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(RESEARCH ARTICLE)

# Improving grid reliability with grid-scale Battery Energy Storage Systems (BESS)

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## Abstract

The modern electric power system is stable because generation and demand are balanced in real-time. To provide grid managers the leeway to maintain this balance, grid-scale energy storage devices are seeing increased deployment. Another existing technique to achieve a stable and reliable power system today is integrating renewable energies with a battery energy storage system (BESS). Integrating grid-scale BESS to improve grid dependability is crucial since renewable energy sources, which may be somewhat unpredictable, are increasingly being integrated into existing power networks. With its massive electrical energy storage and distribution capabilities, BESS contributes to the grid's ability to balance supply and demand. The BESS helps maintain grid stability by storing energy that is not used during peak hours. This energy comes mostly from renewable sources like solar and wind and is then sent back to the system when the demand is highest. Primary function of BESS includes energy storage and time-shifting, regulation of frequency, voltage support, and enhancement of grid reliability. Development in battery technologies and controls has made them cheaper and inevitable for future power networks. The functions and elements of BESS, the types of electrochemical batteries, the implications of their degradation, and their applications for grid optimization and reliability are discussed in this research. In conclusion, BESS is a significant enabler of grid modernization, resilience, and the evolution of the energy system.

**Keywords:** Renewable Energy Integration; Voltage Support; Electrochemical Technologies; BESS; Grid-scale Energy.

## 1. Introduction

Traditionally, power generation has been adjusted to meet demand, maintaining balance in the electrical grid. However, with an increasing presence of intermittent renewable energy sources, this approach becomes insufficient and detrimental to plant efficiency and longevity. To address these challenges and optimize the grid's carbon intensity while maximizing efficiency, grid-connected energy storage systems provide a crucial buffer, decoupling demand from generation capacity[1].

Grid-connected energy storage using BESSs is starting to become financially feasible in many parts of the world[2]. Electrochemical energy storage battery modules provide the capability to be highly scalable and flexible, offering superior round-trip efficiency, prolonged cycle life, and low maintenance requirements. A variety of grid support functions may be carried out by BESSs, increasing revenue by making networks more efficient and stable[3][4]. Importantly, many of the valuable advantages of grid-connected energy storage can only be realised with battery systems because of their rapid reaction rate [5][6].As a rule, the following parts make up a BESS conventional centralised architecture [7]:

- **Battery pack:** This is made up of many battery cells arranged either serially or parallel.

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- **Battery management system (BMS):** Each battery pack in a BESS is monitored, protected, and kept running optimally by its functions.
- **Converter electronics:** This part communicates with the grid. It connects to the grid and enables a battery pack to convert its DC output to AC power. The BESS is brought into phase lock (PLL) synchronisation with the grid frequency. General system monitoring is the job of supervisory system control, sometimes known as real-time computer control.
- **Communication (ICT):** BESS integration with power systems may be accomplished with the use of ICTs. Lower than the BESS's ramp rate must be the communication delay among the utility and the BESS. Because the BESS ramp rate is less than one second per megawatt, this is the range in which the latency must fall. Figure 1 illustrates the connections between each of these parts in a centralised architecture.

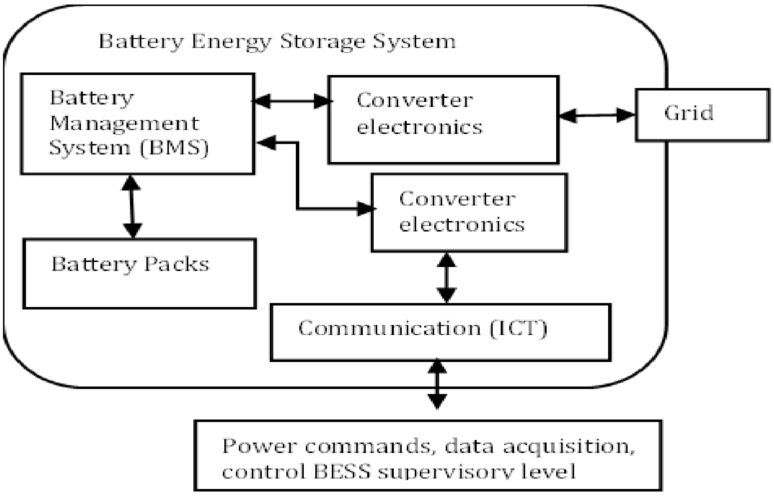

**Figure 1** BESS architecture[7].

Electric vehicles (EVs), photovoltaic (PV) panels, wind turbines, and other bidirectional power components are becoming more integral to the power grid. Use cases, applications, or BESS grid services include regulating frequency, supporting voltage, implementing black starts, smoothing renewable energy, and other similar tasks in power systems that make use of batteries [8][9][10]. Given the rapid development of BESS grid services to meet the needs of the next-generation power system and take advantage of future commercial possibilities, an implementation and assimilation of BESS projects present substantial challenges to their technical and financial success[11][12][13]. With respect to grid-scale ESS, this document also summarizes the characteristics of several energy storage technologies; the main distinctions between these technologies are in the technical specifications and economic viability of the various kinds of energy storage[14].

