

Motivations and Challenges in Deploying Battery Energy Storage Systems (BESS) within Smart Grids

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Abstract:

Climate change mitigation strategies require the wider adoption of renewable energy sources for electricity generation and mobility. The intermittency of renewable generation cannot be handled by conventional grids, leading to power quality issues. A flexible energy management system is therefore required to support the increasing incorporation of renewables in the system. Smart grids can enable the adoption of renewables by facilitating the management of electricity through automated control and continuous monitoring. Battery energy storage systems (BESS) in smart grids can charge during times of low demand when energy is generated in excess, and discharge during times of high demand providing key services such as frequency regulation, peak shaving, renewable firming, and emergency grid support. Hence, BESS is an integral part of smart grids. The study analyses the role of BESS in empowering smart grids and the motivations and barriers to the adoption of BESS. Case studies of BESS-integrated smart grids are also analysed to understand the motivations and barriers.

Keywords: *Battery energy storage systems (BESS), conventional grids, smart grids, energy efficiency, renewable energy.*

1. INTRODUCTION

The adverse effects of fossil fuels, such as greenhouse gas (GHG) emissions and resource depletion, have led the world to an increasing reliance on renewable energy sources (Liu et al., 2024). As of 2022, electricity and heat generation contributed to around 44% of the global carbon dioxide emissions through the combustion of fuels. Adequate steps to lower GHG emissions are necessary to stop the anticipated 2 °C increase in global temperatures, which will have a profound impact on sea levels, wildlife, and climate (Hidalgo-León et al., 2017). Earth is about 1.2 °C warmer than it was in the 1800s due to the cumulative effect of GHG emissions from various sectors. If this increasing trend continues, climate change can lead to intense droughts and affect the hydrological cycle and biodiversity. Hence, global attempts are focused on reducing reliance on conventional energy sources such as fossil fuels. Renewable energy sources are being integrated with the grid as a part of the climate change mitigation strategies (Kumar et al., 2022). This transition can reduce reliance on fossil-fuel-based generation. Renewable energy sources are, however, different from conventional sources in many aspects.

Utility grids are conventional systems, developed over a century ago, enabling a unidirectional flow of energy from its source to sites of consumption. These grids are not designed to manage the dynamic nature of energy generation from renewable sources (Hu et al., 2022; Li et al., 2013). Maintaining a stable grid frequency requires a balance between generated and consumed power. Incorporating renewables has created congestion in the grid, leading to power outages and fluctuations. Hence, there is a need to replace conventional grids with smart grids, capable of handling the dynamic nature of renewable energy sources. Smart grids optimise the generation, distribution, and storage of

energy through coordinated sensing, communication, and control protocols. Storage systems are central to the functioning of smart grids. Storage systems enable the management of excess energy generated when demand is low and deficit energy required when demand is high.

Various types of energy storage systems can be employed in smart grids, such as pumped hydro storage, compressed air energy storage (CAES), thermal energy storage, and electrochemical energy storage. Pumped hydro is the oldest type of storage, in which excess energy is used during off-peak times to pump water to elevated reservoirs during off-peak periods; the water is then released through turbines during peak periods. CAES is based on storing compressed air in underground tanks, which is expanded and passes through turbines whenever needed (Conzen et al., 2023; Zhu et al., 2024). Thermal storage is used to store energy in the form of heat or cold for heating or cooling applications. Batteries are electrochemical energy storage devices that charge and discharge via electrochemical reactions. Among different energy storage systems, battery energy storage systems (BESS) are among the most scalable options for smart grids. The move toward a net-zero energy system has made it easier for renewable energy sources like wind and solar to become part of modern power systems (Hidalgo-León et al., 2017). Even while renewable technologies cut down on greenhouse gas emissions, their unpredictable and non-dispatchable nature makes it very hard for traditional power systems to work. Renewable energy sources that use inverters do not provide much to system inertia, which makes the frequency unstable, the voltage changes, and the grid more likely to be disturbed. If there are not enough ways to be flexible, renewable curtailment is inescapable, which leads to economic losses and wasteful use of clean energy resources.

Energy storage systems, especially battery energy storage systems (BESS), have become an important technology for making the grid more flexible and reliable. BESS enables reliable grid operation under high renewable penetration by providing rapid-response flexibility, meeting peak demand, and offering extra services (Hidalgo-León et al., 2017; Hu et al., 2022). BESS can be installed anywhere, combined with existing renewable energy installations easily, or used together with other storage systems. The scalability and flexibility of BESS make it an ideal energy storage system to be integrated with smart grids. Smart grids integrated with BESS can also provide storage and ancillary services to the grid and increase the economy and efficiency of energy generation, transmission, and distribution. Therefore, the study evaluates the role of BESS, the motivations, and challenges involved in BESS-integrated smart grids. The global CO₂ emissions are around 52000 million tons, as of 2022. China contributes most to global CO₂ emissions, accounting for 30% of the total emissions (Dawn et al., 2024). India and Australia are among the sixteen topmost emitters of CO₂. Figure 1 presents the total CO₂ emissions of various countries according to the Emissions Database for Global Atmospheric Research (EDGAR).

