities for various parties, including EV holders, battery re-purposing organizations, SLB users, and battery recyclers. Additionally, Energy Storage Systems (ESSs) play a crucial role in supplementing renewable energy source (RES) intermittencies and offering ancillary services to the grid. However, the substantial expense of ESSs poses a notable concern. SLB-based ESSs are anticipated to be more cost-effective than new ones while maintaining optimal functionality for grid-related tasks [14][19].

Repurposing retired batteries for a second life also helps reduce the overall need for new batteries. This decrease in demand, in turn, results in a significant reduction in the consumption of extracted chemical materials [15].

Failure to implement appropriate reuse or recycling procedures can pose a risk to the environment and the economy due to the accumulation of numerous retired batteries containing volatile chemical components [15].

The concept of a SLBs comes with both advantages and challenges. On the positive side, it has the potential to reduce waste generated from direct disposal and production costs. However, there are significant issues to be addressed related to battery collection, storage, handling, and recycling. Nevertheless, the idea of repurposing these retired batteries is gaining considerable interest due to their substantial energy potential [15].

The expected lifespan of a battery's initial usage phase can often be determined based on the warranties provided by manufacturers. Many leading EV manufacturers currently offer warranties ranging from 8 to 10 years for their battery packs [14].

## **2.4 Battery Life Cycle 'After End of Life (EoL)'**

A product goes through numerous stages, beginning with conceptualization and creation and ending with disposal or recycling, which are collectively referred to as the product life cycle. Every stage of a product's life cycle must be taken into consideration to create durable, cost-effective products. Numerous industries have had their own versions of the product life cycle developed. The effective and efficient use of secondary resources is a key component of the circular economy concept. This approach, which emphasizes sustainability and resource efficiency, is essential for modern production and consumption [8].

The life cycle of a battery includes several significant phases, such as production, development, vehicle integration, use, and downstream activities at the end of its useful life. Retired batteries might be given a second life after the specified end of their useful lives. An assessment of component conditions, including battery cells, electronics, and housing, is done during the categorization of battery systems. Throughout the course of the product's life, a variety of circumstances, starting with potential quality problems during production and continuing through its usage period, might affect these components. Actual power profiles, temperature conditions, and charging practices all have a significant influence during use. Four separate alternative pathways are identified based on the evaluations provided during categorization [8].

When a battery system maintains a high state of health (SoH) and retains its ability to perform without significant degradation, it can be redeployed in the same application without the need for significant modifications. This process is referred to as "reuse." Battery reuse takes place when a battery from one EV is utilized to replace a component in another vehicle from the same model range [8].

"Repurposing" refers to the practice of using a battery in a different application. To ensure the success of such repurposing endeavors, it is vital to assess whether the used battery is suitable for its new role in a second-life context. Therefore, understanding the requirements of this new application and evaluating the battery's condition are essential steps before integrating it into the new application. Typically, during the repurposing process, the battery is partially disassembled and reassembled. The primary goal is to maximize the reuse of significant components, minimizing the need for extensive disassembly and, consequently, reducing associated process costs [8].

When repurposing a battery, it is possible to omit or add components during the dismantling process to integrate new or modified functions. Core component replacement or repair are examples of repurposing activities. In contrast, "remanufacturing" combines reuse and repair by substituting new parts for some of the original ones to rebuild a product to its original specifications. Because it utilizes already-made components and uses less energy during the process, this method results in a more resource-efficient management of batteries. However, it also poses difficulties, notably with the growing amount of work needed to assure the traceability of the newly installed components [8].

Batteries are recycled by removing the raw chemicals from spent batteries, which are then used as the primary ingredients in the creation of new batteries. Some of the

procedures included in this recycling process include thermoconditioning, mechanical processing, pyrometallurgical processing, hydrometallurgical processing, and direct recycling. Recycling systems that incorporate many of these techniques are routinely used to ensure the effective and efficient recovery of materials from old batteries [8].

The reassignment procedure starts as soon as batteries are brought to the plant for additional processing. The battery needs to be examined and tested thoroughly first. These tests are essential for categorizing the system and choosing the process's next steps [8].

The classification findings are used to choose a specific scenario that follows one of the four previously mentioned routes. The reuse scenario is an effective choice for batteries that have the greatest potential and show no signs of malfunction. Repurposing occurs frequently with batteries that have poorer health indications but are still useful in some applications. There is no longer any possibility of active use when a battery's lifespan forecast becomes less optimistic, and it approaches its genuine end of life. In these circumstances, the batteries are immediately put through a recycling process, adhering to the principles of the circular economy and promoting the creation of new batteries in a more sustainable manner [8].

## **2.5 Applications for Used Battery Products**

Most second-life battery applications fall under the "mobile uses" category, where batteries are anticipated to be in motion while being used. Reusing these batteries for short-range EVs is one possibility. According to conventional EoL standards, a battery's lifespan typically ends when it still has 70–80% of its initial capacity. These batteries can

still provide enough range for most daily travel, nevertheless. To give an example, approximately 75% of drivers can efficiently commute each day on a battery that retains 60% of its capacity. Additionally, this strategy saves money because substantial battery recycling is frequently unnecessary [16].

Second Life Batteries (SLBs) find utility in various applications, much like hybrid trucks designed for urban environments. SLBs have the potential to power small mobility devices like e-bikes, and electric wheelchairs, as well as lightweight vehicles such as golf carts and three-wheelers. In industrial settings, forklifts, pallet trucks, and tractors are examples of equipment that can make use of these batteries for internal energy management or propulsion. While LIBs have their strengths, SLBs offer advantages for specific applications, since they can endure partial electrochemical cycles without significant degradation and offer a greater energy density relative to weight and volume than traditional lead-acid batteries [16].

Residential energy storage applications are also becoming more popular for consumers, particularly in homes and apartments that may have integrated PV and/or EVs. Residential SLBESSs provide a viable solution. Many of the SLBs used in these systems were previously employed in electric vehicles, making them a sustainable choice for residential energy storage [16].

Residential SLBESSs serve several purposes:

1. Load Smoothing: They store surplus energy when consumption is low and release it during times of higher demand. This helps even out the electrical load and allows homeowners to participate in energy arbitrage, offering economic benefits.

Additionally, it contributes to environmental sustainability by reducing the strain on the electrical grid.

2. Integration with Renewable Energy: SLBESSs can be used in conjunction with RESs like photovoltaics (PV), boosting the use of clean energy and a decentralized system for the generation of power.
3. Backup Power: In the event of a power outage, SLBESSs act as an energy backup, ensuring that essential devices and appliances continue to function [16].

The specific capacity requirements for SLBESSs depend on their intended purpose:

- In load-following scenarios, it is generally necessary to have a minimum capacity of 3 to 4 kilowatt-hours (kWh). The usage pattern in such situations involves occasional significant drains and frequent smaller discharges throughout the day, with a discharge rate approximately equal to one-third of the battery's nominal capacity.
- Backup systems, particularly for off-grid use, may require a larger capacity, around 25 kWh. Daily discharges are moderate, with a depth of discharge usually below 50% [16].

Overall, while residential SLBESSs offer various advantages, their suitability depends on specific circumstances, including available space, maintenance capabilities, and safety considerations [16].

Energy Storage Systems (ESSs) find utility in larger-scale applications within the commercial and industrial sectors. This context necessitates substantial investments in storage capacity and adherence to more stringent safety standards [16].

The commercial sector comprises a diverse range of businesses and light industries. Examples of such commercial entities include telecommunications companies, large office complexes, and fresh food distribution centers. Commercial energy demands typically exceed those of residential consumers, making ESSs particularly valuable for specific purposes:

1. **Grid Support:** In commercial situations, ESSs can play a role in maintaining grid stability by providing services like frequency regulation, voltage control, and demand response. These contributions are pivotal for enhancing the reliability and efficiency of the electrical grid.
2. **Load Management:** Commercial establishments often experience varying energy needs throughout the day. ESSs can effectively manage these fluctuations, optimizing energy costs by drawing power from the grid during low-demand periods and storing it for use during peak hours. For load management, the necessary capacity typically ranges from 75 to 100 kWh, making SLBs a viable option in many cases.
3. **Peak Demand Reduction:** ESSs can also help reduce peak demand charges imposed by utilities. In scenarios requiring substantial capacity, such as peak demand reduction (typically around 3,000–4,000 kWh), a common approach is to employ a hybrid solution that combines both new batteries and SLBs to meet storage requirements efficiently. Discharge rates for peak reduction applications often fall between  $1/2C$  and  $1C$ , with daily occurrence.
4. **Emergency Backup:** SLBs can act as backup systems, turning on in the event of unplanned occurrences like power outages. The anticipated discharge rate in this situation is normally about  $C/5$  [16].

The choice between using new batteries and SLBs hinges on specific factors including the application's nature, required storage capacity, and discharge rate. For tasks related to load management and backup, SLBs are often favored due to their lower capacity requirements and capability to handle frequent discharges effectively. Conversely, applications with substantial capacity needs, such as peak demand reduction, may benefit from a hybrid approach that combines both new and SLBs to efficiently meet storage demands [16].

In the scope of industrial ESS applications, such as those used in heavy industries, power demands are even higher compared to residential and commercial situations. Industrial ESSs serve various purposes, including:

1. Load Leveling: By holding onto excess energy during times of low demand and releasing it when demand is high, they help stabilize patterns of energy use by lowering peak loads.
2. Renewable Firming: ESSs play a role in stabilizing the power supply by mitigating the intermittency associated with renewable energy sources such as solar and wind.
3. Spinning Reserve or Area Regulation: These systems provide readily available power capacity to respond to sudden changes in demand or generation, helping maintain grid stability.
4. Peak Shaving: ESSs reduce peak power usage during periods of high demand, leading to cost savings by avoiding peak demand charges.
5. Transmission Stabilization: ESSs can enhance grid stability by mitigating voltage fluctuations and ensuring consistent power transmission [16].

Given the higher power demands of industrial applications, the choice of ESS technology and capacity becomes critical to meet these diverse objectives effectively.

A sizeable amount of capacity, or about 100 MWh, is needed for industrial load leveling when taking the energy requirements of typical industrial loads into account. Relying only on SLBs for this application becomes unfeasible because so many batteries are needed to reach this capacity [16].

In contrast, other industrial applications have lower capacity requirements:

1. Renewable Firming: This application typically demands between 1 and 10 MWh of storage capacity, which is more manageable with a moderate number of batteries. The discharge cycles in renewable firming are frequent, with an intensity of  $C/5$ , making it suitable for SLBs.
2. Spinning Reserve/Area Regulation: For these specific applications, a capacity ranging from 5 to 7.5 megawatt-hours (MWh) is typically required. SLBs are well-suited to handle the discharge cycles associated with spinning reserves and area regulation, which range from  $C/2$  to  $C$ .
3. Peak Shaving: Similar to the commercial sector, peak shaving in industrial applications typically needs a capacity of 75 to 100 kWh. This capacity requirement can be efficiently managed using SLBs [16].

Another notable application is the stabilization of transmission systems, which necessitates a capacity of 140 kWh to manage 500 MW of power. However, this particular application calls for brief bursts of power to regulate voltage and frequency, and the required C-rate surpasses the capabilities of LIBs [16].

Therefore, the choice of battery technology and the suitability of SLBs depend not only on capacity needs but also on the specific discharge characteristics and requirements of each industrial application [16].

Leveraging EV batteries as buffer storage units at charging stations offers a multitude of advantages. These buffer storage systems help reduce the immediate power requirements during the vehicle charging process, thereby alleviating stress on the public grid. Additionally, when combined with renewable energy sources, they can function as decentralized buffer storage solutions, facilitating EV charging in remote areas that lack access to public grid infrastructure [16].