Modern battery chemistries have come a long way, expanding a variety of batteries available for use in novel storage applications and making them more reliable and useful for electric grid applications. Local power system operators may provide regulations, direct finance, or indirect remuneration to encourage the installation of BESSs, which might be expensive. This is necessary for modern power networks to increase efficiency and use renewable generation. As the primary asset, the battery depreciates with time, the BESS must provide a healthy return to investors if it is to propel the deployment of network storage capacity. Value must be gained from various grid services for energy storage to be a viable business option. The challenge lies in minimizing battery degradation while optimizing BESS control to deliver a variety of services. Improving grid reliability and integrating renewable energy sources are a primary goal of this research, which aims to evaluate an advancements and consequences of BESS. The increasing need to resolve renewable energy's intermittency and guarantee a steady, long-term supply of power is driving this effort. Doing so is fundamental to building an energy infrastructure that can withstand and even benefit from natural disasters[15].

### 1.1. Structure of the Study

The paper is organized as follows: Section II provides an introduction to Grid-Scale BESS and their primary functions. Section III discusses the physical components of BESS. Section IV examines different battery technologies and their performance characteristics. Section V presents the effects of BESS degradation. Section VI presents use cases of BESS for enhancing grid stability. In Section VII, a brief literature review on the impact of BESS on grid efficiency is conducted. Lastly, Section VIII provides a summary of the main results and proposes avenues for further study.

## 2. Overview of Grid-Scale Battery Energy Storage Systems

Grid-scale BESS, utilizing modern technology, can store and deliver vast amounts of electrical energy, playing a crucial role in grid stabilization. In essence, BESS devices may help to keep the supply and demand for energy steady by storing the energy during the periods that an energy demand is low and releasing the energy during a period that an energy demand is high. In solar and wind power systems, BESS continue to play an essential role in stabilising power levels and minimising unpredictability. They assist to balance and maintain the efficiency of power systems by offering services among them being frequency control, voltage control, and peak load trimming. As power distribution networks gradually transition to more sustainable models, grid-scale BESS are becoming more important as a result of ongoing advancements in battery technology and control systems[16].

### 2.1. Key functions of Grid-Scale BESS

#### *2.1.1. Energy Storage and Dispatch*

Renewable energy sources like solar and wind can generate excess energy at times, and the BESS can store this surplus, releasing it during periods of peak demand. This capability addresses the balancing of supply and demand in relation to a grid improvement and utilization of less peaking power plant.

#### *2.1.2. Frequency Regulation*

The function ensures the grid maintains a stable frequency by quickly responding to deviations. BESS can rapidly inject or withdraw power within milliseconds, preventing blackouts and equipment damage caused by frequency fluctuations.

#### *2.1.3. Voltage Support*

BESS can provide reactive power to the grid; it can control a voltage level and uphold a standard quality of a power. In the particular situation, where certain share of variable renewable generation is embedded in the network and voltage fluctuations can occur, such support is rather critical.

#### *2.1.4. Grid Reliability and Resilience*

BESS may be fundamental and may enhance the critical infrastructure and the grid stability by delivering electricity during a disturbance or outage. When in islanding mode, BESS may assist in building microgrids that can operate during calamities apart from the main grid.

#### *2.1.5. Renewable Energy Integration*

Renewable energy sources like wind and solar may be more easily integrated into the grid with the help of BESS, which smooths out their output. This reduces the variability and intermittency of renewables, making them more predictable and reliable sources of energy.

#### *2.1.6. Deferral of Infrastructure Upgrades*

Localised energy and capacity assistance from BESS may postpone or minimise the need for expensive changes to the grid infrastructure. This deferral allows utilities to optimize investment in grid expansion and reinforcement.

#### *2.1.7. Market Participation*

Aside from ability reserves, BESS may also provide energy arbitrage as a means of entering the energy market. An individual or organisation may engage in energy market arbitrage by buying and storing energy when prices are low and then selling it when prices are high. Battery energy storage systems are more financially feasible with these services[17].

## 3. Components of Battery Energy Storage Systems

A physical features of energy storage devices that rely on batteries are the primary focus of the research. A grid-connected BESS's circuit diagram is shown in Figure 2. Important components are the step-up transformer, AC and DC filters, battery bank, and DC-to-AC converter. This section focuses on the most important components, which are the power electronics converter and the battery bank. Figure 2 shows the fundamental layout of a grid-connected energy storage system that uses batteries[18].