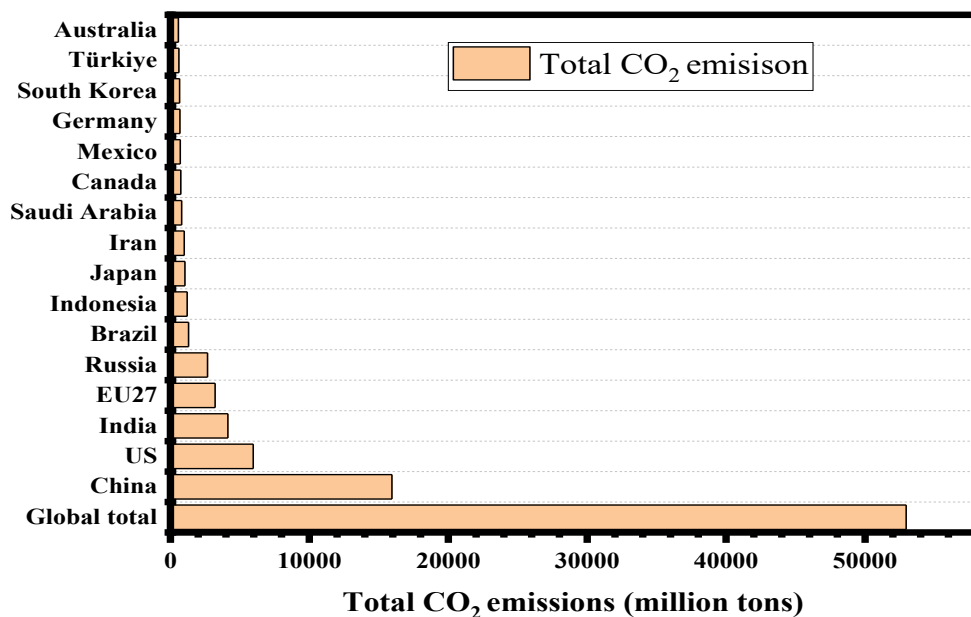


Figure.1. CO₂ emissions from various countries.

The figure highlights a strong concentration of global CO₂ emissions, where a small number of countries contribute the majority of total emissions. This pattern reflects the contrasting dynamics between developed and developing economies, with rapidly industrialising nations such as China and India accounting for significant emissions due to high energy demand and continued reliance on coal-based power generation. In contrast, many developed countries show relatively stable or lower emission levels due to energy efficiency improvements and cleaner technologies (Tariq et al., 2022). The objective of this study is to evaluate the role of Battery Energy Storage Systems (BESS) in enhancing the performance and reliability of smart grids, and to identify the key drivers and barriers influencing their large-scale adoption through a comparative analysis of selected global case studies. The paper is structured as follows: Section 2 presents the research methodology; Section 3 discusses the results, focusing on the technical, economic, policy, and safety aspects of BESS deployment along with comparative insights; and Section 4 concludes the study by summarising key findings and outlining future research directions.