When considering these applications, the use of new batteries can be economically challenging due to their higher costs. In contrast, SLBs offer a more cost-effective solution. They not only meet the necessary technical requirements but also come at a lower price point [16].

Moreover, in the context of employing SLBs for buffer storage at charging stations, if we assume that these SLBs are utilized within a SoH range of 80% to 60%, their projected lifespan extends to roughly 15 years. This extended longevity renders SLBs a practical and sustainable option for such applications, offering cost-efficiency and reliability over an extended timeframe [16].

## **2.6 Challenges of Second Life Batteries**

The increasing emphasis on SLBs highlights the need to tackle several challenges for their effective integration into second-life stationary storage applications. These challenges can be grouped into three primary categories:

1. End of First Life, Collection, and Transport: This phase involves addressing challenges associated with the conclusion of the battery's initial use, collecting used batteries, and transporting them to recycling or repurposing facilities.
2. Screening and Condition Diagnosis: Ensuring that SLBs are suitable for second-life applications necessitates accurate assessment and diagnosis of their current condition. This step involves challenges related to identifying which batteries are in suitable condition for reuse.
3. Dismantling, Processing, and Integration: Once viable SLBs are identified, they must be disassembled, processed to address any degradation or damage, and then effectively integrated into second-life stationary storage systems.
4. Rentability: Ensuring that the use of SLBs in stationary storage applications makes economic sense and is profitable is a crucial challenge. This involves challenges related to financial aspects, such as the cost-effectiveness and return on investment associated with the use of SLBs [17].

Addressing these challenges is essential for realizing the full potential of SLBs in extending the lifespan and sustainability of battery technology and promoting their integration into various stationary energy storage applications.

### **2.6.1 End of First Life, Collection, and Transport**

The suitability of EV batteries for vehicle applications typically reaches its limit when the batteries have around 80% of their original capacity remaining. This percentage is commonly considered the standard EoL criterion in literature. Nevertheless, some experts criticize this fixed definition and emphasize that the aging behavior of batteries in

their second life depends significantly on their previous usage (stress) during their first life [17].

Around the 80% SoH mark in vehicle batteries, a phenomenon known as "non-linear aging" becomes more pronounced. This non-linear aging presents a significant challenge in predicting how the battery will age further. Consequently, it is crucial to repurpose the battery for its second-life application before further predicting how the retired batteries would behave. However, pinpointing the exact and optimal time for repurposing is a complex task and remains unpredictable [17].

The issue is that battery aging is quite varied and affected by elements like temperature and load profiles, which can differ greatly between different batteries. As a result, certain batteries might function properly even when their SoH is below 80% without obviously aging faster. Even when the SoH is known, it is extremely challenging to accurately predict the lifespan of a battery system due to this fluctuation [17].

At the end of a battery's initial operational cycle, the need arises to extract these batteries from the vehicles that they supply power to. This process can pose significant challenges as many batteries are uniquely tailored for specific vehicles and are frequently permanently integrated, rendering their removal a sophisticated endeavor. Subsequently, these LIBs need to be transported to a dedicated facility equipped for repurposing or recycling [17].

However, the transportation of used batteries presents several challenges. These batteries are classified as hazardous waste due to their chemical components, which means their transportation is subject to strict regulations. Compliance with these

regulations involves using trained personnel and approved vehicles, which can significantly increase transportation costs. Furthermore, the batteries being transported are still functional, which poses potential safety hazards due to the risk of electrical discharge or other issues [17].

Handling EoL batteries presents significant safety concerns and logistical complexities, leading some logistics companies to refrain from providing transportation services for these materials. Moreover, air freight is often prohibited for EoL batteries due to their hazardous nature, further complicating the transportation process. This situation creates challenges for companies involved in repurposing EoL batteries when they are seeking suitable business partners, particularly when the responsibility for removal, collection, and transportation falls outside the purview of the Original Equipment Manufacturer (OEM) or a central processing facility. In such cases, there might not be enough knowledge in managing this specialized task [17].

One potential approach to address the knowledge gap in the management of EoL batteries is to allocate sufficient financial resources to engage specialized transport firms with expertise in handling hazardous materials like EoL batteries. It is crucial to emphasize that the transportation of such items must comply with legal regulations [17].

### **2.6.2 Screening and Condition Diagnosis**

The identification of EoL batteries represents a pivotal phase in the process following their collection and transportation to a repurposing facility. This task is complex and challenging, primarily because there are presently no established concepts or protocols in place for this identification process [17].

In situations where there is a lack of clear and standardized battery identification, it may become necessary to reach out to the battery manufacturer to obtain relevant information about the batteries. This adds an additional layer of complexity to the process, as it may involve communication and data retrieval from various sources [17].

Moreover, inadequate labeling of batteries can make automatic identification difficult, which can further extend the time required for the identification process. In such cases, manual efforts may be needed to properly identify each battery, which can be a time-consuming and resource-intensive task [17].

The absence of standardized identification procedures and inadequate labeling of EoL batteries can pose significant challenges in the battery repurposing process, potentially leading to delays and increased resource utilization [17].

An important development to note is the European Union's (EU) initiative to create a battery passport system, which holds the potential to simplify the recognition and assessment of EoL batteries. The battery passport serves as a digital repository for product data, serving a dual role as a unique product identifier and a mechanism for tracking vital product lifecycle information. This data encompasses details about the product's usage history, its supply chain journey, and recycling recommendations. The introduction of the battery passport aims to foster transparency throughout the entire value chain, delivering benefits to manufacturers, consumers, recyclers, and regulatory bodies alike [17-19].

To make well-informed decisions regarding the future second-life application of a battery, it is essential to assess the battery's SoH. SoH provides valuable insights into

how the battery's capacity compares to that of a brand-new battery. However, it is important to acknowledge that there are inherent uncertainties in precisely defining and evaluating SOH [17].

The principal cause of SoH deterioration in a battery is the aging process, which can be measured and assessed through battery aging models. Nonetheless, it is critical to recognize that aging is not the exclusive factor influencing SoH. Other factors, such as damage resulting from vehicle accidents or events that are difficult to determine, like short circuits, can also affect SoH. Consequently, the true condition of the battery is frequently uncertain or imprecisely known [17].

This inherent uncertainty highlights the complexities involved in storing and managing EoL batteries. Effectively addressing these uncertainties is crucial for making informed decisions about repurposing or recycling batteries, as well as ensuring safety and efficiency in second-life applications or disposal processes [17].

There are several significant challenges that must be overcome to effectively assess the SoH of batteries. One of the most frequently discussed issues in literature is the wide variety of EoL batteries. This diversity leads to numerous options regarding various battery characteristics, including cell chemistry, cell type, module dimensions, power capacity, cooling systems, Battery Management Systems (BMS), and operational features. These variations arise from different cell manufacturers and EV models [17].

The diverse range of batteries available means that the tests and methods employed for determining SoH can vary significantly between different types of batteries. This diversity makes it impractical to establish a single unified technical procedure for

SoH assessment. As a result, the screening process for SoH becomes more complicated and potentially more costly [17].

The assessment of batteries' SoH is significantly complicated by the involvement of third-party system integrators and the diversity of participating entities, each with their own protocols and standards. This complexity is further exacerbated by the wide range of battery types and the absence of a standardized SoH determination procedure. All these factors together make the screening process more complex and also potentially more costly [17-19].

In addition to the lengthy process for SoH evaluating, another significant barrier to effectively evaluating SoH in batteries is the need for high-end, specialized testing equipment. Currently, EoL batteries are often sent to recycling facilities after their first life. However, many automotive recyclers lack the requisite testing equipment and expertise needed to accurately assess the SoH values of these batteries [17].

It can be helpful during the evaluation process to have access to battery statistics from the first life. Monitoring the EV battery's usage history, which is typically made available by the BMS, can be used to acquire this crucial information. The BMS continuously monitors and logs crucial information about the battery's performance and condition, such as temperatures, voltage profiles, and charge and discharge cycles. Making SoH assessments more accurate and determining whether to recycle or utilize these batteries in other applications can both benefit from having access to this previous data [15, 17, 19].

### **2.6.3 Dismantling, Processing, and Integration**

The labor-intensive process of dismantling EoL batteries poses a significant challenge. Presently, a substantial portion of this disassembly work is carried out manually, resulting in a significant increase in the overall repurposing costs. Estimates indicate that the expenses associated with disassembling EoL batteries can account for over half of the cost of a new battery pack. This proportion acts as a rough estimate, as labor costs can vary significantly depending on the specific location or country, which can substantially impact the actual dismantling expenses [17].

Furthermore, the battery's structure and interconnections significantly influence the level of effort needed during the disassembly process. Elements and the accessibility of components all have a substantial impact on disassembly costs and, consequently, the overall expenses associated with repurposing. These considerations emphasize the importance of developing efficient and cost-effective disassembly methods to successfully incorporate used batteries into new applications [17].

Another cost factor in the repurposing of battery systems is the typical operation of these systems at around 400 volts DC, with an increasing number using even higher levels, approximately 800 volts DC. This voltage level requires the participation of high voltage trained workers during the disassembly process. Additionally, the process of opening the battery pack and removing individual modules from the system is time-consuming, which negatively affects overall profitability [17].

To address these challenges, several potential solutions are considered:

1. Avoiding Disassembly: One approach is to repurpose the battery at the pack level, avoiding the need for complex module-level disassembly.
2. Automation: Automating the technical processing of EoL batteries is an alternative. However, automation requires a substantial initial financial outlay. EoL batteries are renowned for having a wide range of performance and design qualities [17].

Indeed, the challenges of repurposing batteries extend beyond disassembly and include the reassembly process. Several factors contribute to the complexity of reassembling SLBs:

1. Battery Design Inhomogeneity: Battery designs vary significantly across cells, modules, and packs. This diversity complicates the task of reassembling SLBs, as there is no one-size-fits-all approach due to these design differences.
1. State of Health Variability: Used batteries have different SoH levels, which can vary widely. This variability poses challenges when trying to create uniform SLBs with consistent performance.
2. Cell-to-Cell Variability: Compared to brand-new batteries, used batteries frequently have higher cell-to-cell variability. This unpredictability can make reassembly more difficult, especially for high energy second-life applications that call for matched cell capacities to maximize battery performance and lifespan in the long run [17].

Overall, assembling new battery strings or packs from a diverse pool of second-life batteries becomes challenging due to the need to balance and match various factors like SoH, cell capacities, and other performance characteristics. Developing effective strategies for reassembly is essential to maximize the value and reliability of SLBs in various applications [17].

Another difficulty in the repurposing of SLBs is the creation of a new BMS. If access to the current BMS is impossible, as may happen if the OEM does not offer a suitable communication interface, the need for a new BMS may become apparent. OEMs frequently hesitate to grant access to their BMS out of fear of revealing critical data [17].

Creating a new BMS can result in a large amount of extra work and higher repurposing costs, especially given how difficult it can be to create a BMS for SLBs. This additional complexity is mostly caused by the requirement to balance SLBs, which have greater performance variations than new batteries. SLBs may differ in their performance capabilities, SoH, and other aspects, making it more difficult to manage them efficiently with a single BMS [17].

The upcoming EU battery law, which is predicted to address some of these issues, could eventually offer solutions for issues with BMS access and data sharing. However, the creation and use of a successful BMS for SLBs continues to be a crucial component of their successful integration into second-life applications [17].