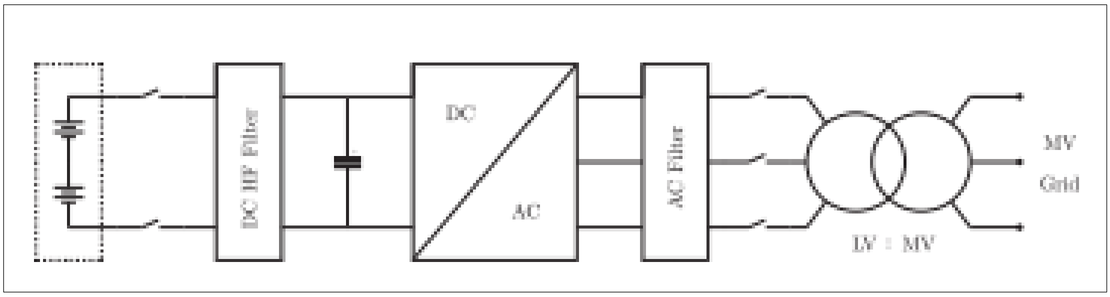

**Figure 2** Basic schematic of a grid-connected battery energy storage system

- The **Battery Management System** (BMS) keeps an eye on and regulates important factors like voltage, temperature, and state of charge. By averting problems like overcharging or overheating, it guarantees safe and effective functioning.
- The **Power Conversion System** (PCS), which includes inverters and converters, handles a conversion of DC from a battery to AC for grid compatibility and vice versa. Charge controllers regulate the charge and discharge rate to maintain safe operation.
- An **Energy Management System** (EMS) optimises energy use depending on demand, power pricing, and the availability of renewable energy sources while coordinating the BESS's overall operation.
- The **Thermal Management System** is responsible for maintaining battery temperature within an optimal range, using cooling and heating mechanisms to enhance performance and battery life.
- The **Communication System** facilitates data exchange between the BMS, PCS, EMS, and external systems, using protocols like Modbus and Ethernet for efficient communication and remote monitoring.
- **Safety and Protection measures** include fuses, circuit breakers and thermal selectors for controlling electrical faults and thermal risks to make sure that system runs safely.
- **Housing and enclosures** are protection and compartments for the battery cells and electronics and insulation to different environments.
- Finally, **auxiliary systems** like ventilation, lighting, security etc. make sure that the BESS functions as well as is maintained safely and efficiently.

## 4. Types of Electrochemical Battery Technologies

Lithium-ion, lead acid, redox flow batteries and sodium Sulphur batteries are probably the most commonly utilized electrochemical technologies in grid applications. Figures 2–5 and the accompanying discussion outline the characteristics of grid-connected electrochemical storage with respect to energy density, efficiency, longevity, and prices.

### 4.1. Lead-Acid Batteries

In 1889, a scientist from Paris named Gaston Plante used lead acid batteries to create the first technology for rechargeable batteries. The lead-acid battery technology has reached maturity thanks to its low cell cost (50-600 $/kWh) and excellent efficiency (80-90%). The main drawbacks of these technologies are their short cycling life (up to 2500 cycles) and poor energy density (20-30 WH/kg). Also, lead-acid batteries don't last as long after a heavy depletion[19][20].

### 4.2. Sodium-Sulfur (NaS) Batteries

Team members from TEPCO and NGK Insulators Ltd collaborated to develop sodium-sulfur batteries. The outstanding performance of NaS batteries is well-known. These batteries have an efficiency of over 80%, a cycling life of up to 4500 cycles, an energy density of 150-240 WH/kg, and an operating temperature of around 300 ∘ C. This technology is already in use as grid-connected energy storage[21].

### 4.3. Redox Flow (RF)

NASA started working on redox flow batteries in 1974[22]. To initiate the oxidation-reduction (redox) process, two electrodes are used to mix the chemical reactants held in separate tanks, which are separated by a membrane. Flow batteries' power is defined by their electrode and membrane systems, while their energy capacity is based on the quantity of reactants kept in the tanks. Subsequently, the ratings for power and energy are split, enhancing the operational and design flexibility. Redox flow batteries may reach up to 75% efficiency and have a low energy density of 15–30 Wh/kg. However, there are no restrictions on the life cycle of reactants or the depth of discharge for flow batteries. In addition to their unique technological characteristics, redox flow batteries' impressive economic performance has made them a promising contender for grid-scale storage. There have been a number of suggested and investigated chemical compositions for the reactants. Nevertheless, the two most common types are vanadium and zinc-bromide based[23][24].

### 4.4. Lithium-Ion Batteries

Sony commercialized lithium-ion batteries in 1991. Anode materials, such as graphite, and cathode materials, such as lithium metal oxide, determine the electrochemical characteristics of lithium-ion batteries. Figure 3 demonstrates that this technology has a long lifespan (up to 10,000 cycles) contingent on the Li-ion chemistry, a high energy density(90-190 WH/kg)[25], and an efficiency (above 90%), but some commercial systems provide a reported round trip efficiency of more than 95%. However, a crucial component in the deterioration process, cell temperature affects the longevity[26].

