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Review of Battery Energy Storage Systems: Advancements and Applications in Power Systems

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Abstract

Battery Energy Storage Systems (BESS) play a pivotal role in the transition towards sustainable energy grids, particularly when integrated with renewable energy sources like solar and wind. Recent advancements, particularly in lithium-ion battery technology, have contributed to cost reductions and performance improvements, driving BESS deployment across residential, commercial, and industrial applications. This review paper covers available energy storage technologies, the importance of BESS and control strategies in ensuring grid stability, deployment of BESS and its applications in detail. The optimization of energy management systems (EMS) and power systems and their integration with various power-generating systems are discussed and elaborated. Ongoing research, paired with strategic investments, will be instrumental in maximizing the capabilities of BESS in the evolving energy landscape. Finally, the paper offers a prospective view on the evolving role of BESS in the global energy sector, economic feasibility, need for further research, innovation, and large-scale deployment to meet future energy demands.

Keywords

Battery Energy Storage Systems (BESS); Lithium-ion Batteries; Energy Management Systems (EMS); Grid Integration; Renewable Energy Storage; Power Conversion Systems (PCS)

1. Introduction

The Paris Agreement aims to limit global temperature increases to well below 2°C, with an ambitious goal of achieving a temperature increase of 1.5°C or less compared to pre-industrial levels [1]. This landmark agreement, adopted by 55 countries and 196 Parties at COP21, came into force in November 2016, underscoring a collective commitment to mitigate the adverse effects of climate change, although only a few countries have retracted from the agreement [2]. Achieving these targets is challenging, particularly in the energy sector, where the variability of wind and solar power generation, the inflexibility of nuclear power, and the increasing unpredictability of electricity demand- driven by the electrification of transport and heat, necessitate greater flexibility in the electricity system. In this context, Battery Energy Storage Systems (BESS) play a crucial role as enablers of a cleaner and more resilient energy infrastructure [3]. These systems are designed to store electrical energy for later release, effectively bridging the gap between energy supply and demand [4]. The integration of battery energy storage systems into modern power systems is a key enabler of the sustainable energy future However, integrating BESS into the grid is not only a technical challenge but also a complex interplay of economic, regulatory, and market dynamics [5].

By 2030, current battery technologies are expected to be prioritized for the circular economy, with an estimated capacity of 4.7 TWh at a cost of $80/kWh [6]. To replace part of the storage capacity currently provided by fossil fuel reserves and facilitate future time-shifting of energy use, countries will require terawatt-hours (TWhs) of electricity storage [7]. The cost dynamics of BESS are also evolving, with economies of scale and technological advancements driving down the cost per kilowatt-hour, making these systems increasingly cost-competitive [8]. Emerging technologies such as solid-state batteries, flow batteries, and advanced grid-scale storage solutions hold the potential to further enhance energy density, safety, and cost-effectiveness [9]. Energy management systems (EMS) and Battery management systems (BMS) are at the heart of optimizing the performance and safety of BESS. Enhanced battery management systems (BMS) employing artificial intelligence and predictive analytics could significantly improve the reliability and safety of BESS [10]. Additionally, innovative business models, such as energy-as-a-service and virtual power plants, are reshaping the market landscape, providing new opportunities for consumers and businesses to participate in the energy transition [11]. The future of battery energy storage systems is promising, with ongoing research and development aiming to overcome existing limitations and unlock new capabilities [12]. This comprehensive review aims to provide an overview of the classification and understanding of the technological, economic, and regulatory aspects of Battery Energy Storage Systems (BESS), offering insights into their current status, applications, challenges, and future prospects.

2. Categorisation of ESS

Energy can be classified according to a number of criteria, including the form of energy stored, the response time, the duration of storage, and the application [13-15].

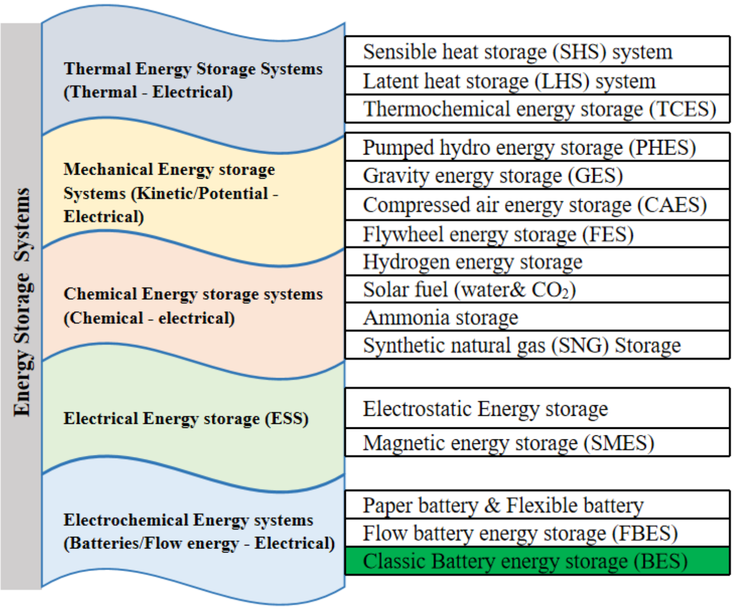

Figure 1. Classification of Energy Storage Technologies.

