Article

A Comprehensive Review of Battery Storage Technology in Renewable Energy Technology

energies

Alimul Khan [1*], Ali Newaz Bahar [1*], Asif Islam [2], and Khan Wahid [1]

[1] Electrical and Computer Engineering, University of Saskatchewan, SK, CA;
[2] Electrical Engineering, KFUPM, Dhahran, KSA;
* Correspondence: ali.bahar@usask.ca

Abstract: Renewable energy resources (RESs) are widely regarded as an essential component of modern energy grids; however, their inherent intermittency and variability result in significant challenges to maintaining grid stability and reliability. As the integration of RESs into energy systems continues to expand, managing energy surpluses and deficits has become increasingly complex, amplifying issues such as grid stability, demand-side management, and long-term system planning. To address these challenges effectively, innovative approaches are essential. Energy storage systems (ESS) offer a promising solution. They are capable of bridging the gap between renewable energy generation and grid demands. This study thoroughly examines the role of battery energy storage systems (BESS) in modern utility grids, emphasizing their applications in enabling the large-scale integration of RESs. The study provides a comprehensive analysis of BESS functionalities, classifying their applications under key areas such as peak shaving, load shifting, backup power, grid stabilization, and islanded operation. This review systematically evaluates the impacts of BESS in these contexts. It aims to provide readers with an in-depth understanding of BESS applications in renewable energy systems. Additionally, it highlights areas that require further investigation to optimize their implementation.

Keywords: Renewable Energy Intermittency, Battery storage technology, sustainable energy.

1. Introduction

For the last few decades, renewable energy resources (RERs) such as hydroelectric power, wind, and solar have become especially popular due to carbon reduction and sustainable energy development[1]. However, the integration of RERs into power grids can cause different challenges[2,3]. Due to the intermittent and variable nature of RERs, power generation often fluctuates. The fluctuating power causes sudden changes in voltage and frequency, leading to grid instability. The instability of a grid affects the quality and reliability of the power system. To minimize the effects of instability, various Energy Storage Systems (ESS) have been used and ESS is a promising solution to those challenges[4]. ESS can also help to balance the demand and supply of power along with the necessity of drawing the demand from fossil fuel-based power generation[5,6]. Among ESS, electrochemical solutions, battery-based storages, are the most useful and feasible, providing more of the economic benefits [7]. This review is an elaborate study of battery energy storage systems (BESS), their contribution to power systems, and their integration with renewable energy generation. The different types of batteries used in energy storage systems have been briefly outlined here with their benefits and technological limitations. This review also discusses the current status of BESS and how they help incorporate renewable energy generation into the power system.

Batteries are essential for managing the variability and intermittency of grid power. They store excess energy produced during times of low demand. This stored energy then

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can be supplied during higher demand or when renewable energy sources are producing insufficient power. One approach is to deploy large-scale battery storage systems strategically throughout the grid. These systems help to mitigate fluctuations in supply and demand, ensuring grid frequency stability [8,9].

Additionally, battery systems can be combined with clean energy options like solar PV and wind generators. They store extra energy produced when generation surpasses demand. This ensures a steady electricity supply, regardless of weather or time of day [10]. Moreover, advanced battery management technologies enable efficient charging and discharging processes, optimizing the use of stored energy and enhancing grid reliability [11]. This study examines how batteries and hydrogen storage can provide 100% renewable energy. The reference [12] examines how time series clustering affects multi-year planning and compares carbon-free energy system topologies. Hydrogen-based solutions prevent battery and wind turbine oversizing, making them essential for 100% renewable energy systems. Only-battery designs cost 155% more than hydrogen-based ones. A large-scale BESS setup for China's national renewable generating demonstration project, including a wind farm and solar PV power station is developed in [13]. The authors explore the technical advantages of a BESS in managing power fluctuations and intermittency. They also highlight its role in improving transmission grid performance through case studies focusing on key technologies for control, management, and operation.

Table 1. Recent related reviews and gaps analyses

Reference	Contributions	Research Gaps
[14]	A comprehensive review is proposed on the integration of BESS into power grids, emphasizing their potential to address challenges posed by increasing penetration of intermittent renewable energy sources, such as solar and wind, and proposing incentivization strategies to promote their adoption.	Further investigation into optimal integration strategies for BESS in power grids and the exploration of alternative BESS technologies beyond lithium and flow batteries to enhance flexibility and scalability in renewable energy integration efforts are needed.
[15]	This review mainly summarizes directed search-based, probabilistic, and rule-based optimization methods for BESS integration in renewable energy systems.	A summary of control battery techniques as well as hybridization of other major energy storage devices are missing.
[16]	A thorough review of energy storage systems (ESS) for renewable source grid integration, covering various ESS technologies and their applications for grid stability and reliability.	Challenges in implementing ESS technologies, such as environmental impact, storage capacity, and cost-effectiveness, still require significant research. Additionally, there is a need for a holistic approach to selecting and integrating ESS based on specific grid requirements.
[17]	A comprehensive review of battery energy storage systems (BESS) focusing on their integration with renewable energy sources, highlighting both the potential benefits and the challenges of using BESS in various grid configurations.	There is a need for further research on the long-term reliability and sustainability of BESS, especially in the context of emerging alternative battery technologies and their environmental impact. Additionally, the review calls for more detailed studies on the economic feasibility of large-scale BESS deployment.
[18]	This review provides a detailed analysis of Hybrid Energy Storage Systems (HESS) integrated with renewable power generation. It discusses the configuration, control strategies, and applications of HESS, highlighting their potential to enhance the stability and reliability of power grids.	The review emphasizes the need for further research on the control and optimization methods for HESS in renewable energy systems. It also identifies challenges in improving the cost-effectiveness, efficiency, and sustainability of HESS technologies.
[19]	This review provides a comprehensive analysis of Hybrid Renewable Energy Systems (HRES), focusing on their architectures, battery systems, and optimization techniques. It covers various configurations such as DC, AC, and hybrid AC/DC microgrids, highlighting their advantages and challenges.	The review identifies the need for more advanced optimization algorithms tailored for HRES and the integration of newer battery technologies. It also highlights the challenge of synchronization in AC microgrids and the necessity of developing better control strategies for hybrid configurations.
[20]	This review provides a critical overview of the latest advancements in Hybrid Energy Storage Systems (HESS) for renewable energy-to-grid integration, discussing components, control strategies, and case studies of successful implementations.	The review highlights the challenges in optimizing HESS for efficient integration with renewable sources, emphasizing the need for improved control systems and advanced energy management strategies to address issues like synchronization and thermal management. It also suggests further research into AI-based optimization techniques for better system performance.
[21]	This comprehensive review covers recent advances in energy storage systems (ESS) for renewable source grid integration. It discusses the types of storage technologies, their applications, and the challenges faced, such as storage capacity, efficiency, and cost.	The review identifies the need for further research on optimizing ESS technologies, particularly in improving their environmental impact and integrating advanced control systems to better handle the variability of renewable energy sources.
[22]	This review focuses on the integration of hybrid renewable energy systems (HRES) with energy storage, analyzing the impact of PV-wind variability on storage requirements. It emphasizes the role of energy storage in managing the unpredictability of renewable sources and optimizing grid stability.	The review identifies the need for further research into optimizing storage solutions specifically tailored to hybrid systems and developing advanced algorithms to better predict and manage energy fluctuations in highly variable environments.
[23]	This review examines renewable hydrogen hybrid energy systems, focusing on their role in a sustainable energy value chain. It explores system topographies, component integration, and the challenges associated with hydrogen generation, storage, and conversion in hybrid systems.	The review identifies key challenges in optimizing system design and sizing methods, particularly the need for improved modeling and integration of hydrogen technologies with renewable energy sources. Further research is required to enhance system efficiency and cost-effectiveness.