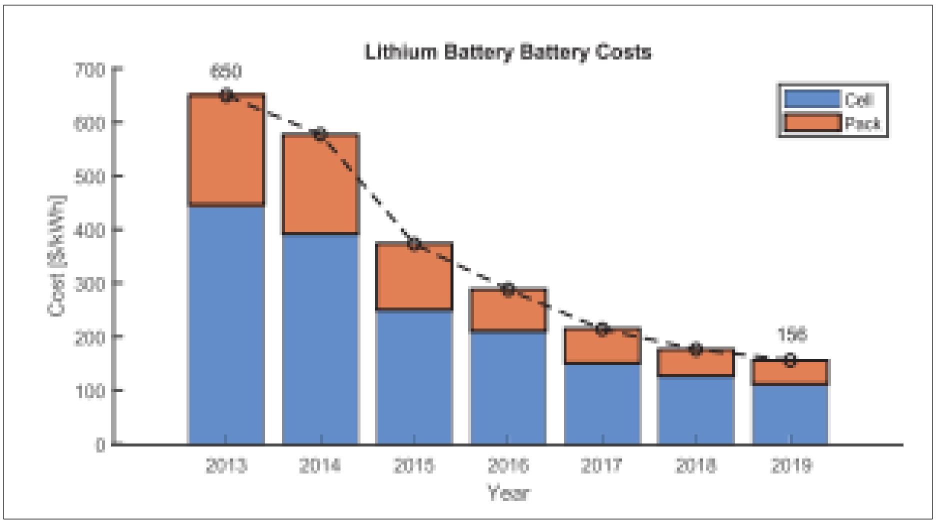

**Figure 3** Costs of lithium-ion battery cell and pack over the last years

A long-term pricing chart of lithium-ion battery cells and packs is shown in Figure 3. The most notable thing is the significant cost decrease, around −75% in 6 years, from 650 $/kWh in 2013 to 156 $/kWh in 2019. Future cost reductions are expected to be much more dramatic. This may lead to energy storage technology' increased use in the power sector and a subsequent decrease in TCO (Total Cost of Ownership). The rapid emergence of lithium-ion batteries as the central technology for EVs is largely attributable to their extensive usage in electronics. This technology is still rather expensive, but it works well for applications that are linked to the grid. These days, you can choose from a wide variety of lithium-ion technologies that use different types of lithium oxides, such as LiCoO2, LiMn2O4, LiNiO2, LiNiCoAlO2, LiNiMnCoO2, Li24Ti5O12, LiFePO4, and lithium titanite oxide[27]. Lithium nickel manganese cobalt, Lithium iron phosphate, and lithium nickel aluminum cobalt are all shown in Figures 6–8. The technique based on lithium, manganese, and cobalt (NMC) provides the greatest results among the electrochemical compositions that were investigated. One of the main reasons NMC has become the go-to Li-ion technology for EVs and stationary storage is its excellent performance.

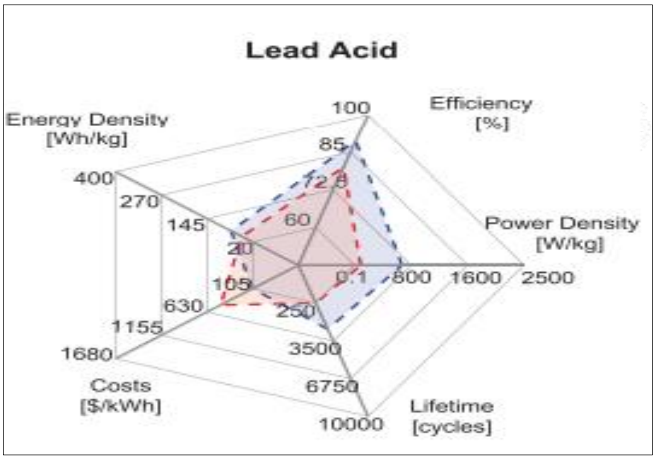

**Figure 4** Performances of Lead Acid

Figure 4 displays the results of the lead acid test. A red shade shows a worst performance whereas blue shade shows the best performances of lead acid.

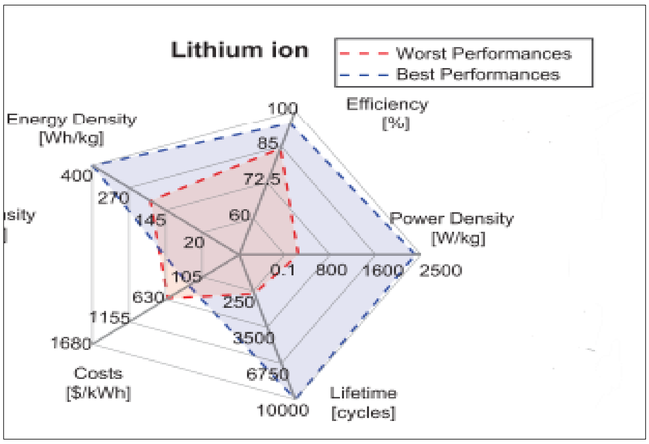

**Figure 5** Performances of Lithium-ion

The Figure 5 represents the performance of Lithium ion. The red shade shows the worst performance whereas blue shade shows the best performances of lithium ion.

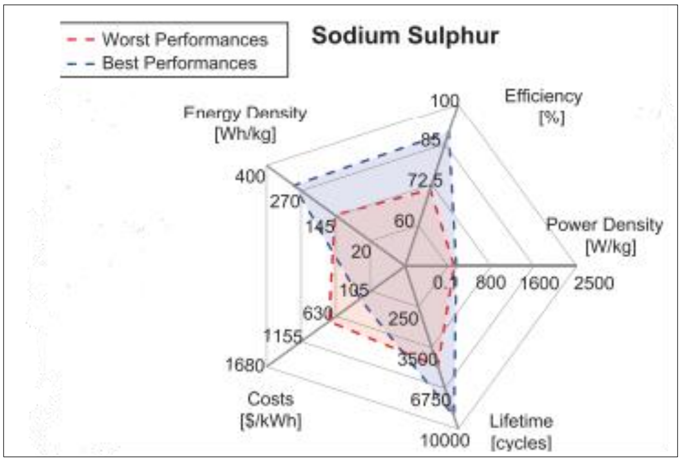

**Figure 6** Performances of Sodium Sulphur

The Figure 6 illustrates the performance of Sodium Sulphur. The red shade shows the worst performance whereas blue shade shows the best performances of sodium Sulphur.

