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(Review Article)

Batteries in PV Systems: A comprehensive analysis of performance, efficiency and cost in personal house use

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Abstract

The rapid shift toward renewable energy sources, driven by decarbonization goals and smart grid development, has elevated the role of Battery Energy Storage Systems (BES) in enhancing the efficiency and reliability of power supply frameworks. This study provides a comprehensive review of BES technologies, focusing on their classification, selection factors, sizing methodologies, optimization techniques, and associated challenges. Various battery types including lead-acid, lithium-ion (Li-ion and LiFePO4), flow, and nickel-cadmium are analyzed in terms of efficiency, lifespan, and suitability for photovoltaic (PV) applications. Key parameters such as depth of discharge, round-trip efficiency, capacity, and cycle life are examined to guide battery selection. Furthermore, the study highlights economic, environmental, and technical challenges including power quality, aging effects, and system integration. By addressing research gaps and presenting future directions, this paper serves as a valuable resource for researchers and engineers aiming to design sustainable and optimized BES solutions for renewable energy systems.

Keywords: Energy storage; Battery energy storage; BES; Battery size; $LifePO_4$

1 Introduction

The energy concepts are evolving all around the world due to increasing technological advancements, decarbonization initiatives, the establishment of the smart grid concept, and the rapid growth in the use of renewable resources. In the past, fossil fuels are critical resources for generating electrical power. Due to global warming and greenhouse gas (GHG) emissions resulting from the widespread use of diesel, petrol, and other fossil fuels, which emit tons of CO2, the world is now approaching decarbonization through low-carbon emission while expanding the utilization of sustainable power sources [1]. The distributed nature of power production, the need for independent microgrids to ensure reliability, the requirement to reduce greenhouse gas emissions, and the ability to adapt blended energy resources to meet creative and erratic demands for a steady power supply are some of the major challenges that the electrical power infrastructures must overcome as a result [2,3]. Because of its potential to reduce greenhouse gas emissions, researchers are finding that using Renewable Energy-Storage Systems (RESSys) is a compelling solution to these problems. However, evaluating batteries RESSys technology for a particular application can be challenging because of the abundance of alternatives and intricate performance matrices [4].

Integrating at least two renewable energy sources (wind, photovoltaic) is the main selling point of RESSys as it can solve the drawbacks, dependability, efficiency, and cost of using only one renewable energy source [5]. However, a common drawback of wind and photovoltaic systems is that they both have high initial costs, are weather- and climate-dependent, and require larger than average systems to ensure that their independent frameworks are robust in the event that neither system is producing enough electricity to meet the load [6]. RESSys frameworks can benefit from the

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application of battery energy system to increase efficacy and eliminate weaknesses. The truth is that these capacity units become indispensable when solar radiation or wind speed decreases or when there is a spike in demand.

As a result, researchers are becoming more and more interested in creating a capable and trustworthy battery energy system. Numerous scholars have devised various optimisation algorithms to determine the optimal result from the conventional battery energy system, considering its low cost, long lifespan, dependability, and minimal environmental effect.

Five categories: mechanical, electromechanical, electrical, chemical, and thermal energy-storage systems, have been established for Energy-Storage (ES) technologies in [7]. The appropriate technology is offered for each application after a comparison of various ES technologies and applications is discussed. Nevertheless, the study did not go into great detail about the difficulties presented by various technologies or the Battery Energy Storage (BES) optimisation techniques.

The majority of the BES sizing in the Renewable Energy Systems (RES) is concentrated in [8]. Four industries have been identified for the use of BES sizing: microgrids; freestanding Hybrid Renewable Energy Systems (HRES); distributed renewable energy systems; and renewable energy power plants. Nevertheless, BES sizing methodologies and optimisation strategies were not covered in detail in the study. Although [9] discusses microgrids and the technologies they are connected with in length, the literature lacks information regarding BES size and optimisation. From the standpoint of distributed energy, a thorough analysis of batteries and non-BES is provided in [10].

The differences in chemical composition of several lead-acid battery types are described in [1]. The longevity, cycles, efficiency, and installation costs of BES and non-battery energy-storage systems have been compared. The literature [11] has discussed many multi-criteria decision-making techniques in BES, criteria-based decision-making approaches, performance analysis, and stockholder interest and engagement in the criteria-based analysis. However, a detailed discussion of BES size and optimisation strategies has not yet been provided. To achieve decarbonisation in the Micro-Grid (MG) application, a thorough explanation of BES sizing techniques is provided in [12].