The categorisation of ESS on the basis of the form of energy stored in the form of thermal, mechanical, chemical, electrochemical, electrical, and magnetic fields, is further classified below.

Thermal Energy Storage Systems: It can be categorized into three distinct types based on the mechanism of energy absorption and release: sensible heat storage, latent heat storage, and thermochemical energy storage [16]. The efficiency of thermal energy storage systems typically ranges from 30% to 50%, depending on the application [13]. TES is employed in a variety of industrial applications, including the recovery of waste heat, manufacturing of materials, mining, metallurgy, and solar thermal energy. Furthermore, thermal storage solutions can be differentiated into low temperature (below 200 °C) and high thermal energy storage systems [17]. The performance of a storage system is primarily determined by the density and specific heat of the substance used, which affect the necessary volume.

Mechanical Energy Storage Systems: The Pumped Hydro Energy Storage stores energy as hydraulic potential energy using an electric pump to elevate water from a lower to a higher reservoir, with energy efficiency of 70-80% ranging with a capacity of 1000-1500 MW [18]. Despite its advantageous long asset life (50-100 years) and low operation costs, finding suitable sites is challenging due to geographical and environmental concerns, making PHES less suitable for modular solutions like BESS [19]. In contrast, Gravity Energy Storage harnesses gravity to store energy by lifting and subsequently dropping masses or pistons. With efficiencies of 75-80% and power outputs of 1-100 MW [20], its large physical footprint limits GES integration with compact systems like BESS. Further Compressed Air Energy Storage stores energy in compressed air with efficiencies of 40-55% (potentially 70% with adiabatic CAES) and power outputs of 50-500 MW [21], requiring substantial infrastructure and specific geological formations, making it less adaptable than BESS for modular and flexible applications. Flywheel Energy Storage System transfers energy via an integrated motor/generator using flywheels, achieving 85-95% efficiency and operating within a power range of 0.1-20 MW [22] but suffers from idling losses; it’s ideal for short-duration, high-power applications, contrasting with the longer-duration suitability of BESS.

Chemical Energy Storage Systems: Hydrogen energy storage systems convert electrical energy to hydrogen via electrolysis or photocatalytic water splitting, comprising a hydrogen generation unit, storage system, and conversion unit like a fuel cell, achieving efficiencies of 30-40% with capacities of 1-100 MW and a lifespan of 20-30 years [23]; BESS is more suitable for long-term than short-term storage. Parallel to hydrogen production, Solar fuel production via artificial photosynthesis, including PEC cells for solar thermochemical and photocatalytic water splitting, has efficiencies of 10-15%, with pilot plants below 10 MW [24] and commercial plants above 10 MW, lasting 15-25 years [25], yet is unsuitable for direct grid storage. Furthermore, Ammonia storage, crucial in chemical operations to prevent leakage and contamination, involves anhydrous ammonia or solution forms with about 30% efficiency, 20-30 years lifespan, and 1-50 MW capacity [15]; while BESS integration can enhance efficiency, it's not ideal for high-efficiency electrical storage. In addition to these technologies, Synthetic Natural Gas storage from coal and biomass involves complex processes like gasification and methanation, achieving 50-60% efficiency, 1-100 MW capacity, and 20-30 years lifespan, stored in various forms or fed into the gas grid [24]; while BESS can aid renewable integration, it's less suitable for short-term applications.

Electrical Energy Storage: Superconducting Magnetic Energy Storage systems utilize a magnetic field generated by direct current flowing through a superconducting coil composed of materials such as niobium-titanium. This system operates at very low temperatures, achieved through a cryogenic cooling mechanism, and is meticulously regulated by a power conditioning system to align with output power requirements during the charge and discharge cycles. Conversely, Electrostatic Energy Storage systems function by storing electric charge between two conductive plates separated by a dielectric, demonstrating a commendable efficiency range of 90-95% and a lifespan of 5-15 years [26]. These systems are particularly adept at providing quick energy bursts and accommodating rapid charge-discharge cycles; however, they are constrained by their energy density, which limits their applicability in long-term storage scenarios. Additionally, supercapacitors represent another category of energy storage, comprising two conductive plates separated by an electrolyte. They enhance energy density through a large specific surface area and are typically employed in applications below 1 MW, with scalability options available. Within this category, electrochemical double-layer capacitors [27] exhibit high power density, while pseudocapacitors offer superior energy density, and hybrid capacitors optimize the balance between energy and power density. With a lifespan of 10-20 years and efficiencies ranging from 85-98%, supercapacitors are particularly well-suited for high-power, rapid-response applications, such as regenerative braking and uninterruptible power supplies [28]. However, their lower energy density relative to batteries renders them less suitable for high-energy, long-duration storage applications.