Table 1 highlights recent reviews on energy storage systems, discussing their contributions and research gaps. Key themes include integration strategies for battery energy storage systems (BESS) into power grids [14–17], hybrid energy storage systems (HESS) configurations and optimization techniques [18–20], and broader energy storage technologies addressing grid stability and environmental challenges [21–23]. Research gaps emphasize the need for advanced optimization methods, better synchronization in hybrid systems, scalability of technologies like lithium and flow batteries, and strategies to reduce environmental impact and costs. These studies underscore the necessity for holistic approaches to improving system efficiency, scalability, and sustainability across renewable energy integrations.

Table 2. Comparison of Intermittent Renewable Energy vs. Conventional Fuel-Based Power Plants [24]

Criteria	Intermittent Renewable Energy	Fossil Fuel-Based Plant
Average Capacity Factor	15-40% (varies with resource)	50-90% (higher stability)
Operational Flexibility	High (subject to environmental conditions)	Limited (steady output)
Emission Levels	Low to Zero (no direct emissions)	High (CO2 and other pollutants)
Fuel Cost Variability	Low (no fuel costs)	High (subject to market prices)
Installation Cost	High initial cost, low operational cost	Moderate initial, higher operational cost
Lifespan	Varies (20-25 years for solar, longer for wind)	30-50 years (depends on plant type)
Maintenance Requirements	Relatively low (especially for solar)	Higher (more mechanical parts)
Energy Source Dependability	Variable (depends on weather, time)	Consistent (not weather dependent)

2. Intermittency

Renewable energies play an important role in meeting global energy needs. The importance becomes greater when considering the reduction of global warming and reducing carbon emissions [25–27]. These sources are environmentally friendly and sustainable, as they are replenished naturally over time. However, some of the resources such as solar and wind are more prone to fluctuating output [28]. UIn contrast to fossil fuels that can be utilized continuously, production of renewable energy sources depends on weather conditions and the time of day. For example, solar panels only produce energy during the daytime when the sun is shining, while wind turbines require a minimum wind speed to generate electricity [29]. A comparison of intermittent renewable energy and conventional fuel-based power plants is provided in Table 2.

Solar energy production is inherently limited to daylight hours. This diurnal pattern means that energy generation ceases during the night, which requires alternative energy sources or storage solutions to meet demand at night. Furthermore, cloud cover and weather variations significantly affect solar energy output [30]. Even the intensity of sunlight can change during daylight hours, leading to a variation in the power of solar panels [31,32]. Top of that, snow fall can cover the panel which significantly reduces the output power generation for a relatively longer period [33]. Higher temperature could be another factor that can reduce the output of solar panel [34]. Figure 1 illustrates the natural factors affecting solar power generation, including seasonal variations, weather variability, temperature effects, daylight limitations, and obstructions, which contribute to solar PV intermittency.

Wind energy is dependent on wind availability, which can be highly unpredictable. Wind turbines require a minimum wind speed to start generating electricity and a maximum threshold to prevent damage, leading to operational variability [35]. Wind farm production is highly dependent on wind characteristics at the installation site. Areas with stable wind speeds, the output power tends to be more consistent. Variable wind speeds in a location create more challenges in generating reliable energy. However, other RERs, such as hydroelectric, geothermal, and biomass energy, are not much affected by external environmental conditions. Hence they can provide a more consistent output than that of solar or wind. Figure 2 highlights the natural factors influencing wind energy generation, such as wind availability, air density effects, high wind speeds, geographical variations, and minimum wind speed requirements, which contribute to intermittency in wind power generation.

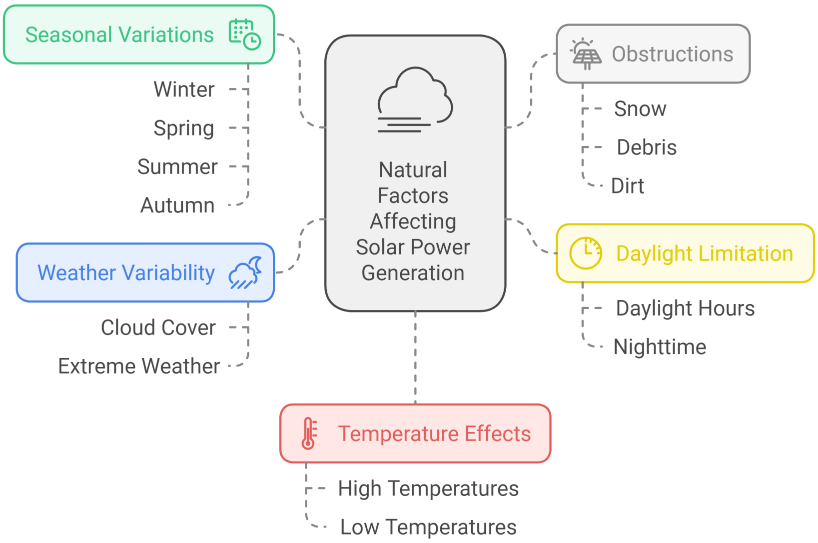

Figure 1. Solar PV and Possible Causes of Intermittency

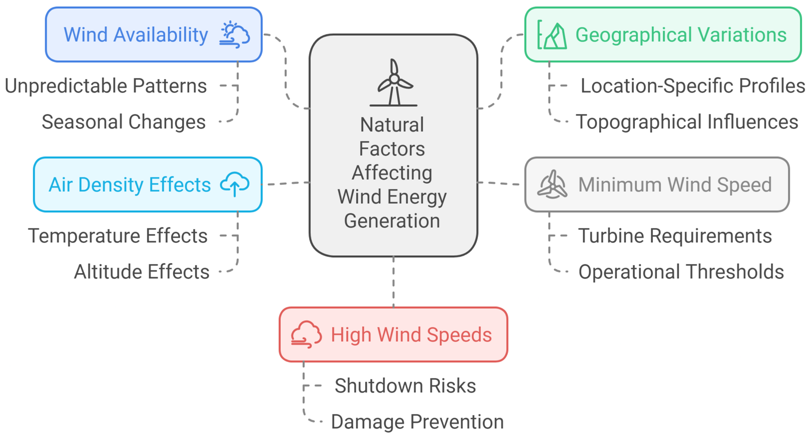

Figure 2. Wind Power and Possible Causes of Intermittency

Weather affects renewable energy, leading to more variable and less reliable power compared to traditional sources [36]. Traditional power grids are controllable and designed for steady output power. However, the intermittency of RERs creates low energy and sometimes extra energy [37]. Abrupt changes in energy from sources can make the electricity grid unstable because they can cause unpredictable changes in power levels [38]. Inconsistent RERs also lead to changes in electricity pricing and market dynamics [38]. The inconsistency of renewable energy is managed with natural gas or battery backups [39]. At times, renewable sources might produce more energy than needed [36]. Renewable plants have lower capacity factors than regular plants due to intermittency. The impacts of grid intermittency, such as increased operational costs, supply-demand mismatches, grid instability, price fluctuations, and energy overproduction, are depicted in Figure 3. it should be 'impacts of intermittency', grid should be removed