Two modes of BES sizing optimisation techniques and algorithms-grid-connected and isolated mode-are described, together with a brief comparative analysis that takes decarbonisation into account. The four main types of BES, mechanical, electromechanical, chemical, and thermal systems, were established by Olabi et al. in [13]. Future issues are discussed after a detailed description of each category's creation and use. The book lacks a thorough explanation of system limitations, BES size, and optimisation strategies. The development and use of BES technology is the only thing being addressed.

This study aims to highlight the importance of battery energy storage system (BES) scaling technologies by providing a focused and comprehensive review that addresses current research gaps in this critical field. It offers a concise comparison of various BES technologies while discussing existing challenges related to system sizing strategies. The significance of this article lies in its role as a unified reference that supports researchers and engineers in understanding the latest electrochemical advancements and their potential integration into renewable power generation and distribution frameworks. The primary objectives are to enhance awareness of cutting-edge BES technologies, examine their limitations and applications, and offer valuable insights that can guide future developments in energy storage systems.

2 Methodology

To provide a comprehensive understanding of battery energy storage systems (BESSys) in renewable energy applications, this study followed a structured review approach. Relevant literature was identified by evaluating the titles, abstracts, and contributions of a wide range of academic publications. The review process was carried out in four key stages. First, various types of batteries commonly used in energy storage systems were examined, highlighting their chemical composition, performance characteristics, and suitability for photovoltaic applications. Second, the study explored critical factors influencing battery selection, including efficiency, cost, lifespan, environmental impact, and compatibility with specific renewable systems. Third, the analysis addressed the current challenges and limitations associated with battery integration, such as degradation, safety concerns, and technological constraints. Finally, the article concludes by summarizing the key insights and offering recommendations for future research and system development aimed at supporting sustainable and clean energy solutions.

3 Types of Batteries

Batteries come in various types, each with its advantages and disadvantages. Lead-acid batteries are the least expensive option but have a shorter lifespan and lower energy density than other types. Lithium-ion batteries are more expensive but have a longer lifespan, higher energy density, and faster charging times [14]. Flow batteries are ideal for large-scale solar systems but are more expensive and require more maintenance. Choosing the right type of battery depends on your energy needs, budget, and system requirements [15]. It's essential to research and consult with an expert before making a decision to ensure choosing the best solar battery for your needs.

There is a diverse range of types available to choose from. Each type has its unique benefits and drawbacks, making it necessary to consider your specific needs when selecting a battery. Lithium-ion batteries are the most common type and are known for their long lifespan, low maintenance, and high energy density. Lead-acid batteries are another cost-effective option but require more maintenance and have a shorter lifespan. Flow batteries provide efficiency and durability, while nickel-cadmium batteries are known for their reliability and long lifespan. Other options include sodium-based batteries, saltwater batteries, zinc batteries, bromine batteries, and even hybrid solar batteries that combine multiple technologies. Investing in the best solar batteries on the market can change the game for those

3.1 Lead-Acid Batteries:

Lead-acid batteries have long been a popular choice for solar power systems due to their cost-effectiveness and reliability [16]. However, they require regular maintenance, such as checking water levels and cleaning terminals. They are suitable for small to medium-sized solar systems and may not be ideal for long-term storage or off-grid use [17]. Despite these limitations, lead-acid batteries remain a common choice for homeowners seeking an efficient and affordable solar battery solution.

3.2 Lithium-ion Batteries:

Lithium-ion batteries have become the most common choice for solar power systems due to their high energy density, longer lifespan, and low maintenance requirements [18]. These batteries are lightweight, capable of storing a lot of energy in a small space, making them ideal for residential and commercial use. They can be charged quickly and are available in various sizes, allowing homeowners to customize their solar systems to meet their energy needs. Although they tend to be more expensive than other battery types, the benefits of lithium-ion batteries make them a worthwhile investment for anyone looking to transition to solar energy [19].

lithium-ion batteries have quickly established themselves as the preferred energy storage technology, thanks to their compact size and long lifespan. They provide higher energy usage efficiency and a much longer lifespan compared to GEL batteries and lead-acid batteries, marking a turning point in solar energy storage. Lithium batteries are equipped with an internal electronic management system, BMS, which will optimize discharge and charging according to the efforts of the solar panels and the inverter charger used. Capacities range from 2 to 10 kilowatts per hour per unit, depending on battery brands. Discharge power can reach 5000 watts in some models [20]. The quality of the building management system will also affect the lifespan of lithium batteries and their ability to discharge, thus returning energy.