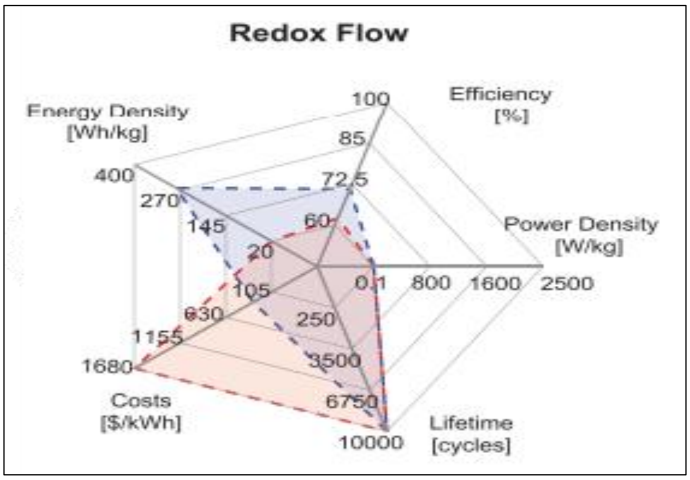

**Figure 7** Performances of Redox Flow

The Figure 7 illustrates the performance of Redox Flow. The red shade shows the worst performance whereas blue shade shows the best performances of Redox Flow.

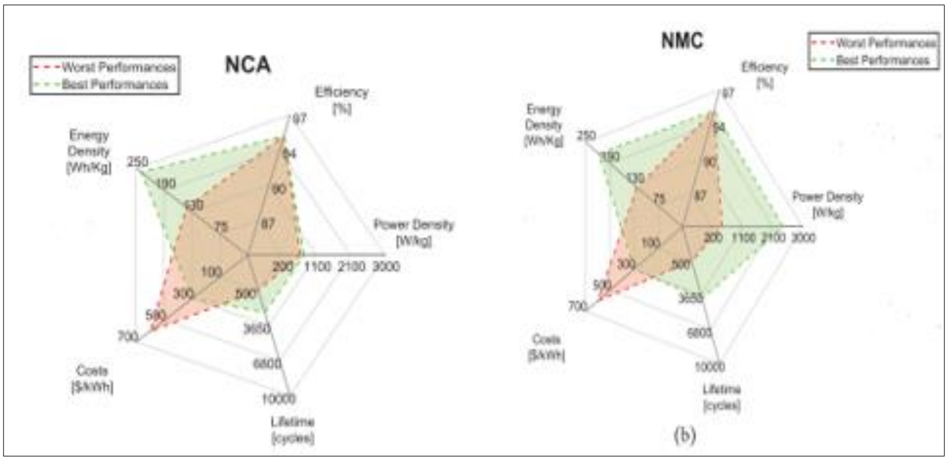

**Figure 8** Performances of different Li-ion battery technologies: (a) Lithium Nickel Cobalt Aluminum Oxide(b) Lithium nickel manganese cobalt

Figure 8 compares a performance of two Li-ion battery technologies, NCA and NMC, using radar charts. The NCA battery exhibits high energy density and efficiency, with moderate power density and lifetime but comes with higher costs. In contrast, the NMC battery offers a more balanced performance across various metrics, including power density, energy density, costs, efficiency, and a longer lifetime. This comparison highlights the trade-offs between different performance aspects, with NCA excelling in energy density and efficiency, while NMC provides a more cost-effective and balanced solution.

### 4.5. Lithium iron phosphate (LFP) Batteries

One material that has been created specifically for use in lithium-ion batteries is lithium iron phosphate, or LFP [87]. The extraordinary thermal stability, outstanding cycle performance, non-toxic features, and cost-effectiveness of lithium iron phosphate (LFP) batteries have brought them worldwide attention. A spike in the disposal of used LFP batteries has occurred, nevertheless, due to the growing usage of these batteries. Degradation of the ecosystem and the mishandling of precious secondary resources are among the potential negative outcomes of improperly managing waste LFP batteries[28]. Although LFP has a somewhat lower energy density compared to nickel-manganese-cobalt oxide, which is currently the most commonly used cathode material, its high-power density (enables rapid energy extraction), affordability, and safety make it an eco-friendly substitute for cobalt-based electrodes. LFP has several commercial uses, such as in maritime technology, consumer electronics, backup home generators, electric cars, and Tesla's home storage batteries, where it will be utilised as a cathode [29]