2. METHODOLOGY

2.1 Research Design

This study adopts a qualitative research design combining an extensive literature review with multiple-case-study analysis to evaluate the role of Battery Energy Storage Systems (BESS) in smart grids. Three well-known projects - Hornsdale Power Reserve, Gateway Energy Storage, and Victorian Big Battery - were selected because they were technologically advanced, had an impact on the grid, were located in different parts of the world, and had a record of good operational performance (Blum et al., 2022; Hu et al., 2022). The selection prioritised systems with substantial installed capacity (greater than 100 MW) and demonstrated operational maturity in real-world conditions. Geographical diversity was also considered to capture variations in regulatory frameworks and market environments. Additionally, only projects with accessible and reliable data from peer-reviewed literature, technical reports, and policy documents were included. Finally, the selected case studies exhibit significant contributions to grid stability, renewable energy integration, and ancillary service provision. Together, these factors ensure that the chosen cases represent diverse technological and policy contexts, enabling meaningful and comprehensive cross-case comparison. These systems show how BESS has changed over time and provide useful information about both successful deployment and problems that come up during operation. The study takes into account several factors, such as technical performance, economic viability, safety and operational risk, regulatory and policy support, and the overall effect on grid stability and the integration of renewable energy sources. The data from peer-reviewed articles, government reports, energy market statistics, and project technical disclosures were used for the study. The qualitative synthesis methodology facilitates the identification of persistent trends, determinants, and obstacles affecting BESS adoption. The study is constrained by its dependence on secondary data sources and lacks primary experimental or simulation-based analysis. Although this is a limitation, the comparative assessment gives a full picture of the real-world problems and challenges that come with putting BESS in modern smart grids (Maly & Kwan, 1995). Various aspects of the BESS, such as investment, revenue, policy support, technology used, and possible hazards, were analysed to understand the motivations and barriers to BESS proliferation. In this analysis, each case was analysed individually based on the defined framework, followed by cross-case comparison to identify common drivers, barriers, and emerging trends. The analysis focused on identifying recurring themes, similarities, and differences across cases, enabling the development of generalisable insights into BESS deployment in smart grids. Understanding the characteristics of different battery technologies is essential for evaluating the performance, safety, and economic viability of BESS in smart grid applications. The primary battery types used in BESS are lead acid (PbA), lithium-ion (Li-ion), nickel-cadmium (Ni-Cd), and flow batteries. PbA are the oldest type of batteries with a liquid electrolyte. They are inexpensive but have low energy and power densities and low charge-discharge cycles. Cycle life and environmental compatibility of PbA are improved by using carbon as negative electrodes. Valve-regulated PbA (VRLAs) are cost-effective with low water-maintenance requirements, owing to the gel electrolyte architecture or electrolyte absorbed onto the separator. In terms of quickly responding to

price volatility and energy arbitrage, Li-ion batteries are better than PbA due to their higher power density. Ni-Cd batteries have a lower energy density than Li-ion batteries and are linked to toxicity concerns due to the heavy element cadmium (Wu & Tang, 2019). Flow batteries allow for the separation of electrolytes and reactants, allowing for the control of power and capacity independently, while the electrolyte flows through the electrochemical cell where the reactions take place. The drawbacks include their substantial tank requirements, costly startup costs, and limited cycle life (Vrettos & Papathanassiou, 2011). Lithium-ion batteries have recently become the industry standard due to their high energy density, rapid response times, and low prices. However, recycling, resource availability, and thermal runaway remain significant concerns (Zhang et al., 2024).

3. RESULTS AND DISCUSSION

The global GHG emissions declined during the pandemic period; however, a significant increase was observed in the post-pandemic phase due to efforts to stabilise economic activities. This temporary shift has led to a partial relaxation of clean energy targets, which needs to be addressed to effectively tackle global climate change challenges. Conventional power grids exhibit inherent limitations that restrict the efficient integration of renewable energy sources (Poullikkas, 2013). Conventional grids are based on the idea of centralised generation of energy and its distribution, whereas smart grids incorporate the idea of distributed generation (Liu et al., 2024). Conventional grids suffer from power loss during the transmission of power. The smart grid consists of advanced metering and measurement systems constituting a smart monitoring system. Automatic meter infrastructures (AMI) enable the procurement of data, analysis, and optimisation in real-time. Smart meters collect consumption data and assist both consumers and utilities in managing the consumption pattern. Sensor networks monitor the status of the grid to determine the electrical and mechanical functionality during generation, transmission, and distribution (Conzen et al., 2023; Saxena et al., 2024). While smart data and information communication systems are intended to handle the flow of real-time high-frequency data, the conventional electricity grids that rely on legacy monitoring infrastructures are inherently inefficient and less suitable for dynamic data-intensive operations.

Figure 2 indicates the traditional power grid that follows a hierarchical and unidirectional flow of power, in which the consumers are passive participants. Power generated in power plants is transmitted to the distribution system via a high-voltage transmission network, which then transmits to the consumer via a low-voltage distribution network. The diagram illustrates the transition from a traditional electricity grid to a smart grid, highlighting significant differences in structure, operation, and functionality. In the traditional grid, electricity is generated primarily from fossil fuel-based power plants and transmitted through high-voltage transmission lines to substations, where it is stepped down and distributed to consumers via distribution lines. This system operates with a one-way power flow, where energy moves only from the generation source to end users, and monitoring is largely manual, making it less efficient and slower in responding to faults or demand fluctuations. In contrast, the smart grid integrates renewable energy sources such as solar and wind, along with advanced technologies including smart substations, IoT sensors, wireless communication, and cloud-based data analytics. These features enable real-time monitoring, automated control, and improved decision-making. A key advantage of the smart grid is its two-way power flow, allows consumers also to act as producers by supplying excess energy back to the grid. Overall, the smart grid represents a more decentralised, efficient, reliable, and sustainable energy system compared to the conventional grid. Digitalisation of batteries can resolve the issues caused by the intermittency of renewable energy sources. The conventional grids are based on non-renewable energy sources and have limited scope for integration of advanced communication systems (Dawn et al., 2024). At the same time, smart grids allow the incorporation of renewables, advanced communication, and monitoring systems, and enable active participation of the consumers in the system (Engels et al., 2019). Table 1 compares the conventional grid and smart grid architectures. The main difference between modern smart grids and traditional grids is that they use digital communication, automation, and intelligent control systems. Real-time monitoring and optimisation of grid operations are possible due to new technologies, including Supervisory Control and Data Acquisition (SCADA), Internet of Things (IoT) sensors, advanced metering infrastructure (AMI), and artificial intelligence-based forecasts. Utilities can find problems,