The capacity factor of a power plant is an important metric that compares the actual output of a plant over a period of time to its potential output if it were operating at full capacity all the time. Because wind and solar depend on daylight and weather, they don't generate as much, resulting in lower capacity factors compared to traditional power plants. The average capacity factor for solar power is often in the range of 15-25%, while wind power can vary widely, with averages between 20-40%. In contrast, conventional fuel-based power plants, such as Coal and natural gas plants often have stable capacity factors above 50-60%. These plants can operate continuously and are not directly affected by changes

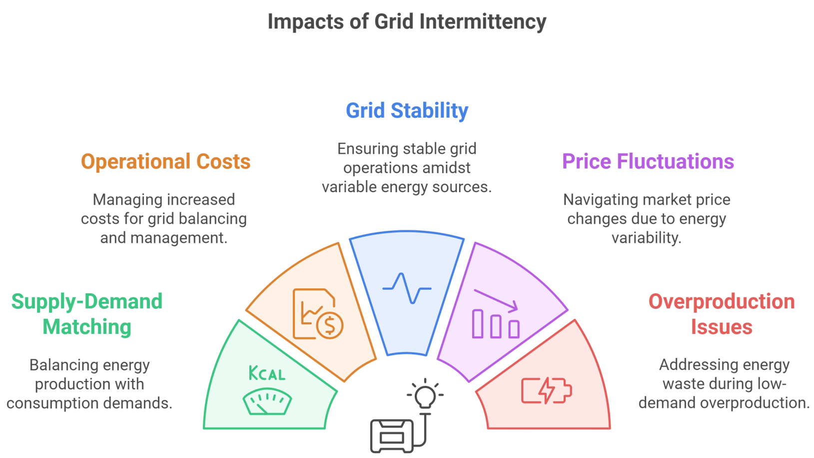

Figure 3. Intermittency and Effects

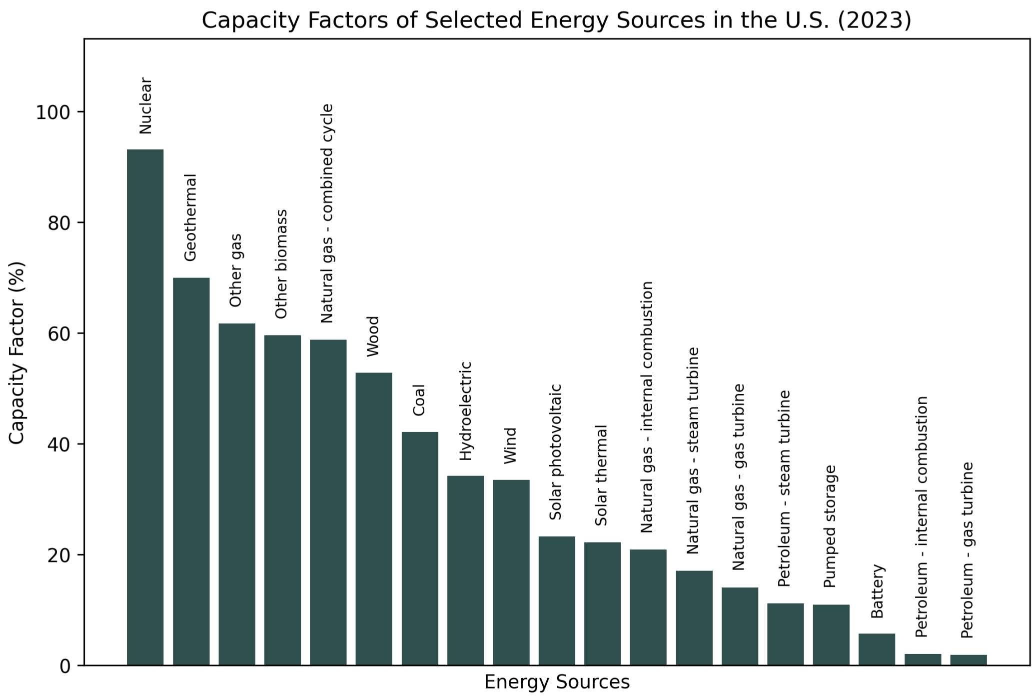

Figure 4. Comparison in Capacity factors of different type of power plant

in weather or time of day. Nuclear power plants, known for their steady output, typically have some of the highest capacity factors, often around 90% [40]. Figure 4 provides a comparative analysis of the capacity factors of different types of power plant in the United States.

Capacity factor of the RER based power plant can also be increased by using energy storage. It is very common to store the excess energy to use at the period of low energy generation for economic operation for the plant. Renewable systems can overcome intermittency by coupling with storage solutions to store and distribute energy when necessary[41]. These solutions can store surplus energy and release it on demand, ensuring that renewable energy sources are available even during unfavorable weather conditions.

Using storage systems with renewable energy makes power plants run better, cheaper, and cleaner, cutting down on fossil fuel use, and minimizing their carbon footprint [42,43]. Integrating energy storage into the energy market allows for new opportunities P2P energy trading and storage services. They can offer value-added services such as two way energy

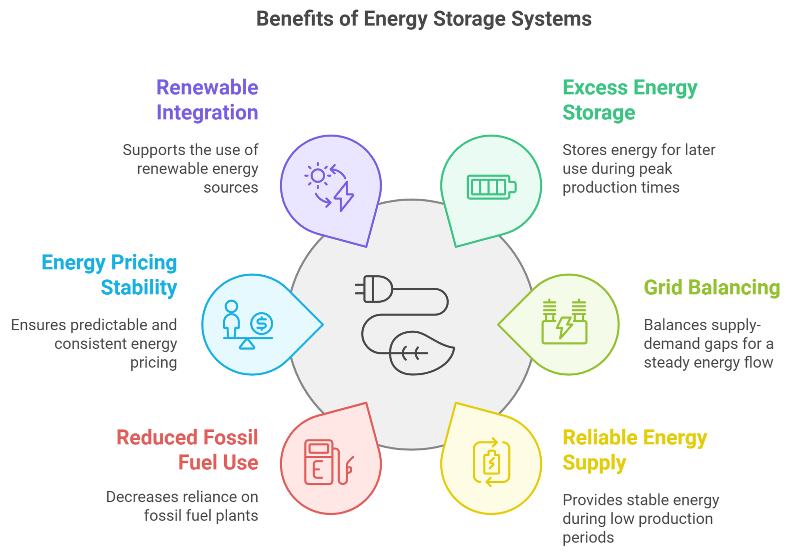

Figure 5. Energy Storage as a Solution to Intermittency Challenges

trading, peak shaving, frequency regulation, and demand response [44]. The benefits of energy storage systems, including enhanced grid reliability, energy pricing consistency, and reduced fossil fuel usage, are illustrated in Figure 5.