3.2.1 . Lithium Iron Phosphate (LiFePO4) Batteries

Lithium Iron Phosphate (LiFePO4) is a subtype of lithium-ion batteries that are particularly well-suited for residential photovoltaic (PV) systems [21]. These batteries are known for their high thermal stability, long lifespan, and superior safety compared to other lithium chemistries. They typically offer over 4000 - 6000 charge/discharge cycles, with minimal degradation, making them ideal for daily solar usage [22,23]. In the market there are many brands offering 8000 -10000 charge/discharge cycles at 25 and 80% DOD.

Although their initial cost is higher, their long-term cost-effectiveness and deep discharge tolerance make them a popular choice for personal home energy storage. Additionally, they are lightweight, maintenance-free, and environmentally friendlier than lead-acid batteries [24,25].

3.3 Nickel-Cadmium Batteries

Nickel-Cadmium batteries are an older technology but are still used in some applications. These batteries have a longer lifespan than lead-acid batteries and can withstand extreme temperatures, making them ideal for harsh environments [26]. However, they are less efficient and have lower energy density than newer battery technologies such as lithium-ion or flow batteries. Regular maintenance is required to prevent memory effects and extend their lifespan. Despite these limitations, nickel-cadmium batteries remain a reliable option for off-grid applications where cost may be a secondary concern compared to reliability [27].

3.4 Flow Batteries

Flow batteries use a liquid electrolyte that flows through battery cells, providing easy capacity upgrades and longer lifespan [28]. Due to these capabilities, flow batteries are an excellent option for wide-scale solar energy storage. They have the ability to efficiently store large amounts of energy, making them an ideal solution for commercial applications [29]. Additionally, these batteries are safer and more environmentally friendly than traditional lead-acid batteries as they lack toxic materials [30]. However, flow batteries may be more expensive upfront compared to other types of solar batteries.

4 Important factors for battery selection

When selecting a solar battery, it is essential to consider several factors to ensure maximum return on your investment. Understanding the specifications of solar batteries can be challenging, but it is necessary to choose the right battery for your solar system [31]. Capacity, efficiency, depth of discharge, power rating, warranty, brand reputation, compatibility, and price are all critical factors to consider [32]. Ensure that the capacity and efficiency of the battery meet your energy needs. Look for a battery with a long lifespan and a warranty that covers both defects and performance.

4.1 Battery Capacity

The capacity of a solar battery is a crucial factor to consider when choosing the right battery for your solar power system. It determines the amount of electricity that can be stored and used when sunlight is unavailable [33]. A battery with high capacity can power more devices, providing greater independence from the grid. Although batteries with high capacity come at a higher price, investing in one that meets your needs will ultimately save you money on utility bills in the long run.