guess when demand will change, and manage dispersed energy supplies well with these technologies (Hidalgo-León et al., 2017; Kataray et al., 2023).

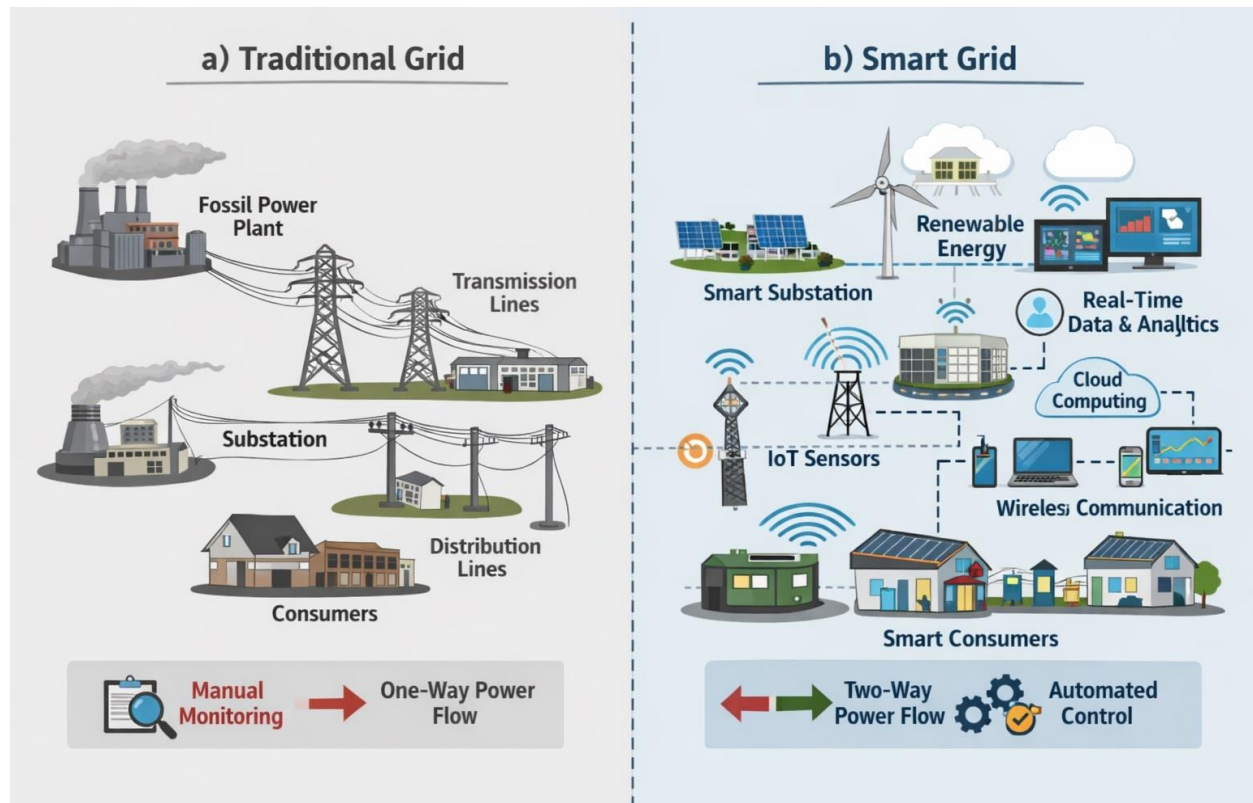


Figure 2. Comparison of grid systems: (a) Traditional grid system and (b) Smart grid system.