When battery packs are reused directly, meaning that individual modules are not replaced or reconfigured, leveraging the OEM's BMS is typically the least costly and most straightforward approach. However, the feasibility of this approach depends on whether the OEM provides the necessary communication interface [17].

SLBs technical preparation and system adaption are complicated by the variety of potential reuse scenarios and the ensuing multitude of needs. It is difficult to integrate SLBs into different second-life applications, and this difficulty is influenced by a few variables:

1. **Lack of Technological Standards:** The absence of standardized guidelines and technical standards for SLBs complicates the integration process. Without established norms, each integration project may require custom solutions, driving up costs and complexity.
2. **Limited Long-Term Experience:** A notable challenge arises from the scarcity of long-term experience and data related to the performance of SLBs in diverse applications. The absence of historical data poses difficulties in forecasting how SLBs will function in various scenarios, thereby impeding the precision of evaluation and decision-making processes.
3. **Data Availability:** The limited availability of data on SLB performance in different applications adds to the uncertainty. Without comprehensive data, it is challenging to assess the suitability of SLBs for specific second-life applications [17].

The absence of technological standards, limited long-term experience and data gaps present obstacles to the seamless integration of SLBs into diverse second-life applications. Addressing these challenges will be essential to unlock the full potential of SLBs and ensure their successful utilization across a wide range of scenarios [17].

#### **2.6.4 Rentability**

The competitive pricing component is a significant factor that has been covered in many studies regarding the economic viability of SLBs. This entails comparing the cost per kilowatt-hour (\$/kWh) of retired batteries, which are recycled for a second life after their initial 8 to 10 years of use, to future battery systems. Cost savings made possible by improvements in production methods and material breakthroughs are already a benefit to these new systems [17].

Conversely, ongoing research and industry efforts aim to enhance battery systems. While these improvements can result in cost savings, they may be counterbalanced by potential future innovations leading to increased material prices. This dynamic could ultimately stabilize pricing levels and potentially make SLBs competitive in the market [17].

The cost competitiveness of SLBs hinges on their ability to offer competitive pricing in relation to new battery systems, considering factors like age and material costs, amid the backdrop of continuous developments and potential material price fluctuations in the battery industry [17, 18].

Repurposed battery systems are regarded as old products, which lowers their perceived value in the eyes of customers owing to potential breakdowns, maintenance, or repairs that may be necessary, which is another set of concerns. To allay unwarranted consumer concerns, there is an increasing emphasis on the need for precise tracking and evaluation procedures for battery quality. The ambiguity around the battery's remaining worth and capacity contributes to this psychological aspect and lowers the costs that consumers are ready to pay. Leasing alternatives also experience the same effect, which may be a commercial opportunity for second-life systems. The profitability of these batteries having a second life is further undermined by the aforementioned issues, which increase the demand for pricey product guarantees [17].

Additionally, there is a comprehensive evaluation of the economic viability of assessing the battery pack's condition and the refurbishment process. Disassembly and technical processes might already cost more than half as much as purchasing a new battery system. The second-life battery scenario is diminished by economic uncertainties

and the potentially significant costs associated with repurposing the battery pack for future applications [17].

These sections provide a comprehensive overview of the primary challenges that must be overcome to fully realize the potential of second-life batteries in stationary energy storage applications [17].

## **2.7 Overview of Current Research and Projects on SLB**

Numerous ongoing experimental and demonstration endeavors are currently employing SLBs as ESS in diverse applications. These initiatives serve to highlight the importance of utilizing SLBs as ESS while stressing the necessity for thorough analysis for their effective deployment. Within Table 2.1, a compilation of academic studies and demonstration projects offers detailed information about SLBs. This includes project locations, battery capacities, applications, and the comprehensive scope of these studies. These efforts collectively contribute to a deeper understanding of the potential and challenges associated with integrating SLBs into various energy storage applications [17-19].

## **2.8 Some SLB Challenges to Overcome**

A significant portion of the improvement efforts should be focused on addressing the numerous barriers and challenges highlighted in section 2.6. While there are some existing standards in place, the establishment of standardized procedures for testing, refurbishing, and integrating second-life batteries into diverse systems remains an essential and ongoing endeavor.

Furthermore, SLBs originate from various vehicles and conditions, resulting in

**Table 2.1:** Some Current Work [17-19].

<b>Authors</b>	<b>Nation</b>	<b>Battery Type</b>	<b>Purpose</b>	<b>Approach or Scope of Study</b>
Gohla- Neudecker et al	Germany	Lithium-ion batteries (NMC/C)	A smart power network integrating rapid electric vehicle (EV) charging with buffering capabilities.	The research involved crafting batteries intended for SLB use. The analysis that followed examined multiple factors such as SoC, C-rate, and cell temperature. The main goal was to create an effective control method to enhance system performance, minimize battery cell aging, and establish a structured, analytical framework for evaluating SLB operation.
Tong et al.	United States	Battery (LiFePO4)	Off-grid photovoltaic EV charging station	The project aimed to assess the feasibility of utilizing basic control methods to repurpose EV batteries for secondary applications. To achieve this, the system underwent modification through an equivalent circuit and underwent testing across various scenarios.
Strickland et al.	United Kingdom	Battery (NiMH)	<ol style="list-style-type: none"> <li>1) Frequency response</li> <li>2) Network deferral</li> <li>3) Energy management</li> </ol>	The primary objectives of the study were to examine the initial usage phase of batteries and gather relevant data. These batteries were scrutinized for potential secondary applications once they had regained 80% of their original capacity. The research focused on exploring three distinct uses for these batteries. Prior to their repurposing, the old batteries underwent Open-Circuit Voltage tests and impedance assessments to ascertain their ability to generate the necessary power for the intended second-life applications.
Casals et al.	Spain	Li-ion batteries excluding NiMH batteries	<ol style="list-style-type: none"> <li>1) Energy arbitrage</li> <li>2) Island installations</li> <li>3) Autonomous use</li> </ol>	This study outlined the environmental impact of EV batteries in eight second-life scenarios, using residual capacity to estimate the batteries' remaining utility. It focused on environmental effects rather than detailed technical analysis of the used batteries.
Casals et al	Spain	Lithium batteries (NMC)	<p>Gas turbine system to provide:</p> <ol style="list-style-type: none"> <li>1) Area regulation</li> <li>2) Frequency regulation</li> </ol>	The aim of this research was to gauge the expected lifespan of SLBs used to bolster gas turbine systems by comparing two different operational scenarios. The batteries in use weren't subjected to a comprehensive technical assessment before their repurposing for a second life. However, during their second-life application, the study meticulously tracked and analyzed factors like temperature, SoC, DoD, and C-rates. These variables played a significant role in influencing both the calendar-based and cyclic aging of the batteries.

performance and capacity variations. Therefore, it is critical to develop methods for assessing and managing this variability effectively. Given that Li-ion batteries fall under hazard class 9 based on United Nation (UN) shipping classification and criteria 'UN 3480' adopted by US department of transportation, they require expert handling to guarantee the safety of second-life battery systems, as they may have undergone considerable stress during their initial use in electric vehicles.

From a cost perspective, although repurposing second-life batteries can offer cost-efficiency compared to manufacturing new ones, optimizing the economic aspects of this process remains a challenge that may benefit from automation.

To ensure safety, dependability, and compatibility with existing infrastructure, regulations and standards governing the use of retired batteries in ESSs must be established.

## **Chapter 3 State Of Health (SoH) Model**

### **3.1 Battery Aging**

Battery aging may be split into two categories: calendar aging and cycle aging. While cycle aging is concerned with the consequences of utilizing a battery over periods of time known as cycles, which entail charging and discharging, calendar aging is concerned with the procedures and outcomes of keeping a battery in an idle condition [14, 20].

#### **3.1.1 Calendar Aging**

Calendar aging represents the irreversible loss of capacity that occurs while a battery is in storage. In simpler terms, it signifies the degradation that happens when a battery is not in use. The rate at which a battery self-discharges can significantly fluctuate based on the storage conditions. As a result, the internal processes and effects within the battery can either speed up or slow down depending on how it is stored. Various experimental studies have demonstrated the influence of storage conditions on this type of aging [14, 20].

The storage temperature is the main factor influencing calendar aging and self-discharge. High temperatures have been shown to increase the likelihood of side reactions, which can result in a greater loss of lithium and eventual capacity deterioration. On the other hand, lower temperatures prevent these unwanted reactions from progressing, but they also cause problems with material diffusion and may change the battery's chemistry [14, 20].

SoC during storage is another significant factor in calendar aging research. Cells age in distinct ways when kept at the same temperature but with varying SoC levels. This disparity levels of SoC indicate that battery deterioration increases with increasing SoC levels. SoC essentially signifies the proportion of ions residing on electrodes. High SoC generates a significant imbalance potential at the interface between the electrode and electrolyte, which in turn encourages prior chemical processes [14, 20].

Since storage temperature and SoC mutually affect capacity and resistance with a non-linear influence over time, these two factors are often investigated in calendar aging research [14, 20].

Battery calendar aging is influenced by temperature, SoC, and time, and both capacity degradation and resistance increase do not follow a linear pattern over time. This indicates a significant connection between the aging process and the passage of time [14, 20].

### **3.1.2 Cycle Aging**

Cycle ageing is the outcome of actively charging or discharging a battery and is caused by several variables including SoC, DoD, temperature, and current demands on the battery. Since the previously indicated aging processes occur regardless of whether the battery is actively used or not, all the previously listed elements that impact calendar aging also apply to cycle aging. A battery that is in use is generally more vulnerable to exothermic effects, which can worsen under hot conditions and accelerate battery aging. However, the consequences of extremely low temperatures on battery aging need to be considered as well [14, 20].

Aside from the above listed considerations, the way the battery is utilized also affects cycle aging. The change in SoC within a single cycle, or  $\Delta\text{SoC}$ , is a factor that is frequently studied in the literature. This is an important consideration, especially when determining how much charge is given during a discharge. The wider  $\Delta\text{SoC}$ , the faster the battery degrades [14, 20].

Depending on how batteries are used, another factor that greatly affects how quickly lithium-ion batteries age, is the voltage at which they are charged and discharged throughout the course of their lifetime. In particular, a battery ages more quickly when it is subjected to high charging voltage. An initial charging phase with a constant current until a certain cut-off voltage is reached, followed by a constant voltage charge until the charging current drops to around 3-5% of the battery's maximum charging current or 1/10C to 1/30C rate, are the usual characteristics of a healthy charge cycle. A higher voltage might cause significant capacity deterioration and a shorter cycle life in the battery cell. This is indicated by the specified constant voltage cut-off level [14, 20].

Flow of electric current stands as a crucial element linked to the aging mechanisms affecting batteries. In essence, a substantial current flow leads to the creation or dissipation of a notable quantity of energy. The increased c-rate, referring to the charging or discharging current, accelerates the degradation of the battery, indicating that a higher rate of current application hastens the battery's deterioration [14, 20].

The gradual increase in impedance over the course of a cell's existence is a natural occurrence, and it can be investigated by studying the effects of both calendar aging and cyclic processes. As the cell operates over time, this growth in impedance becomes

apparent as a reduction in power output, often described as the phenomenon of power fade [14, 20].

### **3.2 Knee Point or Sudden Death**

Lithium-ion batteries exhibit a unique two-phase capacity degradation pattern: first, there is a gradual decline in capacity, and then, at a particular point called the "knee" there is a shift to a phase of accelerated degradation. This results in the formation of a distinctive knee-shaped curve, which persists until the battery gets to its End-of-Life (EoL). This "knee" is associated with the transition to a stage of fast capacity loss by IEEE Standard 485TM-2010. One important factor that determines a cell's cycle longevity is the occurrence of this knee [21].