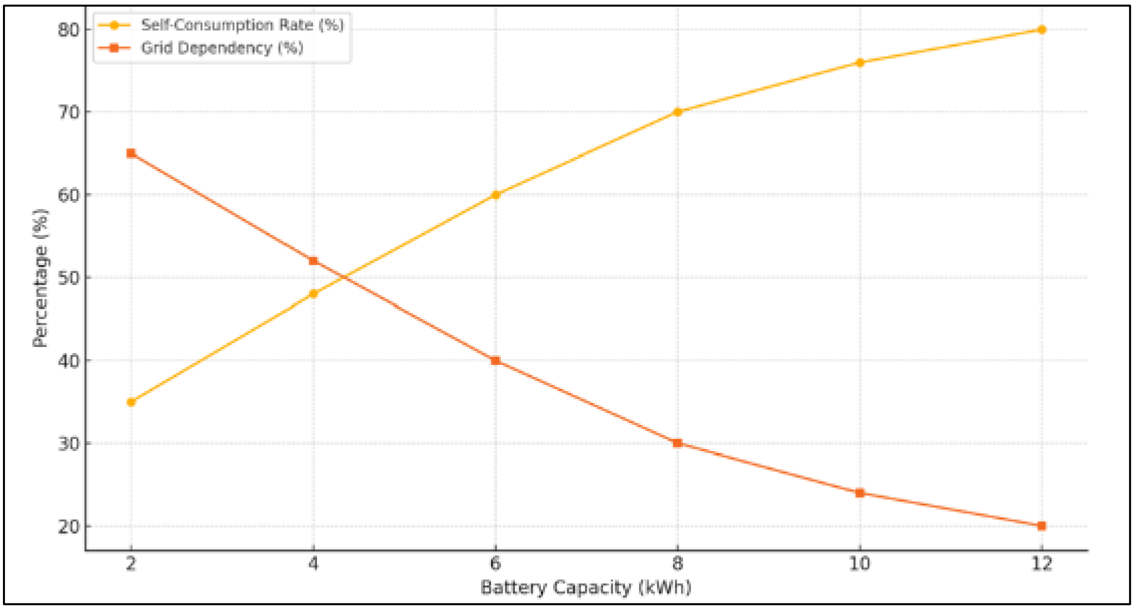

Figure 1 Impact of battery capacity on small-scale PV systems performance

Figure 1. illustrates how increasing battery capacity enhances the self-consumption rate of a small-scale PV system while reducing dependency on the grid.

4.2 Depth of Discharge (DOD)

This refers to the amount of energy a battery can release before needing recharging. Batteries with higher depth of discharge can provide more energy for longer periods. However, relying heavily on deeper discharge cycles can shorten the battery's lifespan [34]. Therefore, it's essential to find a balance between capacity, efficiency, and depth of discharge that aligns with your household's energy consumption habits [35].

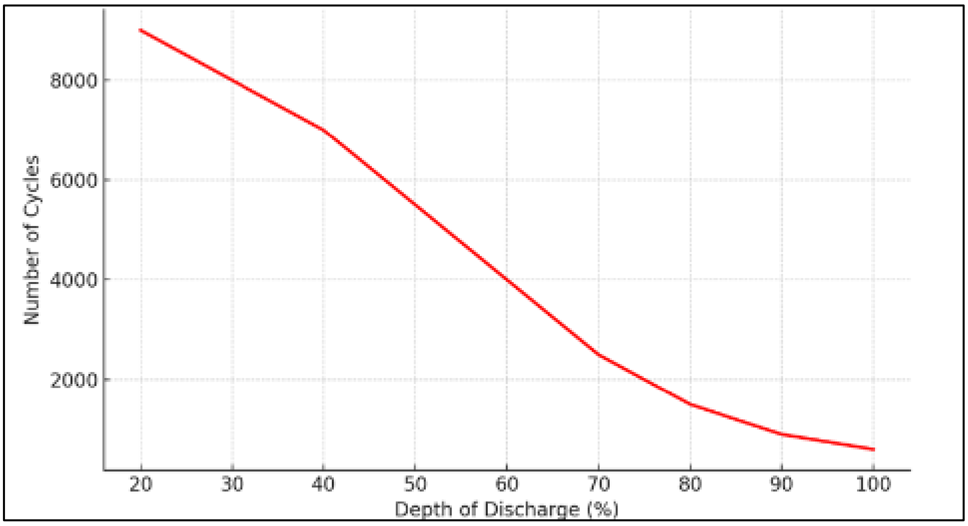

Figure 2 The relationship (DOD) and the Number of Battery Cycles

Other factors such as compatibility with solar module systems and cost also play a role in making this decision. Figure 2. illustrates the inverse relationship between the Depth of Discharge (DOD) and the number of charge-discharge cycles a battery can sustain. As the DOD increases, the number of usable cycles decreases significantly, especially beyond 60%. This trend highlights the importance of limiting the DOD in small-scale PV systems to extend battery life and reduce long-term replacement costs. Operating batteries at lower DOD levels may slightly reduce immediate capacity but greatly enhances overall system durability and economic efficiency.

4.3 Round-trip Efficiency

Round-trip efficiency is a crucial factor to consider. Simply put, it refers to the amount of energy lost during the charging and discharging process of the battery. High round-trip efficiency means more energy will be saved for use, while lower efficiency means more energy will be wasted in the process [36]. It's essential to choose a solar battery with high round-trip efficiency to ensure you get the most out of your solar system and reduce any unnecessary energy loss. Additionally, round-trip efficiency can be influenced by the size, capacity, and type of the battery, so thorough research is necessary before making any decisions [37].