Table 1. Comparison between conventional and smart grids

Comparison parameter	Traditional grid	Smart grid
Architecture type	Hierarchical type	Network type
Power transmission direction	Unidirectional from generators to consumers through substations	Bidirectional power and information flow between generators, consumers, and prosumers
Mode of generation of energy	Centralised	Decentralised or distributed
Efficiency and power loss	Low efficiency and high-power loss	High efficiency and low power loss
Communication and monitoring protocols	Limited communication and monitoring protocols	Well-connected intelligent system

Due to the rise of digitalisation and two-way communication, cybersecurity and data management have become very important parts of smart grid infrastructure. For the grid to stay reliable and for customers to trust it, it is important to make sure that data is transferred safely and that cyber threats are kept at bay. Smart grids also make it easier to connect dispersed energy resources like rooftop solar panels, electric vehicles and microgrids (Hu et al., 2022; Kumar et al., 2022). This turns consumers into active players in energy systems. Smart grids are essential for future sustainable energy systems because they integrate digital intelligence with a distributed architecture to enhance operations, reduce transmission losses, increase system reliability, and facilitate the integration of large-scale renewable

energy sources. Energy storage systems such as batteries are another integral part of the smart grid (Li et al., 2013; Mohassel et al., 2014). Figure 3 displays the functions performed by BESS batteries in a smart grid. As shown in Figure 3, functions performed by BESS in a smart grid include energy storage, providing synthetic inertia, providing voltage support, dealing with peak shaving, frequency regulation, and enabling black start.

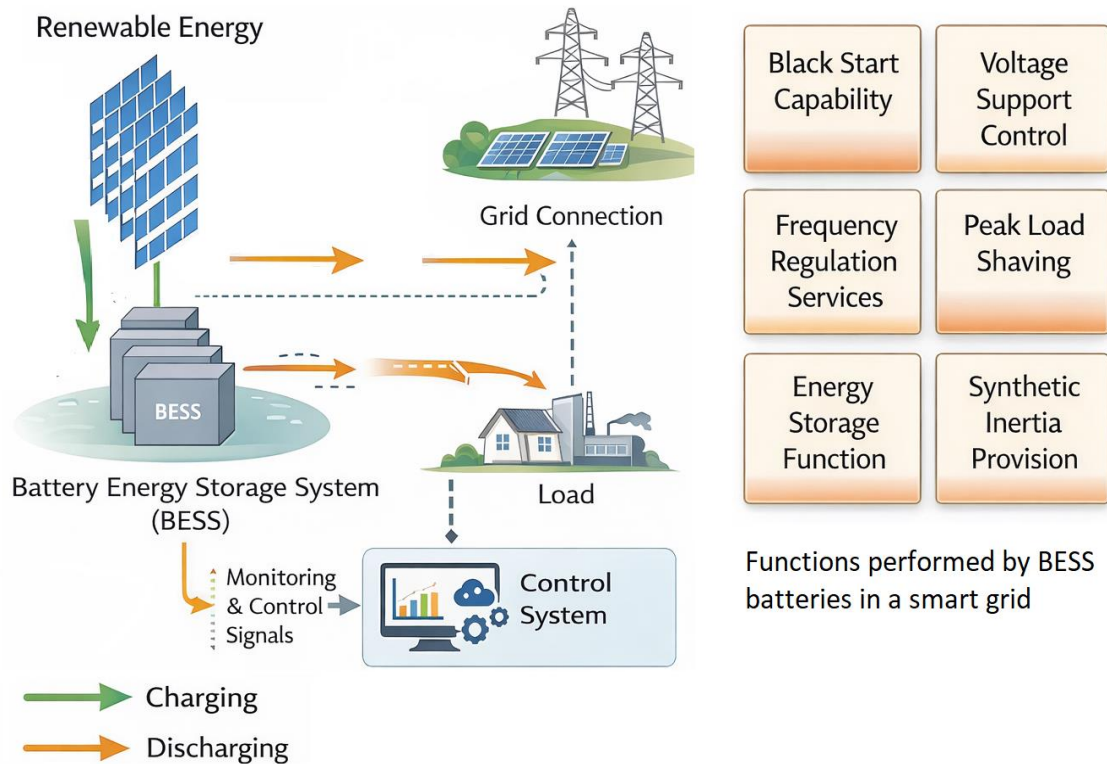


Figure 3. Functions performed by BESS batteries in a smart grid

BESS can reduce renewable-energy curtailment and support primary frequency control and peak shaving. BESS can tackle peak shaving by quickly responding to the frequency fluctuations of the grid by drawing power or discharging it, during low and high-demand situations, respectively (Poullikkas, 2013; Power, 2020). The energy stored in BESS can be used to restart the grid during partial or complete blackouts, known as black start. It can also provide synthetic inertia. Inertia in conventional rotating-generator-based systems provides a stored-energy backup for a few seconds while the grid responds to system failures. The inertia support is significant when conventional generator-based sources are replaced with inverter-based renewables having low inertia support (Reihani et al., 2016; Saxena et al., 2024). BESS can also provide frequency support during fluctuations in grid frequency so that a fixed operating frequency is maintained. The batteries used in smart grids should have high energy density, long life cycles, and the ability to withstand deep-discharge cycles and extreme temperatures.