Being able to identify and predict when the knee point appears in each cell, especially its beginning, is highly beneficial for cell and battery producers. This insight enables them to adapt their standards and guarantees accordingly. For users, this knowledge offers the choice to modify how they use the cell, potentially prolonging its effectiveness. It also helps in planning battery replacement time [21].

Lithium-ion battery capacity faded knee point is an important marker of accelerated battery degradation since it marks the start of a fast and noticeable decline in battery capacity. This knee is helpful for assessing a battery's long-term performance and dependability. As a result, it is essential for qualification evaluations, planning battery replacements in commercial electronic systems, and determining whether batteries may be used for secondary purposes [22].

It is still unknown exactly why the knee point phenomenon occurs. However, one factor that might lead to the development of the knee point is lithium plating. Lithium plating is the process whereby lithium ions accumulate on the electrode's surface and form metallic lithium deposits when they do not intercalate into the electrode material. The capacity of lithium plating to chemically react with the electrolyte solution results in the formation of a Solid Electrolyte Interphase (SEI) layer [23].

SEI development is further enhanced by subsequent chemical interactions between the electrolyte and lithium plating. The enlargement of this SEI layer has the potential to isolate residual lithium, resulting in "dead lithium," which is irreversibly lost. Reduced capacity is the outcome of the loss of lithium inventory, which is caused by both the increasing growth of SEI and the existence of dead lithium. Furthermore, dendrites that are encouraged by lithium plating have the potential to break through the separator and cause an internal short circuit [23, 24].

A side reaction known as lithium plating occurs when metallic lithium separates from the negative electrode (NE) and develops on its surface. This can happen because of two main processes:

1. Thermodynamic plating: In this scenario, lithium plating happens when the negative electrode's surface becomes fully lithiated, and there is no space left for the incoming lithium ions. It is a thermodynamic consequence where lithium ions have nowhere else to go, so they form metallic lithium on the electrode surface.

2. Kinetic plating: This kind of plating happens during fast charging, when the high electrolyte potential speeds up the secondary lithium plating reaction in comparison to the

main intercalation process. The adverse response is more noticeable due to the rapid charging rate [24].

Environmental, operational, and manufactural factors can significantly exacerbate the impact on lithium plating:

- Low temperatures: Plating is more likely to occur in cold conditions.
- High SoC: A high level of charge in the battery can increase the risk of plating.
- High charge current: Rapid charging can exacerbate the plating issue.
- Insufficient negative electrode (NE) mass or electrochemically active surface area: A lack of material for lithium intercalation can lead to plating [24].

When batteries are stored in low temperatures, they degrade at a slower rate, indicating that Lithium plating probably does not happen when the battery is stable without charging or discharging. However, allowing the battery to rest right after a fast charging might encourage the reaction of lithium plating with the electrolyte instead of removing it through stripping [24].

### **3.3 Battery Model**

Battery modeling is a valuable tool for predicting and optimizing fundamental parameters of batteries, including SoC, battery lifespan, and charge/discharge characteristics. For various application sectors, several battery types have been developed over time. The complexity, input needs, accessible outputs, and general accuracy of these models can all differ. There are several characteristics that may be used to characterize battery models, including modeling techniques, modeling timescales, and modeling levels [25].

With the evolution of battery technology, various battery models have also been created. Battery models are essential for illustrating and enhancing our understanding of the fundamental characteristics of batteries. Not only do they provide insights into these features but can also predict battery behavior under different conditions. Several kinds of models have been created for a variety of uses [25].

Each model comes with its own set of advantages and drawbacks, and their suitability for a specific application depends on the desired level of accuracy and complexity [25].

One of the initial considerations in battery modeling is to determine the specific purpose for which the model will be used. The purpose of the model greatly influences the choice of approaches and parameters. Battery models are quite versatile, and their categorization can be somewhat flexible. However, the same model may belong to more than one class, as there are often overlapping applications and requirements for battery modeling. The versatility and adaptability of battery models make them valuable tools for a wide range of applications in battery research, development, and usage [25].

Battery models can be categorized based on several criteria, including:

- Diverse modeling viewpoints:
  - Electrochemical simulations
  - Electrical representations
  - Models of temperature
  - Mechanical representations
  - Models of molecules

- Multidisciplinary model combinations, such as electro-thermal models
- Various modeling levels (Depth):
  - System level
  - Pack level
  - Stack and module level
  - Full-cell level
  - Half-cell level
  - Material level
- Various modeling methodologies or techniques:
  - Electrochemical models that are based on physics
  - Empirical models
  - Mathematical or analytical models
  - Models of equivalent electrical circuits
  - Probabilistic models
  - Models that are hybrid
- Varying models' time scales:
  - Short term (representing dynamic behavior, partial charge/discharge)
  - Medium term (denoting an entire cycle)
  - Long duration (including many cycles and the battery's whole lifespan) [25].

Models that replicate the electrochemical and physical processes that take place in batteries are called Physics-Based Models (PBMs), or electrochemical models. When parasitic side processes such as solvent oxidation and Solid Electrolyte Interphase (SEI)

layer development were included to these models to account for deterioration, they became even more detailed [26].

Nevertheless, PBMs are renowned for their complexity. They need a insightful comprehension of the physical and chemical phenomena at work in the battery and entail a sizable amount of partial differential equations. Furthermore, a variety of factors often impact the aging of lithium-ion batteries, making it difficult to include all pertinent microlevel effects in these models. Because of their complexity and requirement for in-depth understanding of the underlying processes, PBMs are therefore typically preferred by chemical engineers or researchers with a good expertise in the subject [26].

Equivalent Circuit Models (ECMs) use passive electrical circuit elements such resistors, capacitors, and inductors to simulate the dynamic behavior of a battery. These models can be more complicated, include internal diffusion and charge transfer mechanisms, or they can be simpler representations. Based on impedance data, ECMs might include variable components to account for the impacts of aging. Nevertheless, this method requires a large amount of test data to be collected in order to measure aging under different operational situations [26].

ECMs have several benefits, one of which is their mathematical simplicity, which makes them ideal for real-time applications like estimating battery life. These models are frequently used to track and predict the battery's condition in a variety of applications in conjunction with state estimators, such as particle filters or Kalman filters [26].

For estimating SoC and SoH of batteries, machine learning (ML) techniques like support vector machines and neural networks are frequently used. Diverse machine

learning techniques exist, some of which train the algorithm to derive SoH data from characteristics such as the battery's incremental capacity curve or differential voltage curve. These methods have the important benefit of just requiring readily available characteristics, such as voltage, current, and temperature [26].

Other methods train the algorithm utilizing model characteristics such as ohmic resistance, polarization resistance, and polarization capacitance by combining machine learning with various models. To predict SoH, some also combine regression models with empirical modeling approaches. Although ML techniques may estimate SoH with great accuracy, substantial datasets are usually needed to properly train the algorithms and produce reliable predictions [26].

Curve-fitting methods are commonly used in empirical and semi-empirical models (EMs) to determine correlations between different stress variables and data, producing comparatively straightforward analytical formulas. Because of their simplicity, EMs may be used in many other types of research, such as battery management systems, optimization models, and system-level design issues. Additionally, the analytical formulae offer an intuitive comprehension of the many ways in which the system is impacted by stress variables. However, EMs have their limits such as EMs may only be effective for certain phases of a battery's lifespan, or may not perform well in scenarios with highly irregular charging patterns. [26].

### **3.4 Second Life Battery SoH estimation**

It has been demonstrated that recycling and disposal are less sustainable than the use of used batteries in stationary storage applications. Accurately estimating a battery's

remaining useable capacity and remaining life in second-life applications is crucial to maximizing the benefits of reusing batteries. When determining the causes of battery aging, a number of elements are taken into account [27].

Predicting battery SoH is a fundamental aspect of battery aging studies, which are essential for understanding a battery's condition and health during both its initial and second-life applications. However, the precision of SoH estimation can be compromised due to several factors:

- Indirect measurement: Since SoH is an internal battery characteristic, it cannot be measured immediately. It is difficult to get exact accuracy since it is usually obtained from the integration of other observable factors, such current and voltage.
- Data sources: Many SoH prediction methods rely on offline data sets, which may not always capture real-time operating conditions or the full range of factors influencing battery aging. Additionally, the SoH of a battery is influenced by environmental conditions and various internal parameters that change over time.
- Non-Linear Behavior: Battery degradation is highly non-linear, affected by a multitude of internal and external factors. This non-linearity can make SoH prediction methods less reliable due to the complexity of interactions between these variables [27].

Currently available SoH estimation algorithms use a variety of strategies, which may be generally divided into three categories: data-driven methods, model-based methods, and advanced approaches that combine both data-driven and model-based techniques. By evaluating their cycle life and calculating battery SoH, these techniques are used in research to precisely anticipate the potential of second-life batteries for stationary storage applications [27].

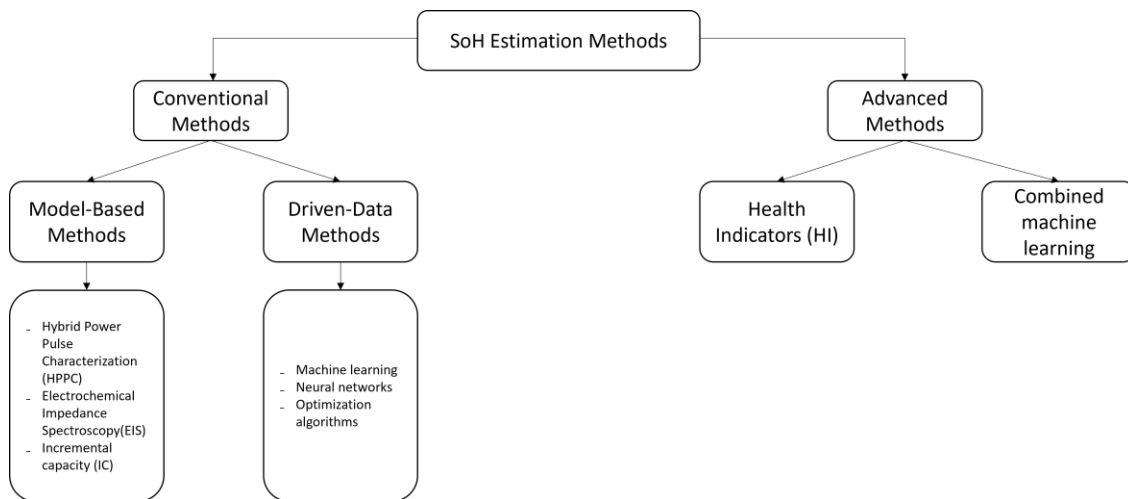
Even though these methods provide insightful information, it is still uncommon to utilize actual data to determine a battery's usable lifetime in a given application. The estimating techniques may be improved and validated with this useful data, increasing their suitability for realistic situations [27].

Figure. 3.1 illustrates the conventional and advanced methods of SoH estimation, reflecting the ongoing efforts to enhance the accuracy and effectiveness of these techniques [27].

An electrical equivalent circuit is frequently used to simulate battery performance and aging in various second-life applications in aging studies for electric car batteries. This circuit model aids in simulating the battery's electrical activity over time. Even though some aging characteristics are known, these characteristics affect and regulate how long the battery lasts [27].