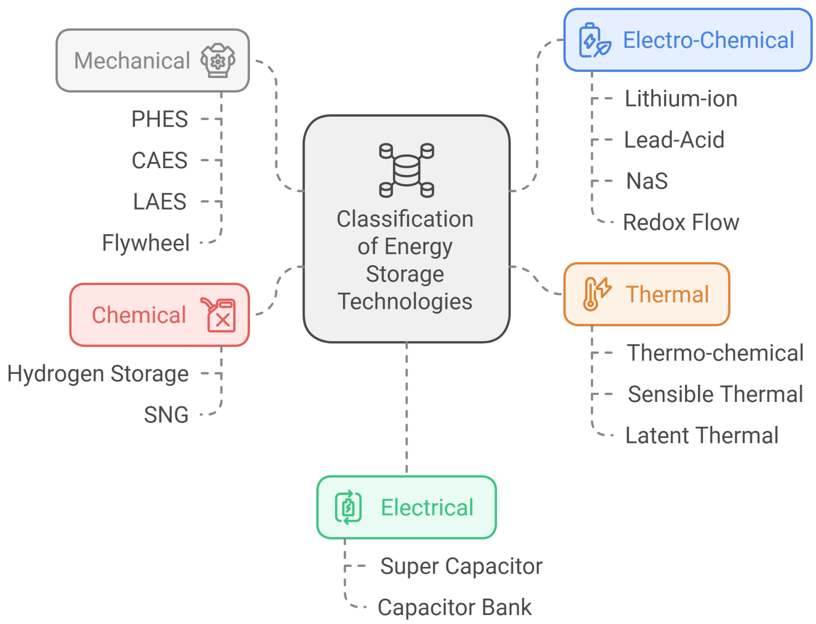

Figure 6. Classification of energy storage technology

3. Energy Storage Technology

Energy storage systems capture surplus energy when production exceeds demand and discharge it during periods of high demand or low renewable energy generation. This helps balance the grid and maintain a stable electricity supply. The excess energy can be stored as mechanical energy, chemical energy, thermal energy, electrical energy or even potential energy. In this section, the various energy storage technologies are described that are commonly used in renewable energy applications. In some cases, it is tough to draw a hard line between the categories. Some authors might categorize them differently. Figure 6 shows a simple classification of available energy storage technologies[45]. Table 3 provides an overview of the characteristics of chosen energy storage technologies. The choice of BESS technology is influenced by energy density, cost, lifetime, and specific applications.

Table 3. Comparison of Key Characteristics for Common Energy Storage Technologies [46,47]

Storage Technology	Energy Density (Wh/L)	Efficiency (%)	Max Power Output (MW)	Typical Discharge Time	Estimated Lifespan or Cycle Count
Hydrogen	600 (at 200 bar)	25–45	100	Minutes-1 week	5–30 years
Li-ion Battery	200–400	85–95	100	1 minute - 8 hours	1,000–10,000 cycles
Thermal (Molten Salt)	70–210	80–90	150	Hours	30 years
Lead-acid Battery	50–80	80–90	100	1 minute - 8 hours	6–40 years
Flywheel	20–80	70–95	20	Seconds-minutes	20,000–100,000 cycles
Flow Battery	20–70	60–85	100	Hours	12,000–14,000 cycles
Compressed Air	2–6	40–70	1,000	2–30 hours	20–40 years
Pumped Hydro	0.2–2	70–85	3,000	4-16 hours	30–60 years

3.1. Electrochemical Energy Storage

Electrochemical energy storage is the most widely technologies that found from portable electronics to large-scale grid storage. They convert electrical energy into chemical energy, and vice versa, enabling energy storage and release. Battery energy storage systems (BESS) are an essential element as an electrochemical storage for renewable integration, grid stabilization, and emergency power.

Among BESS, Lithium-ion batteries stand out for their excellent energy storage capacity and extended lifespan. These qualities make them ideal for various applications, including portable electronics, electric vehicles, and grid storage. They are especially suited for renewable energy systems, offering efficient high-density energy storage, a fact highlighted by the Hornsdale Power Reserve in South Australia [48]. Sodium-Sulfur batteries, operating at high temperatures with significant energy density, are mainly utilized in grid storage, as shown by NGK Insulators' projects in Japan [49,50].

Flow batteries, like Vanadium Redox ones, provide scalability and long life, perfect for big energy storage and renewable energy integration. The Dalian Rongke Power plant in China uses these batteries for renewable energy storage [51]. Lead-acid batteries are still popular for their reliability and affordability, especially in solar systems for rural electrification, despite their lower energy density [52]. Continuous advancements in electrochemical energy storage are making them more efficient and applicable. Especially for renewable energy applications, each offers tailored benefits.

3.2. Mechanical Energy Storage

Mechanical energy storage systems are vital in the energy sector due to their capability to effectively retain substantial amounts of energy. These systems transform electrical energy into mechanical or potential energy, which then can be retained and later converted back to electrical energy as needed. Key technologies in this domain include pumped hydroelectric storage, compressed air energy storage (CAES), flywheel systems, gravity energy storage, inertial energy storage, and mechanical springs.

Pumped hydroelectric storage, such as the Bath County Pumped Storage Station in Virginia, and CAES systems, exemplified by the Huntorf CAES plant in Germany, are prominent for their large-scale energy storage capabilities [53,54]. Flywheel systems, such as those developed by Beacon Power in the USA, and gravitational energy storage, demonstrated by the ARES project in Nevada, offer unique approaches to storing energy through rotational motion and elevation of materials, respectively [55–57].

Smaller-scale mechanical storage solutions such as inertial energy storage and mechanical springs have applications in high-power, short-duration scenarios and everyday devices. Different technologies showcase the flexibility of mechanical energy storage for both large and small projects. They are crucial in updating energy management and including more renewable energy [58].

3.3. Thermal Energy Storage

Thermal energy storage systems are essential in the management of heat production and consumption. They help greatly in improving energy efficiency and integrating renewable energy. These systems store thermal energy by heating or cooling a storage medium and then use this stored energy for heating, cooling, or power generation at a later time. The primary technologies in this domain include Sensible Heat Storage, Latent Heat Storage, Thermo-chemical Storage, Underground Thermal Energy Storage, Ice Storage Air Conditioning, and Molten Salt Storage [59].

Sensible Heat Storage systems, which store energy by changing the temperature of a solid or liquid medium. Latent Heat Storage systems store energy by changing a material's state, like melting or freezing, and are widely used in homes and industries. Thermochemical storage, which involves chemical reactions to store and release heat, offers high energy density and long-term storage capabilities. Underground Thermal Energy Storage utilizes the ground's heat capacity for seasonal energy storage, which is increasingly popular in district heating and cooling [60].

Ice Storage Air Conditioning, which makes ice during off-peak hours for cooling during peak demand periods, is a practical application in commercial buildings for load leveling and peak shaving. Molten Salt Storage, typically used in concentrated solar power plants, stores high-temperature heat that can be converted to electricity. This process is demonstrated by Spain's Andasol Solar Power Station, which utilizes molten salt for thermal energy storage [61].

Thermal storage offers multiple ways to better manage energy, making renewable energy more reliable and steady. They separate energy production from consumption, providing flexibility and reliability to energy systems.

3.4. Chemical Energy Storage

It plays a significant role in improving the efficiency and adaptability of renewable energy systems. Important CES technologies include hydrogen storage, liquid air or nitrogen, synthetic natural gas, metal hydroides, biofuels, and chemical heat storage [62].

Hydrogen Storage is gaining attention for its role in renewable energy, where surplus electricity is being used to produce hydrogen through electrolysis proces. This hydrogen can then be stored and later converted back to electricity via fuel cells [63]. Projects like the Hydrogen Energy Supply Chain (HESC) in Australia demonstrate the practical application of hydrogen as a versatile energy carrier[64]. Biofuels are another form of chemical energy storage which is derived from biological sources [65]. They are being used increasingly as sustainable alternatives to fossil fuels in power generation and transportation.