Despite their low cost, the limited use of lead-acid batteries in large-scale grid storage is a result of their shortened lifecycle and lower energy density. Despite their strong performance, nickel-cadmium batteries are harmful to the environment because of the hazardous elements they contain (Almihat & Munda, 2025). Despite its increased safety features and adaptability to changing energy needs, flow batteries are more expensive up front and take up more room in any given installation. The promise to improve safety, boost energy density, and decrease dependency on crucial raw materials is attracting attention to emerging battery technologies as sodium-ion, lithium-sulphur, and solid-state batteries. The importance of battery recycling and other circular economy measures in reducing energy storage technology' negative effects on the environment is growing (Wu & Tang, 2019; Zhang et al., 2024). Widespread use of BESS in smart grid applications is anticipated to be supported by future

improvements in battery chemistry and management technologies, which should enhance the safety, economic feasibility, and lifecycle of the batteries.

3.1 Motivations and challenges to BESS in smart grids

The case studies of some of the largest BESS in the world will be used to assess the role played by BESS in real situations. Battery energy storage systems are very important for keeping the grid stable because they can quickly and accurately respond to changes in supply and demand. One of the primary functions of BESS is frequency regulation, where the battery injects or absorbs power within milliseconds to stabilise system frequency (Power, 2020; Reihani et al., 2016; Zhang et al., 2024; Zhu et al., 2024). Unlike conventional rotating generators that rely on mechanical inertia, BESS provides synthetic inertia through fast electronic response, which is particularly important in grids dominated by inverter-based renewable sources. BESS also helps shave off peak loads by storing extra energy when demand is low and releasing it when demand is high (Al-Shetwi et al., 2025). This lowers the pressure on generation equipment and cuts down on operating expenses. This feature makes it easier to manage loads and cuts down on the requirement for costly peaking power plants. BESS also helps with renewable firming by smoothing out changes in solar and wind generation (Zhu et al., 2024; Alhasnawi et al., 2025). This enables power delivery to be more reliable and cuts down on renewable curtailment. Another important function is voltage regulation and reactive power support, which improves the quality of the power and reduces transmission losses. BESS can also provide black-start capability, which means that the grid can be restored after a partial or complete system failure (Meng, 2021). BESS can generate revenue by participating in energy arbitrage and ancillary service markets. This also makes the grid more reliable. Even with these benefits, battery degradation from frequent charge-discharge cycles is still a technological problem that needs enhanced battery management systems to improve performance and lengthen operating life.

3.2 Hornsdale Power Reserve

Hornsdale Power Reserve (HPR), in South Australia, is one of the world's first large-scale grid-connected batteries, which confirmed the benefits of a grid-connected battery, with over \$150 million in savings for consumers during the initial period of operation of two years. It was installed in 2017 by Tesla and Neoen, owned by Neoen, and co-located with Hornsdale wind farms. The state government owns the right to call the stored power under certain circumstances. The grid-scale battery is based on multiple Li-ion battery banks. It has a discharge capacity of 100 MW and a storage capacity of 129 MWh. The South Australian government provides funding of over AUD 40 million from its renewable technology fund of AUD 150 million, on a monthly basis. HPR provides a power output capacity of 70 MW and a reserve storage capacity of 10 MWh. The excess capacity is sold by HPR to the National Energy Market (NEM) and generates revenue. HPR provides a fast frequency response (FFR) to maintain the frequency at a fixed operating range of 50 ± 0.15 Hz. Whenever the frequency deviates from this range, HPR responds by adjusting its power dispatch (Nafi et al., 2016). HPR played a major role in reducing the costs for frequency control ancillary services (FCAS), saving around \$116 million in 2019 alone. The BESS in HPR also provides synthetic inertia to stabilise the grid when electricity supply and demand fluctuate. The HPR can provide up to 3,000 MW.s of inertia. The South Australian grid requires 6,000 MW.s to maintain an operational level of inertia. The case study of HPR shows the significance of ancillary services provided by a BESS, especially in a high solar penetration environment. The HPR case study indicates the following drivers in the adoption of BESS:

- Public-private partnerships for successful BESS deployment
- Public-private collaboration for advancing renewable energy technologies
- Energy-arbitrage revenue generation to increase investments
- Monthly-payment/subscription models to reduce upfront government expenditure
- BESS-based storage and ancillary services for grid support and cost savings

The Hornsdale Power Reserve demonstrated the economic and technical viability of grid-scale BESS by significantly reducing the cost of frequency control ancillary services (FCAS) and improving grid stability. Its rapid response capability enabled it to react within milliseconds to frequency deviations, preventing large-scale outages and enhancing system reliability (Wei et al., 2025). The project also generated revenue through participation in energy arbitrage and ancillary service markets, demonstrating a sustainable business model for large-scale storage deployment. The success of Hornsdale has influenced global adoption of similar projects and highlighted the importance of combining public policy support with private investment to accelerate clean energy infrastructure.