The conventional coulomb counting method, which involves continuously measuring the current and comparing the estimated capacity with the rated capacity, is a straightforward technique for assessing battery SoH. However, it has a significant drawback in that it relies on the assumption of a complete battery cycle at 100% SoC, which may not always reflect real-world usage. In practice, batteries often operate under partial charge and discharge conditions, making the conventional coulomb counting method less accurate for SoH estimation in some scenarios [27].

An inventive method for estimating SoH in second-life battery applications is the use of data-driven methodologies. Utilizing the autoregressive integrated moving average (ARIMA) forecasting algorithm is one method for predicting, with an error rate of less than



**Figure 3.1:** Methods to estimate the SoH of a battery [27].

3%, the residual usable life of second-life batteries in stationary applications. Building a time series model using training data from earlier cycles and initializing a model order are the first steps in the process. This method offers a trustworthy means of estimating SoH [27].

It is suggested to use a combined predicting techniques, including neural networks, to address the non-linearity in SoH estimates. By taking into consideration the complex relationships among the battery's constituent parts, this method enables more precise predictions [27].

Using incremental capacity curves and open circuit voltage analysis, another model for aging lithium-ion batteries is developed. A greater degree of precision is provided by this method, which may be used for a variety of lithium-ion battery applications, including situations involving second-life batteries [27].

The potential for further research and practical applications to refine and validate the forecasting model with real-world battery data, allowing for broader use and applicability across different types of batteries, which is a promising avenue for future developments in battery management and energy storage systems [27].

### **3.5 SoH Model**

In both current and future energy storage systems, lithium-ion batteries are an essential technology that is used. The lifespan of these batteries becomes a crucial aspect in assessing profitability since in many applications [28].

It may be expensive and time-consuming to do real-life aging testing for each specific application, which makes it impracticable in many situations. Aging models based

on accelerated aging tests can be used to overcome this difficulty. For every type of cell, these tests only need to be done once. An extensive range of applications may be extrapolated from a given set of accelerated tests by utilizing mathematical functions to imitate the influence of aging-related variables. This method offers an economical and effective way to evaluate battery performance and aging under various usage conditions [28].

Predicting battery lifespan is essential to making sure batteries are successfully introduced to the market. The main objective of this effort is to construct a lifespan prediction model based on accelerated aging testing. For batteries to be commercially successful, it is imperative to create more precise estimations about their lifespan and performance throughout the use of modeling methodologies and accelerated aging data [28].

Numerous aging elements must be considered in order to provide an accurate aging estimate for batteries. These variables include depth of discharge, state of charge range, charge throughput, cycling and storage temperatures, and storage voltage. Numerous studies, concentrating on either calendar life or cycle life, have been carried out to replicate the effects of several of these aspects separately. To give a more comprehensive evaluation of battery performance and lifetime, a thorough aging prediction model should combine and take into consideration the complex interactions of all these parameters [28].

A mathematical explanation of the aging processes is necessary to build an extensive lifespan model based on accelerated aging testing. The analysis in this context is often separated into two main categories: cycling aging and calendar aging.

Understanding the particular mechanisms and conditions that affect battery aging over time—whether from calendar aging or battery cycling caused by charge and discharge procedures—is necessary for each category [28].

### 3.5.1 Calendar Aging Model

Three main variables are changed in calendar aging tests: storage voltage (SoC), temperature, and time. These elements need to be incorporated into the model in order to create a function that appropriately accounts for calendar aging [28].

Many literature sources employ the Arrhenius equation to account for temperature dependency in battery aging models. An essential idea in chemistry and physics, the Arrhenius equation explains how temperature affects the rate at which certain chemical reactions occur. It clarifies how temperature impacts the aging and deterioration of battery components as well as their overall performance in the context of battery aging.

$$\text{Temperature dependency} = 10^6 * \exp\left(-\frac{E_A}{RT}\right)$$

The activation energy of a chemical reaction at a specific temperature is denoted by the symbol  $E_A$ . The gas constant is denoted by  $R$ .  $T$  is the Kelvin absolute temperature [28].

An aging factor  $\alpha$  is presented to develop a mathematical model of calendar aging that takes dependence on voltage and temperature into account. The aging rate during a test time  $t$  is described by this factor. With the addition of this aging component, the model can take into account the combined impacts of temperature, voltage, and time on battery aging, providing a more thorough knowledge of how these factors interact to affect battery aging [28].

$$C_{loss\_Calendar} = \alpha * \sqrt{t}$$

where:

- $\alpha = (A * V - B) * 10^6 * e^{(-\frac{EA}{RT})}$  is voltage and temperature dependencies combination.
- $V$  is the cell voltage this is corresponding to SoC.
- $T$  is the storage temperature.
- $t$  is the time in days.

A framework for computing calendar aging under different voltage and temperature settings is provided by the equations that include dependencies on temperature and voltage in addition to the time. These formulas also serve as the basis for the analysis of cycle aging. [28].

### 3.5.2 Cycle Aging Model

In addition to the aging mechanisms that happen during calendar aging, cycling a battery also adds new ones. Therefore, a capacity model that takes into consideration the number of cycles is required to represent capacity degradation patterns, especially with knee points or discrete stages of deterioration. This model provides insights into the complex interactions between different aging mechanisms by simulating the capacity loss that happens during battery cycling [29].

$$C_{loss\_Cycling} = K_1 \cdot N^{b1} - K_2 \cdot N^{b2}$$

where:

- $N$  is the number of cycles.
- $K_1 \cdot N^{b1}$  is used to simulate the slow degradation stage.

- $K_2 \cdot N^{b_2}$  is to model the knee point behavior (non-linear stage).

Several variables, including the SoC window, C-rate, DoD, and ambient temperature, can affect  $K_1, b_1, K_2,$  and  $b_2$ . These factor-dependent variances must be taken into consideration to develop an effective accelerated aging model and to establish initial values for all of the model's coefficients. Researchers and engineers may create more accurate and dependable accelerated aging models that accurately represent real-world battery aging under various operating situations by taking into account the effects of these factors on the coefficients [29].

During the cycling process, calendar aging continues to occur concurrently. This means that both the number of cycles and the passage of time contribute to the overall aging of the battery [29].

### **3.5.3 Combined Model**

To create a comprehensive mathematical model for SoH, the calendar model discussed in section 3.5.1 and the cycling model explained in section 3.5.2 are integrated in the following manner.

$$NDC = 1 - C_{loss\_calendar} - C_{loss\_cycling}$$

NDC is the normalized discharge capacity.

### **3.5.4 Model Implementation**

To implement this all-encompassing mathematical model, which can be adjusted to suit any specific dataset by tuning its parameters, it is necessary to acquire some relevant data.

To put the model into practice, Sandia National Laboratory (SNL) provided the dataset. Cells were cycled in SNL at three different temperatures (15 °C, 25 °C, and 35 °C) with different discharge currents and DoD. A constant charge rate of 0.5C was applied to each cell. The cycling of these cells was continued at the time of publishing, and it is significant to note that they were cycled until they achieved their EoL with a SoH of 80%. The dataset includes measurements made of current, voltage, temperature, and energy (measured in watt-hours, Wh) during the cycling process [30].

The ISU-ILCC battery dataset was utilized to further the model's implementation. The ISU-ILCC battery aging dataset was gathered through collaborative efforts, initially originating from the Iowa State University Laboratory (ISU) and presently managed by the System Reliability and Safety Laboratory (REIL) at the University of Connecticut, along with Iowa Lakes Community College (ILCC). The purpose of the dataset is to investigate how three stress factors—charge rate, discharge rate, and depth of discharge—affect battery capacity fading. This aging test campaign uses lithium nickel manganese cobalt oxide (NMC) battery cells. The operational voltage window is 3.0 V to 4.2 V, and the rated capacity is 250 mAh [31].

Therefore, two cases were chosen to further investigate this model. The first case from SNL data is when the cell was cycled at 0.5C charging and discharging rate, 100% DoD, and 25°C and by assuming that the cell was stored at 25°C and 50% SoC. Table 3.1 shows the calendar and cycling conditions where Table 3.2 shows Cycle life of the cell. Figure. 3.2 shows how the combined SoH model fits the experimental data. Table 3.3 shows the values of the  $K_1$ ,  $b_1$ ,  $K_2$ , and  $b_2$  coefficients.

**Table 3.1:** Calendar and cycling conditions.

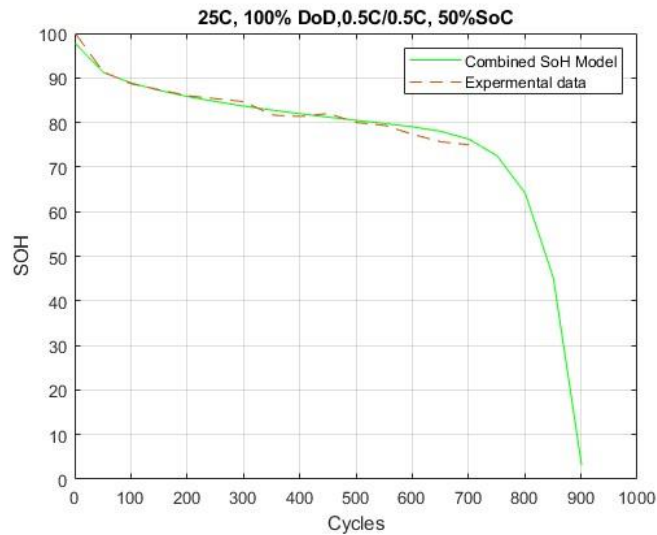
Calendar condition		Cycling condition				
Temp.	SoC %	Temp	Charging rate	Discharging rate	DoD %	SoC % Window
25°C	50%	25°C	0.5C	0.5C	100%	Mean 50% (0%-100%)

**Table 3.2:** Cycle life of the cell.

	100%-75% (SoH)	75%-40% (SoH)
Cycle (0.5C) 2 Hours	701 cycles	156 cycles

**Table 3.3:** Coefficients' values for the first case.

	$K_1$	$b_1$	$K_2$	$b_2$
Value	0.0222	0.348	$2.68 * e^{-44}$	14.70



**Figure 3.2:** The green line represents the model while the red dashed line represents the experimental data. The model fits the experimental data and predicts the remaining useful life of the battery.

The second case from ISU data is when the cell was cycled at 0.5C charging and discharging rate, 25.9% DoD, and 30°C and by assuming that the cell was stored at 25°C and 50% SoC. Table 3.4 shows the calendar and cycling conditions where Table 3.5 shows Cycle life of the cell. Table 3.6 shows the values of the  $K_1$ ,  $b_1$ ,  $K_2$ , and  $b_2$  coefficients. Figure.3.3 shows how the combined SoH model fits the experimental data.

The Equivalent Full Cycle (EFC) acts as the designated cycle count. In practical terms, a battery cycled at 100% Depth of Discharge (DoD) has approximately four times the throughput capacity and cycle time compared to one cycled at a partitioned 25% DoD within a single cycle. Hence, for the 25% DoD cycling range, the cycle count is adjusted to four times that of a 100% DoD cycle within an equivalent timeframe.

### **3.6 Summary**

Battery modeling techniques are developed to evaluate second-life battery SoH and predict its remaining lifespan after examining the elements influencing battery deterioration. This entails using techniques to forecast the battery's remaining usable life and estimate SoH. It is imperative to develop a mathematical SoH model that incorporates both calendar and cycle aging. This model clarifies the process by which the battery deteriorates under particular cycle and storage circumstances. It also helps predict how long the battery will last for a particular charge/discharge pattern.