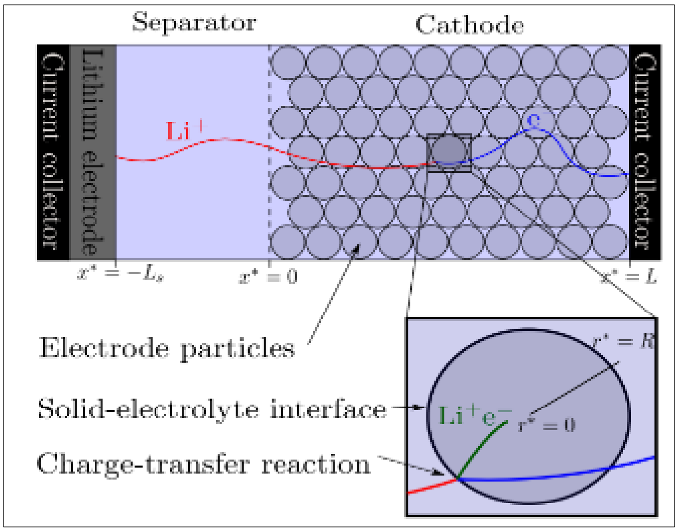

**Figure 9** Illustration of an LFP half-cell.

When studying the electrochemical behaviour of materials used in lithium-ion battery electrodes, it is usual practice to use a half-cell configuration and test the materials alone or in comparison to a conventional counter-electrode. The lithium metal electrode serves as a reference electrode for standardisation in research and is utilised in half-cells. This thesis primarily aims to investigate the behaviour of LFP as a cathode material by concentrating on a half-cell that is based on LFP. In Figure 9, we can see a cartoon representation of a half.

## 5. Battery Energy Storage Systems (BESS) Degradation Effects

Energy capacity of BESS reduces with use and time. Simply said, the capacity of BESS diminishes with every cycle of charging and discharging. Wear on the electrolyte from stress induced by charge/discharge cycles is the primary cause of BESS degradation. Temperature and depth of discharge are two further factors that might hasten deterioration[30]. A variety of battery degradation models, defined by DOD (Depth of Discharge) and maximum cycle count, are therefore available. For instance[31], in, exponential models with the format $N_{100}^{fail} \cdot \mathrm{DOD}^{-k}$ are offered; depending on the kind of battery, k may take values between 0.8 and 2.1. This model attempts to simulate degradation by making use of degradation curves like the one in Figure 10 down below.

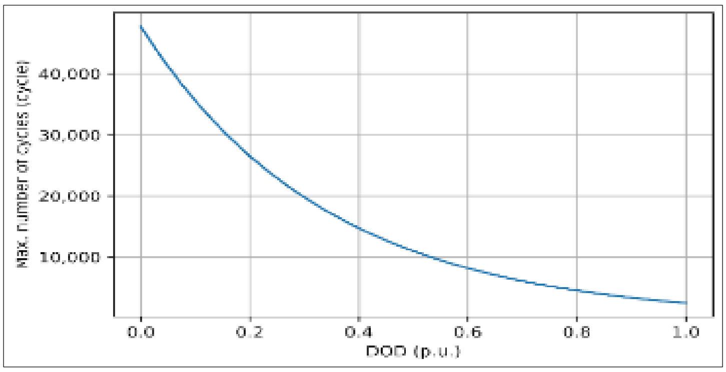

**Figure 10** Degradation curve of Li-ion BESS

Nevertheless, optimisation problems requiring MILP (Mixed-Integer Linear Programming), like BESS's energy arbitrage, cannot be readily addressed by the nonlinear degradation models that have already been mentioned. In order to tackle it, the deterioration curve is linearized by several techniques, including the piecewise linear approximation approach and the large M method[32]. This study uses an upper piecewise linear approximation approach to describe deterioration. Figure 10 illustrates the division of the deterioration curve (Cyclesvs. DOD) into six linear portions.

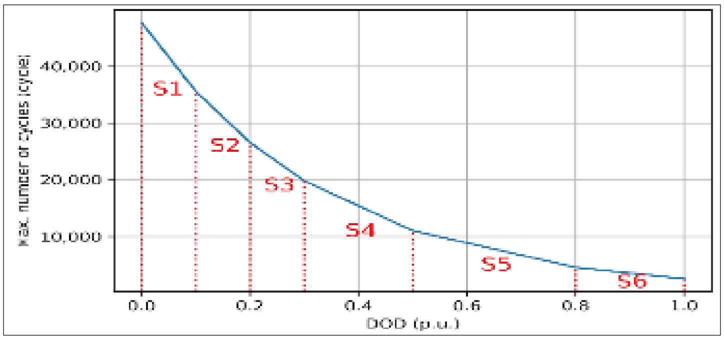

**Figure 11** Linear segments of the Li-ion BESS degradation curve

Assuming a 20% reduction in BESS nominal capacity represents the end of their cycle life, the values shown in Figure 11 are derived[33]. This allows us to calculate the deterioration rate:

$$\beta = \frac{0.2}{N_{max}^{cicles}} \tag{1}$$

Where $\beta$ is the deterioration rate in parts per million per cycle and $N_{max}^{cicles}$ is a maximum amount of cycles for a given depth of discharge (DOD). The deterioration rate curve, shown in Figure 12, is derived from Equation (1).