Synthetic Natural Gas (SNG) is a fuel gas that can be produced from fossil biofuels, fossil fuels, or electricity using power-to-gas systems [66,67]. SNG produced from renewable sources creates a way to store excess energy and utilize existing natural gas infrastructure. Liquid Air Energy Storage (LAES) uses excess electricity to liquefy air. The stored liquid air is then used to drive a turbine and generate electricity during periods of high demand. A prominent example of this can be the Highview Power plant in the UK[68]. Metal Hydrides and Chemical Heat Storage are the latest in tech for storing hydrogen and waste heat, making use of them later [69]. Chemical energy storage technologies are crucial for advancing a sustainable and renewable energy future. They offer flexible and efficient methods for storing and utilizing energy in different forms.

3.5. Electrical Energy Storage

Electrical energy storage directly captures and retains energy in an electrical form. It is essential for diverse applications, ranging from powering small electronic devices to managing large-scale power grids. This type of storage is important for balancing power supply and demand, improving the reliability, and integrating RERs. Capacitors, Inductive Storage, Dielectric Elastomers, Superconducting Magnetic Energy Storage (SMES), Piezoelectric Energy Storage, and Nanostructured Energy Storage are some of notable technologies in Electrical Energy Storage.

Capacitors, known for their ability to quickly charge and discharge, are widely used in electronic circuits, power conditioning systems, and for providing short-term power backup. Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field generated by the flow of direct current in a superconducting coil. They are primarily used for power quality management and grid stabilization. An example of this is the SMES system at Brookhaven National Laboratory in the USA, showcasing its power quality improvement [70].

Dielectric elastomers (DEs) are electromechanical transducers that convert electrical energy into mechanical energy [71]. Piezoelectric (PE) devices converts mechanical stress to electricity. Both DE and PE are used in various sensing and energy harvesting applications. Inductive storage works by utilizing electromagnetic fields in the inductors. Nanostructured energy storage uses nanomaterials to enhance storage capabilities. They are cutting-edge advancements in electrical energy storage.

3.6. Virtual Energy storage

Virtual energy storage , an innovative concept, shifts electricity use from peak to off-peak times, eliminating the need for physical storage. This technique increase grid reliability and cuts down on the use electricity during peak-hour. By smoothing out demand fluctuations, virtual energy storage presents a cost-effective solution for managing energy resources more efficiently. Virtual energy storage helps smoothing out the fluctuations, making it an efficient and economic way to provide power[72].

All the energy storage technology are different in terms of usability, cost, size, life time, and technology. The different energy densities make them perfect for different types of applications. The system power ratings, shown in Fig. 6, illustrate the module size and the corresponding discharge times at rated power [73]. Table 1 presents a comprehensive comparison of ESS technologies in terms of their maximum power rating, typical discharge time, lifetime, energy density, and efficiency [74]. It provides valuable information that can aid in the selection of the most suitable ESS technology for a specific application. For instance, flywheels can release their stored energy quickly, making them great for immediate needs, whereas lithium-ion batteries pack a lot of energy into a small space, offering longer use.Similarly, there are technologies that stand out due to their longevity or higher efficiency levels, suiting them to certain roles.

4. BESS and Categories

Among all energy storage technologies, battery energy storage systems (BESS) are a key part of renewable energy systems. They store excess energy for use during periods of high demand or low production. Batteries can be classified based on their design, chemistry, and application, with several different types of batteries available for use in energy storage systems. The following are some of the most common types of batteries used in energy storage systems. Common battery types for energy storage include those listed in Table 4, which compares their applications, benefits, and limitations.

Table 4. Comparison of Battery Types for Different Applications

Battery Type	Applications	Pros	Cons
Lithium-ion (Li-ion) batteries	Portable electronics, electric vehicles, stationary energy storage systems	High energy density, long cycle life, low maintenance	Relatively expensive, safety and environmental concerns
Lead-acid batteries	Backup power systems, off-grid solar systems, telecommunications applications	Low cost, proven reliability, high surge current	Limited cycle life, high maintenance, low energy density
Flow batteries	Grid-scale energy storage, renewable energy integration, microgrids, off-grid systems	Scalable, long cycle life, high efficiency	Relatively expensive, heavy and bulky, limited commercial availability
Sodium-sulfur (NaS) batteries	Grid-scale energy storage systems, wind farms, microgrids, off-grid systems	High energy density, long cycle life, high power output	Expensive, high operating temperature, safety concerns
Solid-state batteries	Electric vehicles, portable electronics, stationary energy storage systems	High energy density, fast charging, improved safety	Currently more expensive, limited scalability, technical challenges

4.1. Lithium-ion (Li-ion) batteries

Lithium-ion (Li-ion) batteries are a widely used rechargeable battery technology that has transformed energy storage across various applications. These batteries utilize lithium ions that move from the negative electrode to the positive electrode during discharge and back when charging. The movement of ions allows for efficient energy storage which makes Li-ion batteries highly effective for a wide range of applications.

In a Li-ion battery, during discharge, lithium ions move from the anode, typically made of graphite, through an electrolyte, to the cathode, typically made of a lithium metal oxide. During charging, the process is reversed, and the lithium ions move back to the anode which are by Equation 1 and Equation 2. This process is facilitated by the electrolyte, a lithium salt solution, which allows the movement of ions while preventing the flow of electrons inside the battery [75].

$$\text{Anode: } C + xLi^{+} + xe^{-} \longleftrightarrow Li_xC_6 \tag{1}$$

$$\text{Cathode: } LiCoO_2 \longleftrightarrow Li_{1-x}CoO_2 + xLi^{+} + xe^{-} \tag{2}$$

Li-ion batteries are commonly used in portable electronics like smartphones, laptops, and digital cameras. Their popularity is due to their lightweight design, high energy density, and long lifespan, allowing for hundreds of recharge cycles with minimal performance loss. They are also increasingly being used in electric vehicles (EVs), where they offer long-range and fast charging capabilities. In addition, Li-ion batteries are employed in power tools and medical devices, demonstrating their versatility across various sectors [76].

Li-ion batteries are essential for energy storage solutions, particularly in solar and wind energy systems. They store surplus energy produced during peak sunlight or wind conditions and release it when solar or wind activity is low, helping maintain a steady energy supply.

A significant example of Li-ion batteries in renewable energy is the Tesla Powerwall, a residential energy storage unit that allows homeowners to store solar energy for use during power outages or periods of high electricity demand. On a larger scale, the Hornsdale Power Reserve in South Australia, equipped with Tesla's Powerpacks, is a notable instance. They are important in the field of renewable energy for grid stability, energy storage, and reducing costs.

Li-ion batteries bring advantages but also face challenges. Their high cost limits widespread use, especially in large-scale settings. There are safety concerns, including the risk of thermal runaway. Environmental problems from producing Li-ion batteries, particularly mining, require us to recycle and source responsibly.

Overall, Li-ion batteries play a crucial role in energy storage solutions. They boast high efficiency and a lengthy cycle life. These batteries are used in everything from consumer electronics to extensive renewable energy systems. [77].

4.2. Lead-acid batteries

Lead-acid batteries are among the oldest and most well-established rechargeable battery types, valued for their durability and affordability. These batteries function through a chemical reaction between lead, lead dioxide, and sulfuric acid, which creates a flow of electrons and generates electrical power.