3.3 Gateway Energy Storage, California

Gateway Energy Storage is a large BESS owned and operated by LS Power, which is an independent power company. The BESS is composed of LG Chem Li-ion cells and the total capacity is 250 MW. A section of the 250-MW site caught fire in 2024. This points to a major risk associated with large-scale BESS. The harmful gases and the possibility of re-ignition and thermal runaway increase the scale of damage incurred (Song et al., 2024). The incident also triggers opposition against proposed facilities in residential neighbourhoods. Once a BESS catches fire, the facility remains vulnerable to re-ignition unless a complete recovery and repair have occurred. The structure of the facility had several drawbacks, such as poor visibility into the facility and lack of clearly organised fire-mitigation standards inside the facility (Biswas et al., 2025; Negi et al., 2026). The case study indicates the necessity for technology evolution to develop safer alternatives to Li-ion technology. The safety concerns also raise opposition to the development of big batteries in populated regions (Vrettos & Papathanassiou, 2011). Li-ion batteries are the most frequently employed type of battery in mobility and electricity. Reasons for this are the decline in the cost of Li-ion batteries from \$1,400 per kWh in 2010 to \$140 kWh in 2023, higher energy densities than PbA, and technological evolution to make battery packaging more compact. Though Li-ion fires are not a frequent phenomenon, as a technology being employed worldwide in large-scale projects, safety is a major concern. The investment made in the project in terms of land procurement, operation, and maintenance is also a major concern during such unanticipated events. The case study points to certain barriers and risks associated with the deployment of BESS:

- Limited technological advancement in batteries
- Safety constraints on BESS siting
- Fire and toxic gas risks in residential areas
- Limited availability of environmentally benign batteries
- Lack of regulatory standards for BESS deployment

The Gateway Energy Storage project highlighted the safety risks associated with large-scale lithium-ion battery installations. The fire incident emphasised the importance of robust thermal management systems, early fault detection, and strict safety protocols to prevent thermal runaway and hazardous gas emissions (Poullikkas, 2013; Power, 2020). Regulatory bodies have since strengthened guidelines for fire safety, monitoring, and site selection of BESS installations. The incident also revealed the need for improved public awareness and risk communication, as safety concerns can influence public acceptance and regulatory approval of future projects.

3.4 Victorian Big Battery

Victorian Big Battery is the largest Li-ion battery system in the southern hemisphere with a discharge capacity of 300 MW, owned by Neoen and funded by the Australian government's green bank, Clean Energy Finance Corporation. Initiatives such as green banks encourage private investments in clean energy sectors by using public funds (Blum et al., 2022; Vrettos & Papathanassiou, 2011). This shows the significance of Federal-level policies in strengthening private investments in clean energy assets. The Victorian Big Battery aims to protect Victorian households from electricity blackouts by providing energy support. The BESS has a contract with the Australian Energy Market Operator (AEMO) and is equipped to provide emergency response and grid support during unexpected outages.

The Victorian Big Battery also experienced a fire incident due to the inadequate cooling system, which had leaks (Blum et al., 2022). This led to a thermal runaway in the Li-ion BESS. The gravity of the incident was reduced due to active pre-accident measures laid out by Tesla and awareness programs, such as door-to-door awareness. The case study points to some of the drivers and barriers in developing BESS:

- Policy initiatives supporting BESS development and investment
- Enhanced grid resilience through BESS
- Lack of standards for BESS circuitry (e.g., coolants)
- Limited monitoring systems for early fault detection
- Low post-incident awareness in residential communities

The Victorian Big Battery demonstrated the importance of grid resilience and emergency response capabilities provided by BESS. Despite experiencing a cooling system failure, the project showed how proactive risk mitigation strategies and community awareness programs can minimise the impact of operational incidents. The project also highlighted the role of government-supported green financing in accelerating clean energy investments (Conzen et al., 2023; Hu et al., 2022). By providing rapid response during grid disturbances, the Victorian Big Battery strengthened system reliability and supported renewable energy integration, reinforcing the importance of BESS in future grid infrastructure. Each case study indicates the significance of BESS in strengthening the efficiency of grid performance. BESS is central to the concept of smart grids to respond dynamically to unforeseen power outages or fluctuations (Joshani, 2026). In addition to encouraging the incorporation of renewables and increasing energy efficiency, the BESS also offers scope for new job opportunities and community integration and awareness (Kataray et al., 2023). According to the International Energy Agency battery adoption should increase approximately sevenfold, implying around 25-30% per year, to achieve the net zero target by 2030 (International Energy Agency, 2024). The drivers and barriers identified in the study are shown in Table 2.