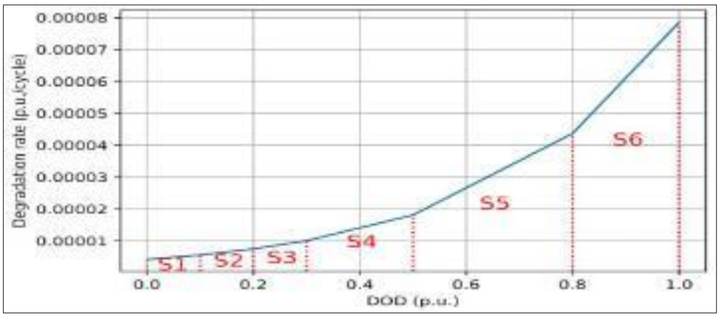

**Figure 12** Linear segments of the Li-ion BESS degradation rate curve

A following is a description of the curve segments depicted in Figure 12:

$$\beta_d = (\beta_d^M \cdot DOD_{t,d}) + \beta_d^B \tag{2}$$

where $DOD_{t,d}$ shows a DOD in segment $d$ at timeperiod $t$,$\beta_d$is a degradation rate valuefor an specific DOD in a segment $d$,$\beta_d^M$is a slope of a segment $d$, and $\beta_d^B$ is the y-intercept point of a segment $d$. A formula that follows restricts DOD to a certain segment:

$$DOD_d^{min} \leq DOD_{t,d} \leq DOD_d^{max} \tag{3}$$

Each segment d has a minimum and maximum value of DOD, which are represented by the parameters $DOD_d^{min}$and $DOD_d^{max}$, respectively. To take the BESS deterioration into consideration, the optimisation problem must include the following constraints:

$$P_t^{dc} . \frac{\Delta t}{E_0^{cap}} = \sum_{d\in D} DOD_{t,d} \tag{4}$$

$$DOD_{t,d} \geq DOD_d^{min} . S_{t,d}^{DOD} \tag{5}$$

$$DOD_{t,d} \leq DOD_d^{max} . S_{t,d}^{DOD} \tag{6}$$

$$\sum_{d\in D} S_{t,d}^{DOD} \leq 1 \tag{7}$$

$$\beta_t = \sum_{d\in D}(\beta_d^M . DOD_{t,d}) + (\beta_d^b . S_{t,d}^{DOD}) \tag{8}$$

$$E_t^{cap} = E_{t-1}^{cap} - \beta_t . E_0^{cap} \tag{9}$$

Where "$\beta_t$" represents the deterioration rate at time period t, and "$S_{t,d}^{DOD}$ " is a binary variable denoting the segment to which the BESS discharge relates. Equation (4) establishes a relationship among the power discharge and DOD. The total DOD, which is determined with Equation (7), is assigned to a particular section of the curve by Equations (5)-(6). At time-interval t, the deterioration rate is decided by equation (8). The last step is to determine the new capacity upon deterioration using Equation (9).

## 6. Applications of Bess For Grid Reliability and Efficiency

BESS are essential for improving grid dependability because of the many services they provide, which aid in balancing and stabilising the grid, which is especially important when dealing with demand variations and growing integration of renewable energy. The key applications of BESS for grid reliability are discussed below:

### 6.1. Energy Arbitrage

BESS provides the vital service of energy arbitrage whereby electricity is bought when it is readily available, and cheap and then sold when it is scarce and costly. This has a positive effect on the balance in supply as well as demand on the grid.

### *6.2.* Frequency Regulation

Frequency control is the process of maintaining the frequency of the power grid near to the set standard value, for instance, 50 or 60 Hz. The BESS has the capability to rapidly respond and balance frequency deviations by providing either power or absorbing it thereby maintaining balance in the electrical grid.

### 6.3. Voltage Support

Sustaining stability in voltages is paramount in relation to the sound working of the power system. BESS also has an ability to provide reactive power which is so crucial in controlling a voltage level within a stipulated range within a power system.

### 6.4. Effect on Grid Reliability

BESS are also used for the purpose of controlling voltage levels by either providing or consuming reactive power. This assists in preventing voltage fluctuations that may include periods of sags or spikes to at least minimize on the probabilities of blackouts or harm to outcome equipment[34].

### 6.5. Load Shifting and Peak Shaving

BESS possesses the flexibility to perform the conversion of energy by peak demand hours to off-peak demand hours known as load shifting. Though load shifting and peak shaving both improve the grid reliability by relieving the load on a grid during peak hour. This enhances a reliability of a system and thereby removes the need to have to frequently alter one's infrastructure[35].

## 7. Literature Review

### 7.1. This section provides a literature review on Grid-Scale BESS.

This study, Mviri, (2022), focuses mainly on the implementations, strategies and ecological impacts of BESS. Other energy storage methods are also compared to BEES's ideas and accomplishments for electrical networks. For the benefit of BESS researchers, we address these issues and more to provide a whole picture. Lastly, this research offers important suggestions for how economists and practitioners might create a BESS that is successful, efficient, resilient, and robust, which will lead to a better implementation[36].

This research, Peñaranda, Romero-Quete and Cortés, (2021), aims to provide a feasible plan for arbitrage in the Colombian power market that would optimise profits for a BESS owner. We compare statistical, seasonal, and neural network-based arbitration processes using the literature. The optimal operation of BESS is determined by a MILP optimisation problem that incorporates an upper-piecewise linear approximation model for battery deterioration. Net present value (NPV) analyses of the arbitrage techniques always come out negative, meaning that BESS's profits from energy arbitrage in Colombia aren't enough to pay their investment expenses[37].