In a lead-acid battery, the positive electrode (cathode) is made of lead dioxide, and the negative electrode (anode) is made of sponge lead, with both immersed in a sulfuric acid electrolyte. During discharge, the lead and lead dioxide react with the sulfuric acid to produce lead sulfate and water, releasing electrical energy. When charged, the process reverses and lead sulfate and water are converted back to lead, lead dioxide, and sulfuric acid. The complete bidirectional equation of the reactions are shown in equations 3.

$$2\,PbSO_4(s) + 2\,H_2O(l) \rightleftharpoons PbO_2(s) + Pb(s) + 2\,H_2SO_4(aq) \tag{3}$$

These batteries are widely used in automotive applications, particularly for starting, lighting, and ignition (SLI) in vehicles because of their ability to provide high surge currents. They are also employed in backup power systems for emergency lighting, alarm systems, and uninterruptible power supplies (UPS), where their reliability is crucial. Additionally, lead-acid batteries are used in forklifts, golf carts, and in marine applications [78].

In the field of renewable energy, lead-acid batteries are commonly used in small-scale solar installations, particularly in residential and remote area power systems (RAPS). They store excess solar energy during the day for use at night or during cloudy periods. Their economic advantage makes them suitable for off-grid solar systems in developing areas where cost matters most.

A notable example of lead acid batteries in renewable energy is their use in rural solar electrification projects, where they provide essential energy storage to enable a consistent power supply. They are also used in large-scale solar farms as part of the energy storage solution to balance the grid and provide backup power.

Despite their widespread use, lead-acid batteries have certain limitations. The low energy density makes them bulky and heavy relative to their energy storage, problematic in areas with limited space. They also have a limited cycle life and are less suited for applications requiring frequent deep discharge cycles. Regular maintenance, particularly for flooded lead-acid batteries, is necessary to ensure longevity and performance. The lead and sulfuric acid in these batteries pose environmental hazards and require proper recycling to avoid contamination.

However, the low cost of lead-acid batteries, combined with their proven reliability and established recycling processes, continues to make them a popular choice in a variety of applications, including certain areas of renewable energy [79].

4.3. Flow batteries

Flow batteries, also known as redox flow batteries, are a unique type of energy storage device that stores electrical energy in liquid chemical solutions. Their design is unique, separating storage and generation, allowing more versatile and expandable energy storage methods.

Flow batteries consist of two tanks of liquid electrolytes, one with a positively charged solution and the other with a negatively charged solution. These electrolytes are pumped through a cell stack where they are separated by a membrane. During discharging, ions flow through the membrane, and a chemical reaction occurs that generates electricity. When charged, an external power source reverses the chemical reaction, restoring the electrolytes to their original states. The complete process is summarized in Equation 4. The power output of flow batteries is determined by the size of the cell stack, while the energy capacity is determined by the volume of the electrolytes in the tanks.

$$VO_2^+ + V^{2+} \rightleftharpoons VO^{2+} + V^{3+} \tag{4}$$

Flow batteries are primarily used for grid energy storage, including peak shaving, load leveling, and frequency regulation. They are also employed in microgrids and for backup power systems in critical applications such as hospitals and data centers. Due to their scalability and long discharge durations, they are well-suited for uses that demand significant energy storage over prolonged durations [80].

Renewable energy systems are using flow batteries more frequently to store the surplus energy generated by solar and wind. They help smooth out fluctuations in renewable energy sources, providing a stable and reliable electricity supply. Their ability to discharge for longer makes them ideal for use cases that demand energy supply over extended durations, such as during low wind or sunlight conditions [81,82].

The Gills Onions facility in California uses a Vanadium Redox Flow Battery. This VRFB system manages energy needs and costs efficiently. It stores and supplies renewable energy effectively. In Hokkaido, Japan, a large flow battery system is utilized. It is combined with solar and wind energy sources [83].

Despite their benefits, flow batteries have higher upfront costs and need larger spaces. They also necessitate a larger area for tanks and pumps [84]. However, their long cycle life and minimal maintenance requirements are positives. The environmental safety that they offer, being non-flammable and nontoxic, is advantageous. This makes them promising for large-scale energy storage, especially with renewable energy[85,86].

4.4. Sodium-sulfur (NaS) batteries

Sodium-sulfur (NaS) batteries are a type of high-temperature battery technology that stands out for its high energy density and efficiency. These batteries are mainly utilized in large energy storage projects, recognized for their distinctive makeup and the way they work.

The primary elements of a NaS battery include molten sodium (Na) for the anode and sulfur (S) for the cathode. These components are separated by a solid beta alumina ceramic electrolyte that only allows the passage of sodium ions. The battery operates at temperatures around 300 to 350°C, at which both sodium and sulfur are in the molten state. During the discharge process, sodium ions move through the electrolyte to the sulfur side, releasing energy in the form of electrons. During charging, the process is reversed, and the sodium ions move back to the sodium side which is shown in 5.

$$2\,Na + S \rightleftharpoons Na_2S \tag{5}$$

NaS batteries are primarily used for grid energy storage, including load leveling, peak shaving, and providing emergency power supply. They are also being used in industrial and commercial applications where large-scale, high-capacity energy storage is required.

In the context of renewable energy, NaS batteries stand out as the ideal fuel storage medium to balance the variability of sources such as wind and solar power. They are capable of providing long-duration energy storage, which is crucial for maintaining a stable and reliable energy supply when renewable energy generation is low.

An example of NaS battery usage in renewable energy is their application in wind farms and solar power plants in Japan. The Buzen Substation in Japan utilizes NaS batteries for storing solar energy, demonstrating their effectiveness in large-scale renewable energy integration [87,88]. NaS batteries are recognized for their excellent energy density and high efficiency. However, they come with limitations and challenges. One major concern is their high operating temperature. This necessitates specialized thermal management systems. Additionally, the molten sodium in these batteries can be hazardous. Proper containment is thus essential. Moreover, the high cost and complex management systems limit their widespread adoption [89].

The distinctive characteristics of NaS batteries are their long cycle life. They have an impressive discharge capacity. Their quick adaptability to energy requirements is exceptional. Consequently, they are favored for broad energy storage solutions. This is true especially in renewable energy settings [90].

4.5. Solid-state batteries

The advent of solid-state batteries represents a significant step forward in the evolution of battery technology. Opting for a solid over a liquid electrolyte, they redefine traditional battery design. This transformation opens the door to numerous advantages. Hence, solid-state batteries are recognized as a promising alternative for energy storage in the future.

Solid-state batteries operate on the same basic principle as traditional batteries – moving ions between electrodes during charging and discharging. However, instead of a liquid electrolyte, these batteries use a solid electrolyte, which can be made from various materials, including ceramics or solid polymers. This solid electrolyte carries ions while also separating the anode and cathode to avoid short circuits. The design mitigates risks of leakage and flammability linked to liquid electrolytes, increasing battery safety [91].

Although still under development, solid-state batteries are expected to revolutionize sectors that focus on safety, high energy density, and weight considerations. Solid-state batteries are projected to transform the electric vehicle industry, offering the advantages of extended range, rapid charging, and improved safety. The high energy density and stability of these batteries also make them suitable for devices such as smartphones and laptops [92,93].

This makes them well-suited for capturing renewable energy from sources like solar and wind. The safety features make them suitable for residential applications, where space and safety are most important.

While solid-state batteries have not yet been widely commercialized, several companies and research institutions are actively developing this technology. Notable examples include prototypes and research projects by major automotive manufacturers aiming to incorporate solid-state batteries into future electric vehicles. These efforts underscore the industry's belief in the potential of solid-state technology to revolutionize energy storage in the coming years [94].

Solid-state batteries offer many advantages, however, technical issues must be surmounted for them to become widely used. The issues include ensuring the stability and robustness of the solid electrolyte, scaling up production techniques, and cutting down on expenses. Researchers are also working hard to solve problems at the spot where the solid electrolyte meets the electrodes, which is very important for the battery to work well.