**Table 3.4:** Calendar and cycling conditions.

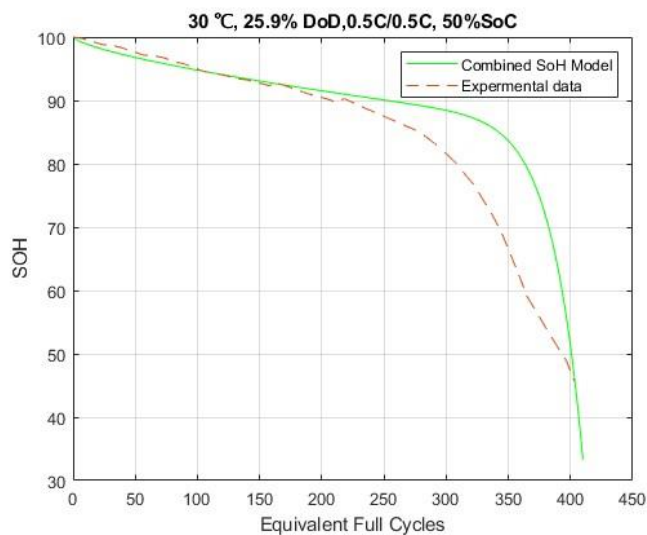
Calendar condition		Cycling condition				
Temp.	SoC %	Temp	Charging rate	Discharging rate	DoD %	SoC % Window
25°C	50%	30°C	0.5C	0.5C	25.9%	Mean 50% (0%-100%)

**Table 3.5:** Cycle life of the cell.

	100%-80% (SoH)	80%-40% (SoH)
Cycle life (0.5C) 2 Hours	307 Cycles	100 Cycles

**Table 3.6:** Coefficients' values for the second case.

	$K_1$	$b_1$	$K_2$	$b_2$
Value	0.00192	0.708	$2.68 * e^{-44}$	16.57



**Figure 3.3:** The green line represents the model while the red dashed line represents the experimental data where the battery cycled to 45% SoH.

# **Chapter 4 Optimal Storage and Cycling Conditions for Batteries**

## **4.1 Introduction**

Users seek to maximize the benefits and cost-effectiveness of their lithium-ion batteries aiming for extended longevity. Understanding the myriad factors impacting battery life is crucial. Knowledge of optimal storage and cycling conditions is key to prolonging the battery's lifespan. This chapter delves into these conditions, shedding light on how to store and cycle batteries optimally to ensure their long-term durability.

## **4.2 Storage Conditions**

Battery calendar aging is impacted by a combination of factors including temperature, State of Charge (SoC), and time. It is crucial to understand that both capacity degradation and the rise in resistance do not follow a linear pattern over time. This suggests a substantial interconnection between the aging process and the passage of time. The nonlinear behavior implies that battery degradation is not consistently gradual but rather involves varying rates and interactions between these influential factors across time [14, 20].

### **4.2.1 Temperature**

The primary factor impacting the aging and self-discharge of batteries is their storage temperature. To comprehend how temperature influences a battery's lifespan, the calendar model outlined in Section 3.5.1 is employed. Employing this calendar model allows for the prediction of battery degradation over time at various temperatures, assuming similar SoC levels. However, using this model to project battery degradation at

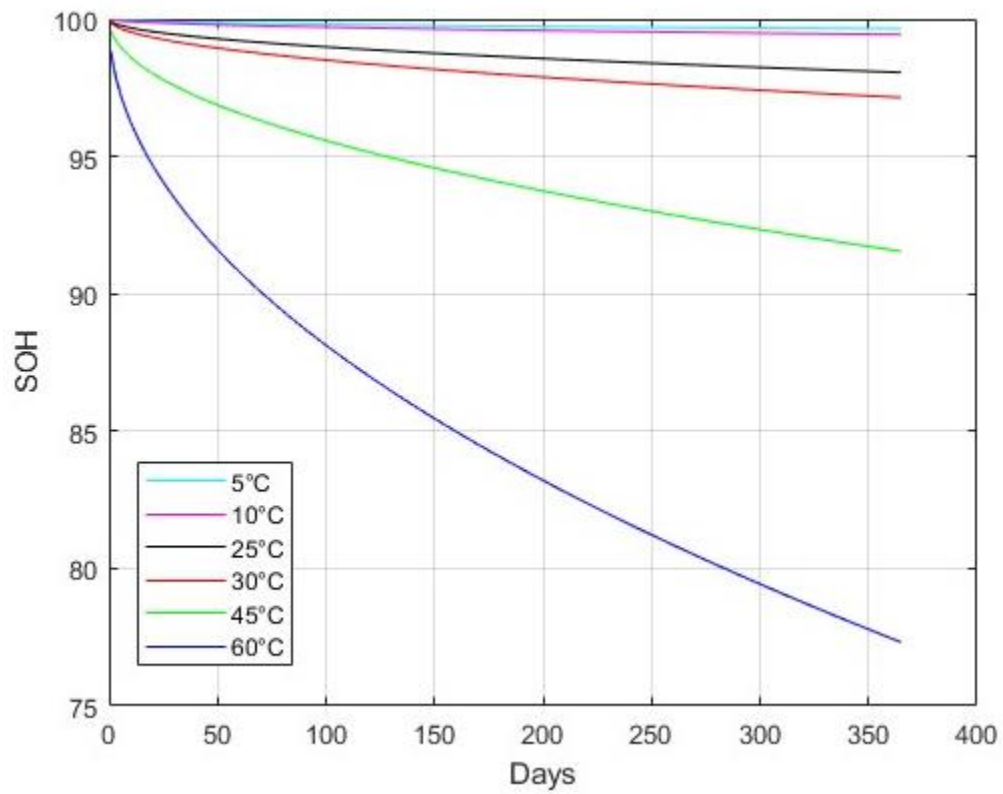
extremely low, sub-frozen temperatures would not be suitable. Consequently, this model lacks the capability to estimate how batteries would degrade under such very low-temperature conditions. Figure. 4.1 illustrates the degradation of the battery when stored at various temperatures along with the assumption that the battery was stored at 50% SoC, are generated solely by the model. Using only the model to generate this data provides valuable considerations for understanding the effects of temperature on battery behavior under specific storage conditions.

Mostly, storing batteries at high temperatures causes more side reactions and significant losses of usable lithium, resulting in decreased capacity. Conversely, storing them at lower temperatures decreases the occurrence of side reactions but also slows the movement of Li-ions in the electrolyte. This slower movement can lead to the deposition of metallic lithium on the anode, causing a reduction in usable lithium and subsequent capacity loss [14].

Suggested storage temperature range for batteries typically spans from 5°C to 25°C. However, situations requiring immediate access or emergencies might not favor storing batteries below 20°C, as this would require preheating to reach their optimal operating temperature. Rapid degradation might occur if the battery is cycled at very low temperatures caused by lithium plating. Therefore, maintaining the battery within the range of 20-25°C could be a more practical choice when quick availability is crucial to prevent potential degradation issues associated with extreme temperature cycling [32].

#### **4.2.2 State of Charge (SoC)**

SoC is a secondary factor influencing battery lifespan. It is assumed as a theoretical measure of the ions present on electrodes and in the electrolyte. A high SoC



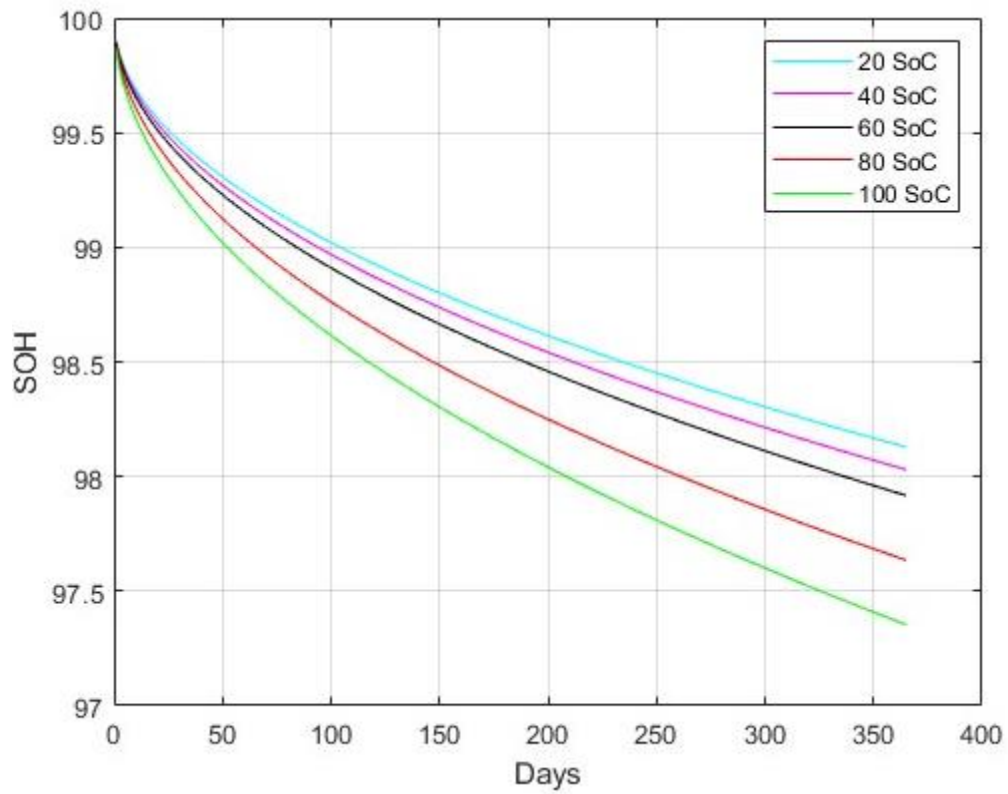
**Figure 4.1:** Degradation of the battery when stored at various temperatures.

indicates an imbalance in the distribution of Li-ions within the cell. This disparity in ionic concentration between the electrode and electrolyte encourages side reactions, leading to the depletion of usable lithium and an increase in capacity degradation [14].

The calendar model described in Section 3.5.1 is utilized to understand the impact of SoC levels on a battery's lifespan. Utilizing the calendar model enables the prediction of battery degradation across time at different SoC levels, assuming consistent temperature. Figure. 4.2 depicts the degradation pattern of the battery under various storage SoC levels. The observations presented, coupled with the assumption of a 25°C storage environment for the battery, are exclusively derived from the model. Relying solely on the model for data generation offers important insights into comprehending how SoC influences battery behavior within defined storage conditions.

Figure. 4.2 demonstrates an expected trend where degradation exhibits a proportional relationship with the SoC level. Accordingly, storing the battery at higher SoC levels leads to faster degradation, while lower SoC levels correspond to a slower degradation rate.

Storing a battery with an excessively elevated SoC can lead to various detrimental consequences, such as: electrolyte breakdown, SEI (Solid Electrolyte Interphase) breakdown, deterioration of binder material, dissolution of transition metals, lithium plating, and exfoliation of graphite. These problems can subsequently result in diminished battery capacity and heightened electrical resistance. On the other hand, storing a battery with an extremely low SoC level can result in several adverse effects, including current collector corrosion, disruption of electrical connections, and formation of lithium plating.



**Figure 4.2:** Degradation of the battery when stored at different SoC levels.

These issues can subsequently lead to reduced capacity and increased resistance in the battery [33].

Optimally storing a battery at a specific SoC involves several considerations. Self-discharge is a crucial factor, especially as the battery degrades, leading to an increased self-discharge rate. Notably, high self-discharge occurs at full state-of-charge and high temperatures. Additionally, allowing the cell to remain in a low-voltage state for over a week can promote the growth of copper dendrites, causing elevated self-discharge and potentially compromising safety [34].