In this study, Zhao et al., (2023), suggests a quantitative approach to assess BESS application consumption trends over time and, after reviewing hardware characteristics, to provide an outline of BESS workload profiles Ingrid applications. A major emphasis is on the frequency management service and how it interacts with energy storage, production, and consumption. Research like this improves communication and establishes ties between academic and business projects like degradation studies and battery use optimisation by shedding light on the duty cycle analysis of BESS applications[38].

In this study, Frate, Ferrari and Desideri, (2021), the performance and cost of these storage methods are the primary foci of the reviews. Review findings are used to evaluate the present and future economic prospects of storage, with a particular emphasis on the Italian context. The study finds the greatest yearly income by optimising the storage process at the hourly level. By using a linear programming (LP) method, the optimisation is carried out. We estimate the energy price change necessary to achieve viability as none of the storage options we studied are economically viable. Such findings allow one to measure the gap between the present state of affairs and a storage-friendly ideal state[39].

This study, Rampersadh and Davidson, (2017), explores energy storage devices that will revolutionize the world's use, control, and dispatch of electrical energy. With renewable energy entering transmission and distribution grids and rooftop solar installations, energy storage is unlocking new opportunities. New energy distribution and control systems are being revolutionised by rapidly developing technologies such as grid-scale battery storage, flywheels, compressed air, and hydrogen[40].

This work, Oladiran Kayode Olajiga et al., (2024), discusses the advantages of grid energy storage technologies, such as stabilising the grid, regulating frequencies, reducing peak loads, and boosting overall efficiency. Improving grid dependability and decreasing operating costs are highlighted via an analysis of real-world case studies and installations. Nevertheless, it also tackles obstacles and difficulties that may prevent broad implementation[41].

This research, Molina, (2019), examines energy storage devices and the systems that condition their power so that they may be connected to the grid. Discussed are a design and execution of power electronic applications and control systems, as well as their effect on electricity production, transmission, and distribution. Table 1 summarises each research on Grid-Scale BESS, including its objectives, methods, main findings, and difficulties[42].

**Table 1** Summarizing the related works on Grid-Scale BESSS

| Study | Focus | Key Contributions | Methodologies | Challenges/Obstacles |
|---|---|---|---|---|
| [36] | BESS deployments, methodologies, and environmental impact | Comparison of BESS innovations and achievements with other energy storage technologies | Review and comparative analysis | Concerns and obstacles in BESS deployments, offering a comprehensive picture for researchers |
| [37] | Arbitrage approach to maximize economic benefits of BESS in Colombia | Comparison of seasonal, statistical, and neural network-based arbitration procedures | MILP optimization with battery deterioration model; financial evaluation | Negative NPV for BESS arbitrage, indicating insufficient income to cover investment costs |
| [38] | Long-term usage patterns and workload profiles of BESS applications | Energy storage, generation, and consumption as well as frequency control service integration overview | Quantitative framework for duty cycle analysis | Challenges in optimizing battery usage and mitigating degradation |
| [39] | Performance and economic outlook of storage technologies in Italy | Assessment of current and future storage economic feasibility | Linear programming (LP) for storage operation optimization | Economic infeasibility of current storage technologies and required energy price modifications |
| [40] | Revolutionizing energy use, control, and dispatch with storage technologies | Exploration of emerging storage technologies like grid-scale batteries, flywheels, compressed air, and hydrogen | Review and exploration of new opportunities | Challenges in the integration and scalability of emerging storage technologies |

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| [41] | Benefits and effectiveness of energy storage solutions for the grid | Analysis of real-world case studies and deployments for grid reliability and cost reduction | Case studies and deployment analysis | Barriers to widespread adoption of energy storage solutions |
| [42] | Power conditioning systems for grid-connected energy storage technologies | Influence on electricity generation, transmission, and distribution; power electronic applications and control strategies | Design and implementation strategies for power conditioning systems | Design challenges and influence on grid stability |

## 8. Conclusion

A significant advancement in enhancing grid stability and efficiency, BESSs serve as an important buffer between power generation and consumption. Since renewable energy sources such as wind and solar are intermittent, grid-scale BESSs are essential to modern power networks for making these sources more efficient and reliable. These systems leverage advanced technologies to manage the scheduling and flow of electricity across the grid, enabling the storage and distribution of large quantities of energy.

A potential grid stabiliser that works in tandem with intermittent renewable power sources is BESSs, which store excess energy during off-peak hours and then provide it during peak demand times. A capabilities of BESSs extend to energy storage and dispatch, voltage support, frequency management, and overall grid reliability enhancement. The increasing significance of BESSs in today’s energy systems is driven by new control options and battery systems that have led to cost reductions.

This paper provides an overview of BESSs, including their components, various electrochemical battery technologies, and the impact of these technologies on degradation. It also explores how BESSs can be employed to optimize grid capability and reliability. BESSs are integral to the modern vision of the grid, contributing to its enhancement and the creation of a more robust and resilient energy infrastructure.

### *Future Work*

Future work should focus on the comprehensive utilization of BESSs by refining control strategies for multi-service operations while considering battery degradation. Research should also target improvements in battery chemistries and technologies to enhance the economic viability and lifespan of BESSs. Additionally, a thorough examination of the financial models and regulatory frameworks that could encourage broader adoption of BESSs is necessary. Better energy sustainability can only be achieved by integrating BESSs into the electrical grid, which can be achieved if these areas are addressed.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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