The rapid decline in battery costs, increasing renewable penetration, and demand for grid flexibility are major drivers for BESS adoption. Market reforms enabling participation in ancillary service and capacity markets further enhance economic feasibility. Government incentives, research funding, and green financing mechanisms also play a crucial role in accelerating deployment. However, several barriers remain. Safety risks, particularly thermal runaway and fire hazards, continue to pose significant challenges (Hidalgo-León et al., 2017; Li et al., 2013). Environmental concerns related to battery material extraction and recycling require sustainable lifecycle management. Regulatory gaps and lack of standardised safety guidelines can delay project approvals and increase operational risks. Additionally, high initial capital costs and public perception issues may hinder large-scale deployment in certain regions. Addressing these challenges through technological innovation, regulatory standardisation, and sustainable material management is essential for long-term growth of BESS infrastructure (Blum et al., 2022; Kumar et al., 2022). Technology evolution is another factor influencing the deployment of BESS. Policy interventions play a key role in coordinating efforts to increase the adoption of BESS. Policy interventions have multiple roles to play, such as 1) Accelerating research and development activities leading to mature technology; 2) Increasing the economy of BESS through policies and supporting private investments; and 3) Setting regulations to ensure the safety of BESS, especially in utility-scale projects.

Table 2. Drivers and barriers to the proliferation of BESS in each case study.

Case Study	Drivers	Barriers	Key Insights
Hornsdale Power Reserve	Strong public–private partnership	High initial capital investment	Demonstrates strong economic and technical viability of BESS with clear market-based revenue streams and grid stabilisation benefits
	Revenue generation through FCAS and energy arbitrage	Dependence on the market	
	Proven fast frequency response capability	Mechanisms for revenue stability	
	Policy support and renewable integration incentives		
Gateway Energy Storage	Large-scale deployment	Fire incident and thermal runaway risks	Highlights critical safety and regulatory challenges associated with large-scale Li-ion BESS deployment
	High-energy-density Li-ion technology	Public safety concerns and opposition	
	Market-driven energy storage expansion	Lack of robust safety standards and monitoring systems	
Victorian Big Battery	Strong government funding	Cooling system failure leading to fire incident	Emphasises importance of policy support and risk mitigation strategies in ensuring reliable BESS operation
	Policy-driven clean energy investment	Lack of standardised safety regulations	
	Grid resilience and emergency response capability	Need for improved monitoring and fault detection systems	
	Public awareness initiatives		

4. CONCLUSION

Battery energy storage systems have emerged as a critical component of modern smart grids, enabling efficient integration of renewable energy, improving grid stability, and enhancing operational flexibility. The study demonstrates that BESS provides multiple technical and economic benefits, including frequency regulation, peak shaving, renewable firming, and emergency grid support. Real-world case studies highlight both the potential and challenges associated with large-scale deployment, particularly in terms of safety risks, regulatory requirements, and technological limitations. Supportive policy frameworks, technological advancements, and declining battery costs are key drivers accelerating global adoption. The findings further highlight that deployment of BESS is increasingly becoming system-critical in regions with high renewable energy penetration, where grid flexibility requirements are intensifying. However, addressing safety concerns, improving recycling practices, and establishing standardised regulations remain essential for sustainable deployment.

Future advancements in BESS technology are expected to transform smart grid operations through improved efficiency, safety, and scalability. Artificial intelligence-based battery management systems will enable predictive maintenance, optimised charging cycles, and enhanced lifecycle performance. Long-duration energy storage technologies are being developed to support multi-day renewable variability, reducing dependence on fossil-fuel backup generation. Hybrid energy storage systems combining batteries with hydrogen or thermal storage may provide enhanced flexibility and resilience. Grid-forming inverters integrated with BESS are expected to provide stable voltage and frequency control in renewable-dominated grids. Continued decline in battery costs and improvements in recycling technologies will further strengthen economic and environmental sustainability. Global deployment of BESS is projected to increase significantly over the next decade, playing a central role in achieving net-zero emissions and supporting reliable, decentralised, and intelligent power systems.

This study has three limitations. First, it relies on secondary data sources, which may limit the availability of detailed or standardised information across case studies. Second, the analysis is restricted

to three case studies, which, although representative, may not capture all global variations in BESS deployment. Third, the study does not include primary data collection, experimental validation, or simulation-based analysis. Despite these limitations, the comparative approach provides valuable insights into real-world applications and challenges associated with BESS integration in smart grids.

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