4.4 Usable Storage Capacity

Considering usable storage capacity is crucial, indicating the amount of energy that can be stored and used in your home or business [38]. This includes available energy that can be used during power outages or periods of low sunlight. To determine the needs for usable storage capacity, consider your daily energy usage, the size of your solar panel system, and any backup power requirements [39]. Generally, lithium-ion batteries offer higher usable storage capacities compared to other battery types, making them an excellent choice for those with high-energy requirements. However, consider that they may come at a higher price point.

4.5 Battery Lifespan: Productivity and Cycles

One of the most critical factors to consider is its lifespan. Productivity and cycles are measures reflecting the duration before the battery needs replacement [40]. Productivity refers to the total amount of energy that can be stored and discharged by the battery over its assumed lifespan [41]. At the same time, cycles refer to the number of times the battery can be charged and discharged before it begins to lose capacity. Lithium-ion batteries are known for their high productivity and long lifespan, making them ideal for most solar power systems.

5 Issues and challenges

The process of creating an effective BES is time-consuming since so many variables need to be taken into account, such as price, dependability, the right kind of storage, power and voltage quality, frequency variations, and environmental concerns. Nonetheless, scientists are working to create more advanced technologies that take into account every aspect and can be integrated with other ESS technologies. Below is a summary of the most typical difficulties.

5.1 Economic impact

The financial parts of creating a BES system are typically the most difficult. The literature makes it abundantly evident that the majority of researchers concentrated on the cost-benefit analysis when determining the size of BESS. The types of BES that are chosen, the number of energy sources integrated, the location, the installed area feature, the cost of installation, and the cost of maintenance all affect how much a BES costs [42]. The capital power cost of the installation and maintenance is included in the converter interface, the yearly fixed operating and maintenance cost, the capital replacement cost, and the capital energy cost of storage capacity [43]. The estimated yearly expenditures for BES components, labour, property taxes, insurance, and other expenses are included in the fixed operation cost. On the other hand, the cost of maintenance includes the following: testing insulation resistance, adjusting sensors, auditing operation because of unusual vibrations or noise, operating protective devices like relays and circuit breakers, and maintaining the battery controller, pumps, fans, and other system components [44]. The lifespan, battery capacity, rate of battery deterioration, power loss, and SoC are the variables that impact BES prices. To minimise the overall cost of the BES installation, the size and capacity of the BES technology must be chosen appropriately [45]. An oversized BES will raise the system's overall cost as well as its power loss. Conversely, a BES that is too small will result in a frequency deviation and an imbalance between supply and demand [46].

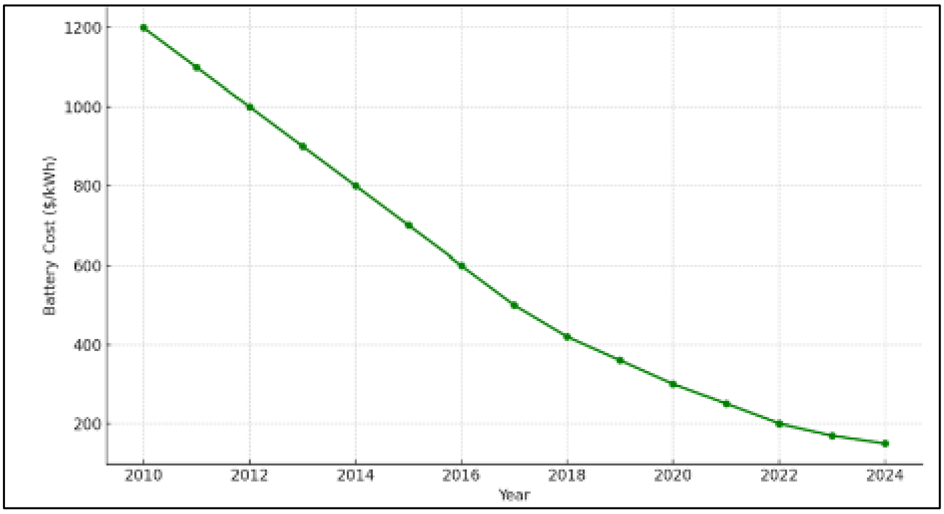

Figure 3 Battery cost trend for PV system (2010-2024)

Figure 3. illustrates the steady decline in battery costs for photovoltaic (PV) systems over the past 15 years, from 2010 to 2024. This trend highlights a significant reduction in the price of battery storage, dropping from around $1200/kWh in 2010 to nearly $150/kWh in 2024[47] [48] [49]. The decrease is largely driven by technological advancements, increased production scale, and growing market competition. This reduction in cost has made battery energy storage systems (BESS) more economically viable for small-scale PV installations, supporting greater adoption of renewable energy and enhancing grid independence [50].