In cycling conditions, batteries tend to degrade more rapidly when kept at extremely low or high SoC levels compared to mid-range SoC levels. Therefore, storing the battery within the 40-50% SoC range could be preferable to balance readiness for use and mitigating degradation effects, providing a reasonable compromise for both immediate access and prolonged battery health.

### **4.3 Cycling Conditions**

Cycle aging arises from the active charging or discharging of a battery and is influenced by various variables such as State of Charge (SoC), Depth of Discharge (DoD), temperature, and the current demands placed on the battery during its use. The complexity of cycle aging stems from the multitude of factors affecting this process [14, 20].

Importantly, the factors impacting calendar aging, including SoC and temperature apply to cycle aging as well. This highlights that regardless of whether the battery is

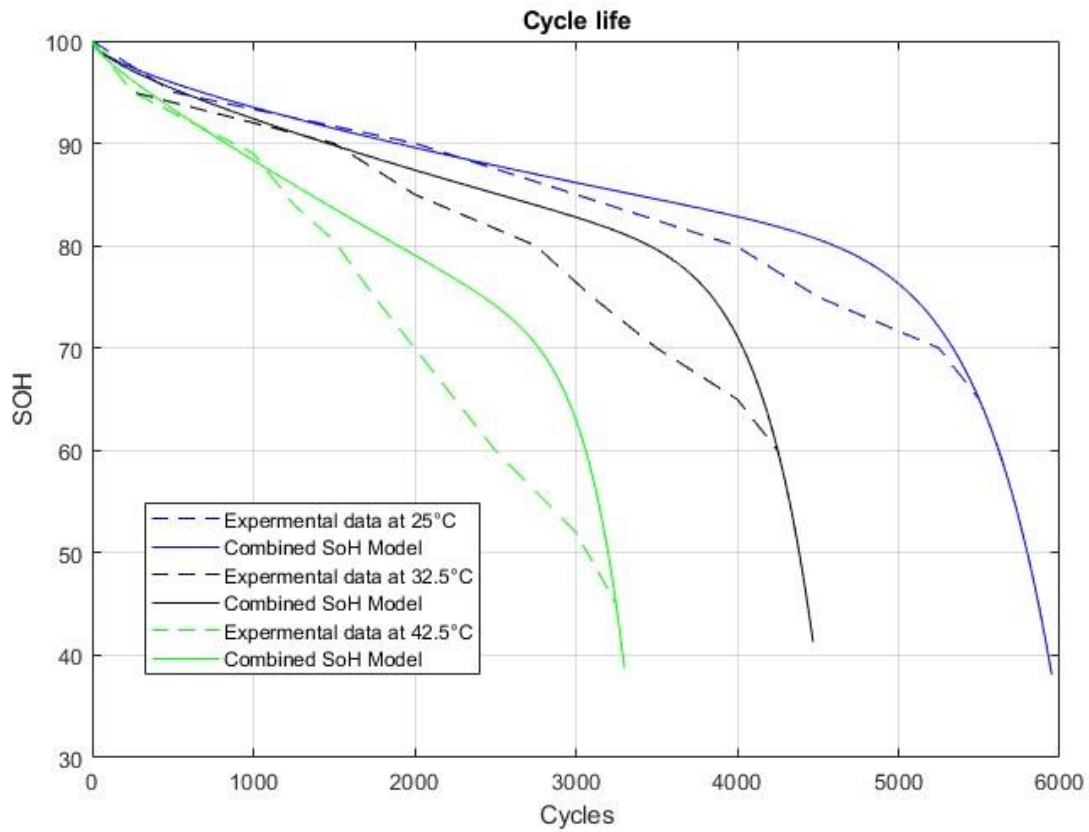
actively utilized or not, these elements play a significant role in the aging process of the battery during charging and discharging cycles [14, 20].

Considering that calendar aging impacts the battery during cycling, employing the comprehensive model described in Section 3.5.3 becomes crucial to determine the optimal cycling conditions. This model considers the interplay between various factors, including calendar aging effects, to establish the most suitable conditions for the battery's cycling performance and longevity. By integrating both calendar and cycle aging factors, this model aids in defining the optimal parameters for maintaining battery health and efficiency during use.

#### **4.3.1 Temperature**

Cycle aging in batteries is notably impacted by the operating temperature, particularly showcasing the most significant increases in capacity fade at low temperatures [14]. Exploring how the operating temperature influences battery lifespan involved employing the comprehensive model detailed in Section 3.5.3, assuming storage temperature and SoC level at 25°C and 50%, respectively.

Figure 4.3 visually illustrates the impact of temperature on cycle aging when assuming a storage temperature of 25°C and SoC level at 50%, highlighting that capacity fade experiences notable increments at higher temperatures. This emphasizes the direct correlation between higher operating temperatures and accelerated capacity degradation during cycling processes in batteries. The experimental data was obtained from [35] and comprehensive model outlined in Section 3.5.3 is used. Table 4.1 shows the values of the  $K_1$ ,  $b_1$ ,  $K_2$ , and  $b_2$  coefficients.



**Figure 4.3:** Degradation of the battery when cycled at various temperatures. The charge and discharge rate were 1C and the SoC range was 0–100 %.

**Table 4.1:** Coefficients' values when the battery is cycled at different temperatures.

	$K_1$	$b_1$	$K_2$	$b_2$
Value for (25 °C)	0.000100	0.840	$0.08 * e^{-50}$	13.430
Value for (32.5 °C)	0.000105	0.875	$0.08 * e^{-50}$	13.875
Value for (42.5 °C)	0.000120	0.950	$0.08 * e^{-50}$	14.370

Operating below 25°C triggers the primary aging mechanism involving the formation of metallic lithium deposits on the anodes. These deposits subsequently react with electrolyte, reducing the available cyclable lithium. On the other hand, temperatures above 25°C accelerate distinct degradation reactions. These include cathode deterioration and the development of a SEI film on the anode. These processes collectively contribute to a reduction in capacity and an increase in internal resistance [32].

Irreversible capacity loss during cycling caused by elevated temperature stems from various factors, which may involve structural alterations in the insertion electrode, electrolyte decomposition, dissolution of active materials, phase transitions in the insertion electrode, formation of a passive film on electrode surfaces, and changes in the current collector surface. These mechanisms collectively contribute to the degradation of battery performance during operation, manifesting as irreversible capacity loss over time [32].

The recommended operational temperature range for the battery falls between 18°C and 35°C. Therefore, either high or low operating temperature can have adverse impacts on the battery, influencing factors such as charge acceptance, round-trip efficiency, the electrochemical system, and overall reliability [36].

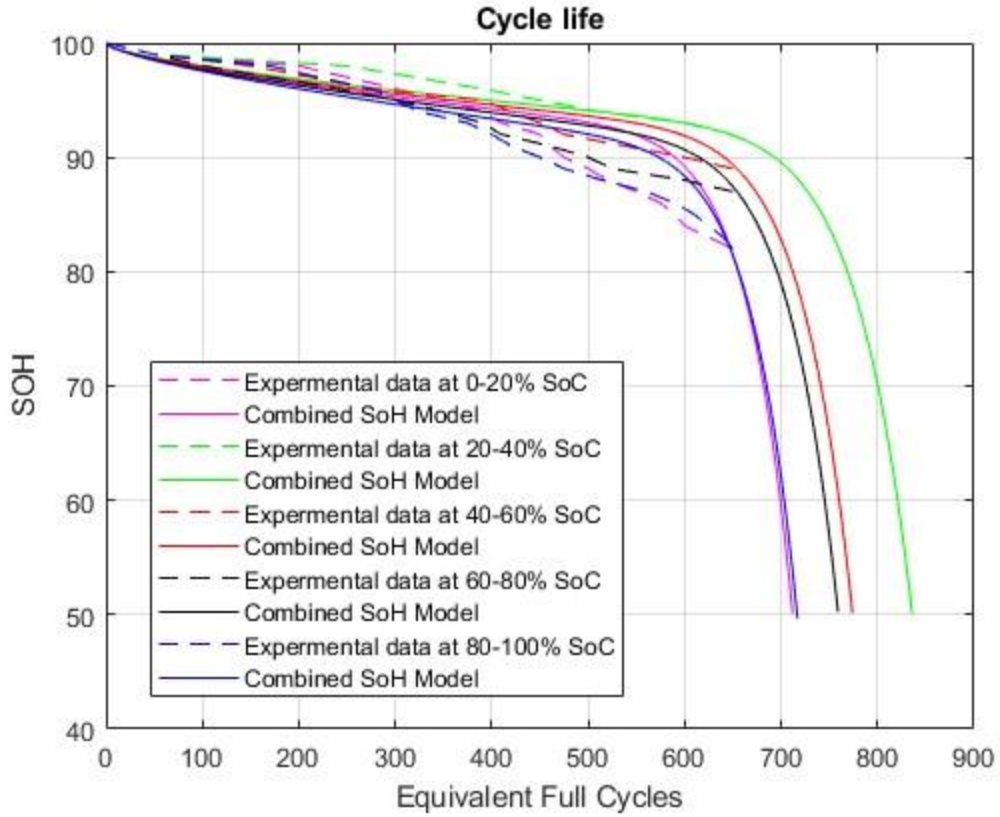
#### **4.3.2 State of Charge (SoC) range**

Studying how the SoC range impacts the lifespan of lithium-ion batteries involves utilizing the comprehensive model illustrated in Section 3.5.3. Assuming an operating temperature of 25°C, storage temperature at 25°C, and storage SoC level set at 50%, examining various SoC ranges is necessary to understand how battery degradation

varies accordingly. However, to conduct this study, specific data pertaining to different SoC ranges and their corresponding effects on battery degradation would be required. Gathering this data will enable a comprehensive analysis of how different SoC ranges impact battery lifespan and degradation patterns.

Studying battery cycling across various SoC intervals, specifically in 20% increments from 0–20% to 80–100%, revealed distinct outcomes. Cycling within the 0–20% range led to increased impedance and capacity loss. Higher SoC ranges (80% to 100%) experienced more degradation due to the loss of active material (LAM) and lithium inventory (LLI). Conversely, medium SoC cycling (20% to 80 %) resulted in lower capacity loss, proving more favorable compared to both high and low average SoC cycles as shown in Figure 4.4 when assuming a storage temperature of 25°C and SoC level at 50% and the experimental data was obtained from [37]. Cycling within the 0–20% range as explained in literature lead to the significant impact of anode copper current collector corrosion and structural disordering in the cathode's active material on battery longevity [37] and comprehensive model outlined in Section 3.5.3 is used. Table 4.2 shows the values of the  $K_1$ ,  $b_1$ ,  $K_2$ , and  $b_2$  coefficients.

Maintaining operations between 30–70% SoC proves advantageous for NMC batteries, assuming all other conditions remain constant. However, the extent of this benefit largely hinges on the required energy extraction. Sustaining cycling between 20–80% SOC, with a 60% DoD, would offer notable advantages for the battery's performance [37].