The progress of solid-state batteries is under intense scrutiny from various industries. They are recognized for their safety, efficiency, and superior capacity. This makes them crucial for sectors such as automotive and renewable energy [95].

The discussed battery types have the common goal of energy storage for diverse applications. Each type is rechargeable and has distinct features and limitations, making it appropriate for particular applications. Although batteries share similarities, there are several key differences among the five types of batteries. Selecting the right energy storage system (ESS) is important for incorporating renewable energy sources into the electricity network. The Figure 7 shows the storage capacity versus discharge time for typical ESS, covering a wide range of system power ratings and applications. When making a decision, it is essential to evaluate factors like power rating, discharge duration, lifespan, energy density, and efficiency.

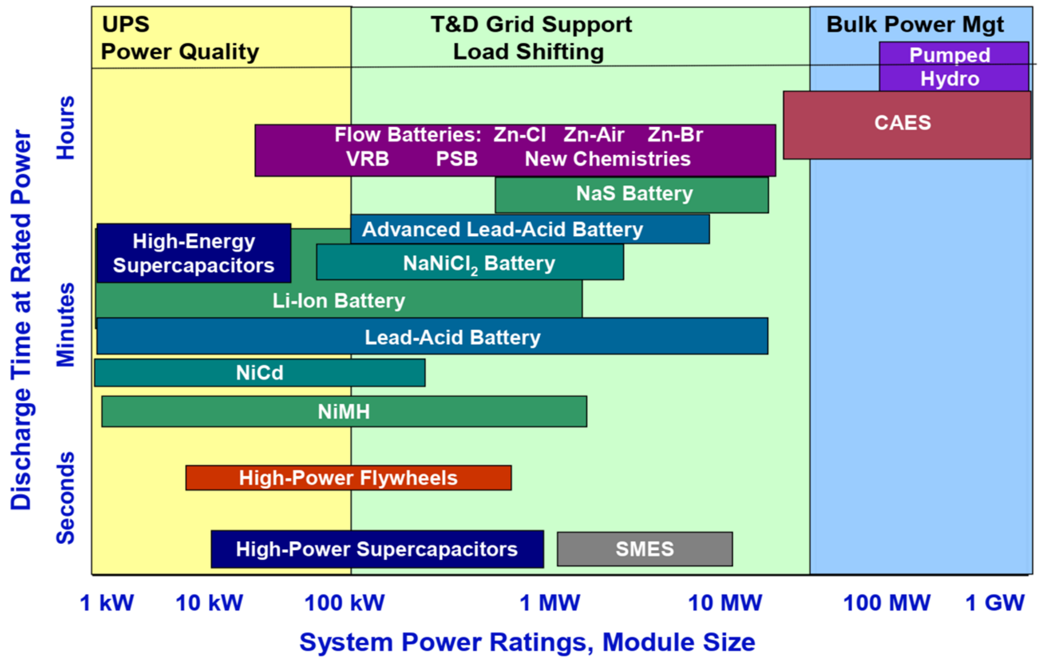

Figure 7. Storage Capacity vs Discharge time for typical ESS

5. Application of BESS in Renewable Energy Integration

Battery Energy Storage Systems (BESS) play a key role in integrating renewable energy, enhancing energy system efficiency and reliability. BESS mitigates the impact of the intermittent nature of renewable sources and optimizes power grid operations. The detailed discussions of various applications of BESS in renewable energy are given below.

5.1. Peak shaving

Peak shaving, an important use of BESS, aims to lessen the load on the electrical grid during times of highest demand. This procedure is essential in reducing the necessity for expensive peak power plants, activated chiefly in moments of intense demand. BESS stores energy during off-peak hours when the demand and electricity prices are low. When demand increases, instead of drawing more power from the grid, the stored energy in the BESS is used. This strategy helps to decrease the cost of using power when demand is high and also reduces the load on the power grid. A BESS for peak shaving must have a high energy density to store sufficient energy, the capability to rapidly charge and discharge to respond to peak demands swiftly, and a long cycle life to ensure its viability over many years. The system requires absolute safety and reliability to function properly in a variety of environmental circumstances. An example of a peak shaving using BESS can be seen in industrial facilities where the energy demand varies significantly throughout the day. Facilities use BESS to reduce the peak of their energy use, thus reducing their energy costs and dependency on the grid during peak times [96–99].

5.2. Load shifting

This strategy is essential for maintaining grid stability, particularly as renewable energy sources become more integrated into existing power systems. BESS charges during periods of low energy demand and discharges during high demand periods. By doing so, it reduces the reliance on traditional, often fossil fuel-based, peaking power plants, leading to a more sustainable energy mix. Batteries used for load shifting need to have a high energy density for substantial energy storage, rapid charge and discharge capabilities to respond to grid demands promptly, and a long cycle life for long-term operation. They must also be capable of operating with high efficiency, ensuring minimal energy loss. In residential areas with solar panel installations, BESS is used to store excess solar power generated during the day. This energy is then used during the evening, reducing the demand on the grid during peak hours [100–102].

5.3. Backup power

Providing backup power is a crucial application of BESS, especially in ensuring the reliability of critical systems during power outages. In the event of a grid failure, BESS can provide instantaneous power, ensuring the continuous operation of essential systems. This holds significant importance in places prone to electricity outages or in crucial establishments like hospitals and data centers. A BESS used for backup power must have a high energy density to provide prolonged power support, the ability to sustain a consistent power output over time, and a long cycle life. The quick response to power outages and the ease of transition from grid power to battery power are essential features. Hospitals often use BESS as a backup power solution. During a power outage, BESS guarantees the uninterrupted operation of life-saving equipment and essential systems [103,104].

5.4. Grid stabilization

Grid stabilization is a significant application of BESS, involving services such as frequency regulation, voltage control, and reactive power support. BESS can quickly respond to fluctuations in power demand and generation, helping to maintain the reliability and stability of the grid. For grid stabilization, BESS must provide high power output and rapid response times, along with the ability to charge and discharge quickly. Long cycle life and minimal maintenance are also crucial for ensuring long-term reliability. Large-scale BESS projects, like those integrated with wind farms, have been implemented to provide grid stabilization services [99,105].

5.5. Islanded operation

Islanded operation involves battery energy storage systems in creating isolated microgrids that have the ability to operate on their own, away from the central power grid. This application is important for improving the resilience and reliability of the power supply in remote or isolated areas. In an island-based microgrid, BESS and renewable energy sources like solar and wind collaborate to deliver consistent power, even when disconnected from the main grid. Batteries for islanded operation must possess high energy density, quick charging and discharging capabilities, and long cycle life. They should be robust, requiring minimal maintenance, and capable of providing high power output to support the microgrid's needs. Remote islands or rural communities often rely on islands with BESS. These framewords assure a stable and sustainable power grid, intrigrating local renewable energy sources [106,107].

6. Benefits and Limitations of BESS

Battery storage technology aids in integrating renewable energy, but attention must be paid to its limitations and negative aspects. Battery storage systems play a key role in keeping the power grid stable. They do this by improving frequency regulation, voltage control, and reactive power support. This makes the power grid more reliable, even when using energy sources that don't always provide power steadily. These systems offer a way to save on energy costs by cleverly shifting when to use electricity—from high-cost times to lower-cost times—and by providing crucial backup power during times of peak demand [108]. BESS helps increase the utilization of renewable energy sources by storing excess energy generated during periods of high renewable energy production and making it available during periods of low renewable energy production [109]. It provides backup power during grid failures, ensuring critical systems remain operational [110].