5.2 Power quality impact

The primary objective of incorporating BES into the distribution network is to guarantee electricity transmission stability and dependability. The performance of the distribution network as a whole may suffer from a decline in power quality. Voltage sag and swell, overvoltage, undervoltage, voltage imbalance, frequency deviation, and harmonic distortion are among the most common traditional power quality issues [51]. Numerous researchers have developed a variety of techniques to improve power quality, such as the power electric transformer with control strategy, the application of PV capacity firming with BES to improve voltage un-balance and smooth power swings, and the use of ESS in conjunction with distribution static synchronous compensator (DSATCOM) for flicker compensation to improve voltage profile through receive power control strategy [52–54].

5.3 Aging impact

The battery ageing impact must be taken into account when constructing a BES system since it directly affects the system's total cost. Each battery has a certain lifespan and is made up of different chemical components. Calendric and cyclic ageing are the two categories of ageing. Calendric ageing is the continuous destruction of the battery caused by the chemical agents of the BES being active owing to temperature and voltage, even while the battery is inactive. The battery's charging and discharging factors determine the rate of cyclic ageing. Quick charging, gradual discharging, and extended lifespan are the three primary components of an effective BES system. Numerous academics put forth various approaches for BES size that take SoC constraints into account to accomplish this aim [55] [56][57] [58].

5.4 Environmental impact

Reducing greenhouse gas emissions is one of the main effects of applying BESS, helping to attain a sustainable environmental aim. There are certain environmental effects of BES itself. Hazardous materials and chemicals are used in the manufacturing of BES cells. Chemical waste may significantly affect the environment when a battery's life is over. Batteries that have decayed can be recycled and used again. Roughly 95% of the primary components of lead-acid batteries are recyclable and reusable [59–63]

5.5 Availability of technologies

Global warming is caused by the usage of fossil fuels rising in tandem with the fast pace of industrialization. A dependable and clean energy source is required to replace the state-of-the-art fossil fuel-based energy supplies now in use. The potential for BES to replace energy supplies derived from fossil fuels is quite high. However, a standalone BES installation is not able to address every issue. BES should be incorporated with MG or other RES to enhance power quality and lower loss. It will take new developments in technology and control strategies to make sure that BES and RES are properly integrated in DG and MG applications. Appropriate optimisation techniques are required, taking into account the problems and limitations in particular to lower GHG emissions. Furthermore, because of the high installation costs and system availability, BES technology and applications are only available in high-income nations. Thus, it remains to be investigated if these technologies may be introduced in middle-class and upper-middle-class countries [64] [65] [66] [67] [68].

6 Conclusions

Battery Energy Storage Systems (BES) are integral to the successful integration of renewable energy sources, particularly solar photovoltaic (PV) systems, into modern energy networks. This review has provided a detailed examination of various battery technologies, including their performance characteristics, advantages, limitations, and suitability for residential and grid-connected PV applications.

The selection of an appropriate battery type depends on multiple factors such as depth of discharge, round-trip efficiency, lifespan, capacity, safety, and cost. Among the reviewed technologies, lithium-ion batteries especially $LiFePO_4$ stand out for their high efficiency, long cycle life, and safety, making them a leading choice for residential PV systems. However, lead-acid batteries remain a viable low-cost option in certain applications despite their shorter lifespan and lower efficiency.

Optimization and proper sizing of BES are essential to maximize system performance, minimize costs, and ensure energy reliability. Moreover, integrating BES into renewable systems presents challenges such as power quality issues, degradation over time, environmental impacts, and recycling concerns. These must be addressed through improved battery management systems, policy support, and technological innovations.

Future research should focus on advanced materials, hybrid energy storage configurations, and intelligent energy management strategies to overcome existing limitations. Overall, BES will continue to play a crucial role in enabling clean, resilient, and efficient energy systems in the transition toward a sustainable energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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