**Figure 4.4:** Degradation of the battery when cycled at various SoC ranges.

**Table 4.2:** Coefficients' values when the battery is cycled at different SoC ranges.

	$K_1$	$b_1$	$K_2$	$b_2$
Value for (0-20% SoC)	0.00026	0.830	$2.68 * e^{-44}$	15.14
Value for (20-40% SoC)	0.00023	0.815	$2.68 * e^{-44}$	14.78
Value for (40-60% SoC)	0.00025	0.820	$2.68 * e^{-44}$	14.95
Value for (60-80% SoC)	0.00030	0.820	$2.68 * e^{-44}$	14.99
Value for (80-100% SoC)	0.00031	0.835	$2.68 * e^{-44}$	15.12

### 4.3.3 Depth of Discharge (DoD)

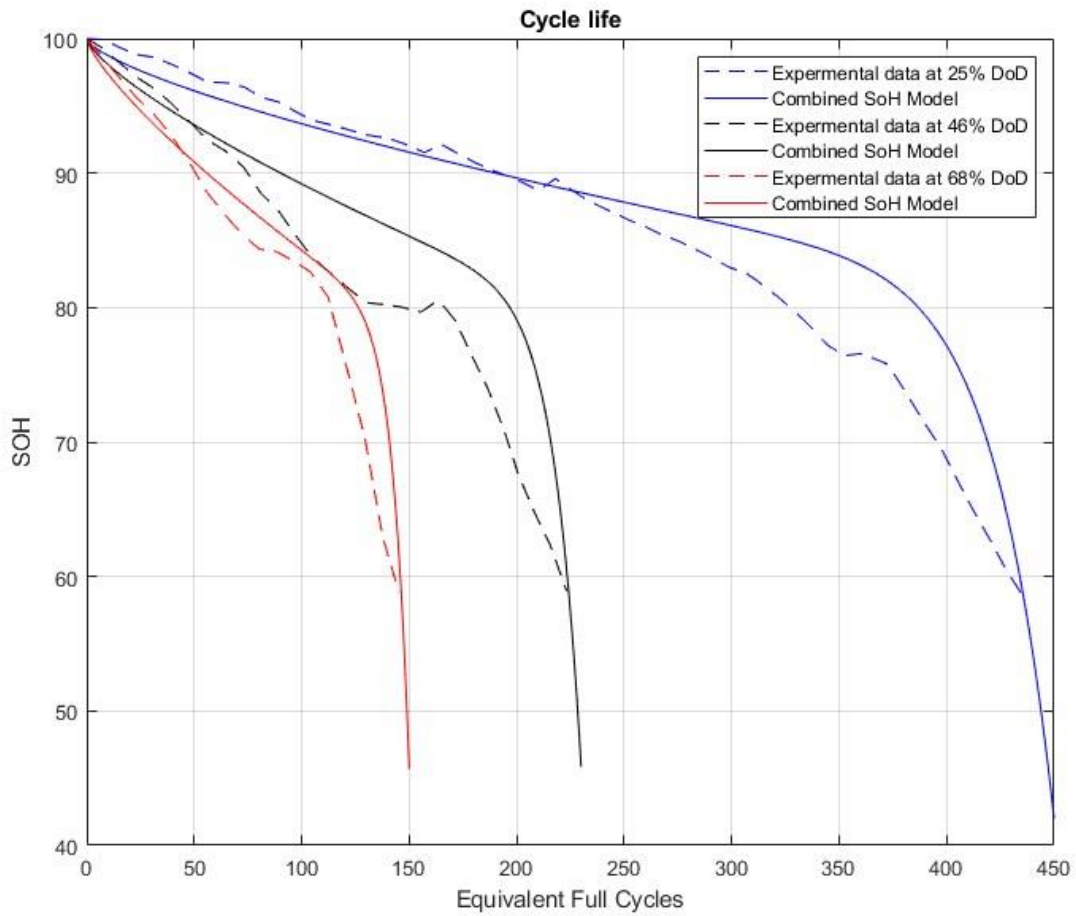
DoD plays a pivotal role in cell degradation. Increased DoD often leads to a more significant volume change in active particles during cycling, potentially causing stress, cracking, and overall cell degradation. Hence, there exists a direct correlation between cell degradation and DoD; the higher the DoD, the faster the cell tends to degrade [38].

Determining the optimal DoD hinges on the required energy extraction from the battery. It is advisable to avoid exceeding 60% DoD based on the SoC range described in the previous section 4.3.2 to mitigate rapid degradation and preserve the battery's lifespan. This balance allows for extracting a reasonable amount of energy while minimizing the detrimental effects associated with higher DoD levels [38].

Figure. 4.5 provides a visual representation of the impact of DoD on cycle aging when assuming an operating temperature of 25°C, storage temperature at 25°C, and SoC level at 50%, demonstrating notable increases in capacity fade at higher DoD levels. This emphasizes the direct correlation between higher DoD and accelerated capacity degradation during cycling processes in batteries. The data experiment is obtained from [31] and the comprehensive model outlined in Section 3.5.3 is used. Table 4.3 shows the values of the  $K_1$ ,  $b_1$ ,  $K_2$ , and  $b_2$  coefficients.

### 4.3.4 C-rate

Surprisingly, not all instances of higher charging rates result in a more significant decline in battery capacity, as discovered in some papers. It was observed that the rate at which a battery ages is minimally impacted by the C-rate when the temperature remains consistently stable. Batteries cycled under 1C and 2C at a temperature of 20°C degrade



**Figure 4.5:** Degradation of the battery when cycled at various DoD.

**Table 4.3:** Coefficients' values when the battery is cycled at various DoD.

	$K_1$	$b_1$	$K_2$	$b_2$
Value for 25 % DoD	0.0017	0.748	$2.68 * e^{-44}$	16.27
Value for 46 % DoD	0.0027	0.780	$2.68 * e^{-44}$	18.25
Value for 68 % DoD	0.0037	0.800	$2.68 * e^{-44}$	19.80

at a slower pace compared to those cycling under 0.5C. Moreover, elevating the temperature from 20 to 34°C has been shown to enhance battery life when subjected to several high C-rates. This occurrence might be influenced by lithium plating [37].

Further investigation could be conducted to delve into this unusual pattern of degradation triggered by the C-rate in cells with substantial capacities, often attributed to lithium plating [37].

Other papers contend that the impact of current rates remains negligible within the range of rates employed, particularly at a consistent temperature. The analysis extended to varying discharge current rates yielded a similar conclusion [39].

The degradation of batteries becomes more complex when both the C-rate and temperature are considered. Despite inconclusive findings on how the C-rate impacts battery lifespan, within a working temperature range of 18-35°C, and maintaining consistent C-rates, it has been observed that as the temperature rises, the impact of lithium plating on the aging of the battery diminishes. Additionally, it is noted that elevating the charging C-rate enhances the influence of lithium plating on the reduction of battery capacity when the temperature remains constant. However, operating the battery below 18°C—although not recommended—suggests that lower C-rates are preferable for enhancing the battery's lifespan [40].

However, when DoD is considered, the situation becomes more complex. In instances of high DoD, it is advisable to reduce the C-rate. Under identical temperature conditions and high DoD, A higher C-rate at such elevated DoD levels can expedite the

degradation process of the battery. In cases where DoD reaches 60%, it is recommended to employ a lower C-rate to mitigate battery degradation [41].

#### **4.4 Summary**

A comprehensive understanding of factors affecting battery life, including optimal storage, and cycling conditions, remains crucial, yet some findings are inconclusive. Identifying the best operational settings significantly contributes to extending the life cycle of second-life batteries, although ongoing research aims to resolve uncertainties in this domain.

## **Chapter 5 Summary, Conclusion, and Future Work**

### **5.1 Summary**

This thesis explored the critical importance of energy storage systems (ESS) in the contemporary energy landscape, especially with the rising adoption of renewable energy sources. Additionally, it emphasized the potential viability of second-life batteries as a feasible option for ESS instead of new ones. This thesis delved into the application of a mathematical combined State of Health (SoH) model for estimating SoH and predicting the remaining useful life of batteries. Through comprehensive analysis and experimentation, the thesis highlighted the effectiveness of this model in determining optimal conditions to extend the lifespan of second-life batteries.

### **5.2 Conclusion**

Accurately determining State of Health (SoH) encounters complexities attributed to factors such as indirect measurements, data source variations, and non-linear behavior. Current methods for SoH estimation employ a range of strategies, including data-driven, model-based, and hybrid approaches. These approaches are pivotal in precisely evaluating cycle life and estimating battery SoH, particularly in the context of researching the potential utilization of second-life batteries for stationary storage.

To achieve precise battery aging estimation, it is imperative to consider diverse factors such as depth of discharge, charge range, cycling patterns, temperatures, and storage SoC. While studies often concentrate on specific elements like calendar life or cycle life, a robust aging prediction model should comprehensively address the complex

interactions among all these parameters for a holistic evaluation of battery performance and longevity.

The development of a comprehensive lifespan model for batteries necessitates an understanding of aging processes, typically derived from accelerated aging tests. Battery aging analysis conventionally categorizes into cycle aging and calendar aging, demanding a comprehension of specific mechanisms and conditions influencing aging from both cycling and time-related aspects. A crucial component is a mathematical SoH model integrating both calendar and cycling aging, providing insights into degradation under varying conditions, which in turn utilities can use in predicting the remaining lifespan of the battery.

Users seeking to maximize the benefits and cost-efficiency of lithium-ion batteries prioritize extending battery longevity. A thorough understanding of factors influencing battery life, especially optimal storage and cycling conditions, is paramount. The developed model not only facilitates the estimation of SoH but also predicts the remaining useful life of the battery, potentially influencing user behavior to optimize usage patterns. The model relies on initial usage data to enhance its accuracy and effectiveness.

The model illustrates that subjecting batteries to elevated temperatures results in increased side reactions, leading to a substantial reduction in usable lithium and diminished capacity. Additionally, it highlights that storing a battery at higher states of charge (SoC) speeds up degradation, while lower SoC levels slow down this process. However, high SoC levels can contribute to reduced capacity and heightened resistance in the battery.

Furthermore, the model indicates that the operation of a battery at high temperatures expedites degradation. Additionally, it reveals that cycling within medium SoC ranges results in reduced capacity loss, proving more beneficial when compared to both high and low average SoC cycles.

Moreover, the model establishes a direct correlation between battery degradation and Depth of Discharge (DoD), emphasizing that a higher DoD leads to a faster degradation of the battery.

### **5.3 Future work**

As with any scholarly pursuit, this research has opened doors to further inquiry and exploration. The complexities of second-life batteries offer prolific ground for continued investigation. Future endeavors could delve deeper into refining the SoH model, further exploring factors influencing battery health, and expanding the applicability of these findings across diverse energy storage technologies.

Continuing research aims to delve deeper into validating SoH model's ability to precisely outline battery degradation mechanisms and predict its remaining usable life. This pursuit seeks to support confidence in the model's accuracy, solidifying its role in predicting battery deterioration and estimating the remaining operational lifespan more reliably.

Once the data is collected, employing a more advanced approach like machine learning becomes viable for estimating the SoH of the battery and predicting its remaining useful life. Machine learning techniques such as Support Vector Machine (SVM) or Neural

Networks (NN) are potential options for this purpose. These methods can effectively leverage gathered data to provide insights into the battery's condition and future lifespan.

The forthcoming plan involves conducting an experiment to explore the battery's aging mechanisms under diverse storage and cycling conditions. By subjecting the battery to varied operational settings and storage environments, the aim is to develop a better understanding how these factors influence its lifespan and performance. This experiment seeks to uncover valuable insights into the complex processes that drive battery aging, paving the way for more informed strategies to improve longevity and optimize its usage in various applications.

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## **Vita**

Yousef Alamri, originally from Saudi Arabia, completed his high school education in 2013 and immediately continued an undergraduate study in electrical engineering, earning his Bachelor of Science degree by 2018. Following his undergraduate studies, Alamri chose to further his education at the University of Tennessee, Knoxville, where he pursued a Master of Science in electrical engineering. During his time as a master's student, Alamri engaged with the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT), focusing his research on the estimation and prediction of the state of health (SoH) for second-use electric vehicles batteries.