However, BESS can be expensive, particularly for large-scale applications, and may not be economically viable in all situations [111,112]. The process of creating batteries and disposing of them can damage the environment, especially certain types [113,114]. The process of mining and refining specific materials for batteries also has environmental and social impacts [115]. In some cases, BESS offers lower energy density and capacity compared to other energy storage methods, like pumped hydro or compressed air energy storage.

Moreover, BESS has a limited lifespan and may need to be replaced after several years of use, which can add to the cost of the system [116,117]. Battery storage technology has lots of benefits for adding renewable energy sources, more than its limitations. However, it's necessary to think carefully about the system's specific requirements. This ensures that battery storage as a solution that's both affordable and good for the planet.

7. Challenges for BESS

Battery storage could play a big role in renewable energy, but several challenges need to be tackled to achieve its full potential. The challenges faced in battery storage technology are the foundation of innovation and making things better. The major challenges are discussed in this section.

7.1. Economic Viability

The high cost of battery storage technology for large-scale applications is stll a major issue. The capital expenses for battery production, along with the costs associated with installation, maintenance, and end-of-life management, impact the overall economic feasibility. Advances in battery manufacturing processes, material science, and economies of scale have the potential to reduce costs. Creative financial model and business strategies can lower the cost of Battery Energy Storage Systems, making them easier to get and use [118–120].

7.2. Scalability and Grid Integration

Scaling up BESS involves complex challenges for integration of large-scale RERs into existing grid. Ensuring compatibility, efficiency, and reliability of BESS at a larger scale is a non-trivial task. Technological advancements in grid management systems can facilitate better integration. Studies in creating BESS designs that are both modular and flexible can help make them easier to scale up [121–124].

7.3. Durability and Reliability

BESS needs to be durable and reliable to provide the expected benefits for the integration of renewable energy. This includes the challenges of ensuring consistent performance during their useful life and resilience against extreme environmental conditions. Improving the chemical composition and design of batteries, their life spans can be significantly extended. Predictive maintenance strategies can make things more reliable [125,126].

7.4. Environmental Sustainability

For a balanced and sustainable relationship between technology and nature, it is important to develop battery storage systems that are good for the environment. The process of extracting raw materials, the energy used in manufacturing, and the disposal of products at the end of their life cycle impact the environment. Improving recycling technologies and exploring less harmful materials can reduce the deadly impacts. Policies and regulations that support careful selection and reuse of materials can help reduce harm to the environment [127,128].

7.5. Safety and Standards Compliance

It is important to ensure the safety of Battery Energy Storage Systems (BESS) regarding fire risks and chemical hazards. Compliance with new safety standards and regulations is also essential for better BESS. Continuous efforts are made to find better materials for batteries and to design BESS with advanced safety features. Strengthening certification processes and will also improve the safety compliance [129,130].

7.6. Energy Density and Efficiency

Improving the energy density and efficiency of batteries is essential to improve storage capabilities and minimize space requirements, especially in space-constrained applications. Researchers are exploring solid-state batteries and other innovative technologies to increase the amount of energy batteries can contain. Improving the structure of batteries and the types of materials used in electrodes can lead to higher efficiency [131,132].

7.7. Lifecycle Management

Effective lifecycle management of batteries, including manufacturing, usage, and disposal, is essential for sustainable operations. This includes challenges in the recycling and reusing of battery materials. Development of sustainable lifecycle management practices and circular economy models for batteries can optimize resource use. Advances in recycling technologies and second-life applications for used batteries can also contribute to lifecycle management [133,134].

8. Future Prospect and Emerging Trends

As the demand for renewable energy expands, the importance of cost-effective and dependable energy storage solutions grows significantly. This section explores the emerging trends and future prospects for battery storage technology, highlighting technological advancements, integration strategies, policy developments, economic factors, and environmental considerations.

8.1. Advancements in Battery Technology

Emerging battery technologies like solid-state batteries, lithium-sulfur, and advanced flow batteries are at the forefront of research. Developments in nanotechnology and electrode materials are poised to significantly improve energy density and battery life. Solid-state batteries offer higher energy density and improved safety compared to traditional lithium-ion batteries. These technologies also promise faster charging times and longer cycle lives, which are vital for applications in electric vehicles and grid storage [135–137]. Recent research in lithium-air batteries also shows potential for even higher energy densities, although challenges in lifecycle and safety remain to be addressed [138].

8.2. Integration of Energy Storage Systems

Integrating energy storage with renewable sources is key to stabilizing the grid and enhancing energy security. Projects like the Hornsdale Power Reserve in Australia demonstrate successful large-scale battery deployment alongside wind energy. Combining various storage forms, like batteries and pumped hydro, can provide more consistent and reliable power. Advanced management systems using digital twin technology are now being developed to optimize these integrated storage systems [48,139]. The future of energy storage integration also includes vehicle-to-grid technologies, where electric vehicles provide storage capacity to the grid [140].

8.3. Artificial Intelligence and Machine Learning

AI and machine learning are revolutionizing energy storage management. Predictive analytics for battery health, intelligent charge/discharge algorithms, and demand forecasting are areas where AI is making significant impacts. Machine learning models can optimize battery usage and extend its useful life, reducing operational costs. The use of AI in grid management also helps in integrating renewable sources more efficiently, adapting to real-time changes in supply and demand [141,142]. AI-driven automation in battery manufacturing can further reduce costs and improve battery quality [143].

8.4. Policy and Regulatory Developments

Government policies play a crucial role in speeding up the adoption of energy storage systems. Initiatives such as the Investment Tax Credit (ITC) in the United States have been extended to include energy storage, providing financial incentives for deployment. The European Union's Green Deal is another example, promoting renewable energy and storage to achieve carbon neutrality. The growth in microgrid and community energy storage projects is also being supported by local policies and incentives [144–146].

8.5. Economic Viability and Market Dynamics

The declining cost of battery technologies and the increasing demand for electric vehicles and stationary storage are driving market growth. The economies of scale achieved by companies like Tesla have significantly reduced the cost of batteries. Market dynamics indicate a growing trend towards renewable energy storage integration. With the rise of distributed energy resources, the market for residential and commercial battery systems is also expanding rapidly [147,148].

8.6. Environmental Impact and Sustainability

The environmental impact of battery production and disposal is a growing concern. Research into sustainable materials and recycling methods is essential for reducing the ecological footprint of batteries. Efforts to improve the sustainability of the entire battery life cycle are underway. The development of bio-based and recyclable batteries is a burgeoning field, aiming to mitigate the environmental concerns associated with conventional batteries [149–151].

These emerging trends and developments paint a dynamic future for battery storage technology in renewable energy systems, offering opportunities for technological innovation, economic growth, and environmental sustainability.

9. Conclusion

Battery storage technology is a potential solution to mitigate the challenges of integrating RERs into the existing power grids. Its ability to store and deliver energy when energy is needed most has made BESS an integral part of modern energy systems. Battery storage technology provides a more economical choice compared to fossil fuel-based peaking plants. Through BESS, the expansion of renewable energy becomes more feasible. The technology provides an opportunity to decrease fossil fuel consumption, thereby reducing greenhouse gas emissions and paving the way for a cleaner, more sustainable energy future. As a step toward a future that is sustainable in energy, the vital role of battery storage offers a bright and innovative path forward. Its continued development and deployment will be crucial in ensuring a reliable, efficient, and clean energy supply for generations to come.

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