Electrochemical Energy Systems: The paper batteries use a coated ionic solution and carbon nanotube ink on a paper sheet, with lithium as the anode and aluminum rods facilitating electron transfer, making them suitable for micro to milliwatt-scale applications with a 1-5 year lifespan but not for large-scale or high-power use due to lower energy density [29]. In contrast, Flexible batteries include lithium-ion, thin-film, and printed flexible variants, with efficiencies of 90-95% and a lifespan of 5-15 years [23], ideal for wearable devices and portable applications but less suitable for high-energy, long-term storage. Flow battery energy storage systems have emerged as a transformative solution within the realm of grid-scale applications, Prominent examples of FBES technologies, including vanadium redox, zinc-bromine, and iron-chromium batteries, offer 65-85% efficiency and are suitable for grid-scale applications with 1-100 MW capacity and a 10-20 year lifespan, excelling in long-duration energy storage [30, 31].

Yet, they fall short in high-frequency application scenarios, where rapid response is essential.

Conventional Battery Energy Storage systems comprise both rechargeable and non-rechargeable batteries. Non-rechargeable batteries are generally unsuitable for practical applications due to their single-use limitation. In contrast, rechargeable, or secondary, batteries such as lead-acid, nickel-cadmium, sodium-sulfur, nickel-metal hydride, lithium-ion, and sodium-ion batteries are widely utilized for their ability to undergo multiple charge-discharge cycles.

For Battery Energy Storage Systems (BESS), as shown in Figure 2. Battery cell is the core unit where energy is stored chemically and converted to electrical energy.

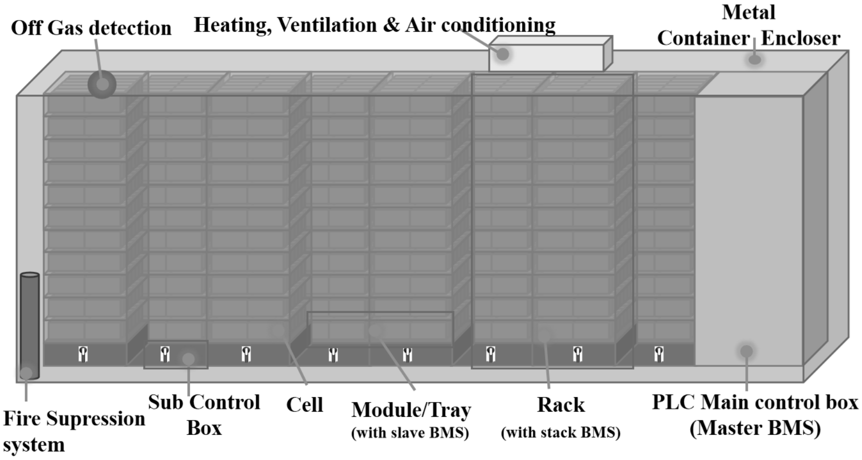

Figure 2. Classification of Energy Storage Technologies.

Predominantly utilizing lithium-ion technology due to its high energy density and declining costs. Further, it can meet energy demands at various scales, from local use, and microgrids to large grids due to its highest specific power and energy, highest power and energy density, highest cell voltage, and highest [32]. Several key components, including the Battery Management System (BMS), Energy Management System (EMS), and Power Conversion System (PCS), are essential for the efficient operation of Battery Energy Storage Systems (BESS). The control architecture of BESS will be further elaborated upon in the following sections.

3. Battery Energy Storage Systems (BESS)

Control Architecture for BESS: Primary control is pivotal for the immediate, local management of the battery system, ensuring safety and operational stability by regulating parameters such as voltage, current, temperature, and state of charge (SoC) at the cell and module levels.

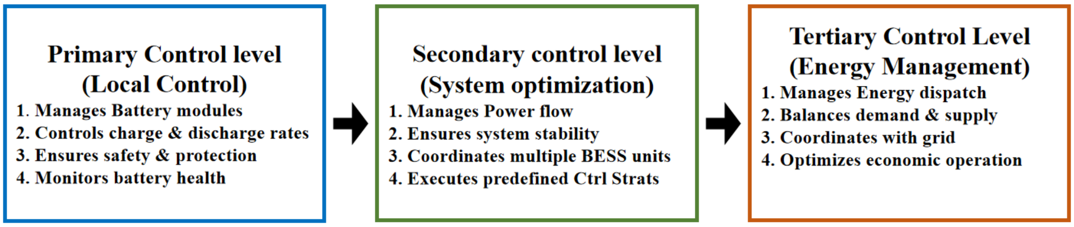

Figure 3. Control Architecture for BESS (Local, system, and EMS level).

Primary Scope: Battery → BMS → Inverter → Grid

This level of control is facilitated by components like the Battery Management System (BMS), which monitors and manages individual cell conditions to prevent issues such as overcharging, over-discharging, and overheating, and the inverter control, which handles DC-AC power conversion and ensures synchronization with the grid.

Moving up to secondary control, this level coordinates multiple BESS units and integrates them with the grid, managing the dispatch of energy based on real-time grid conditions, forecasts, and market signals.

Secondary Scope: Multiple BESS Units → EMS → SCADA → Grid

Key components here include the Energy Management System (EMS), optimizing BESS operations for peak shaving, load leveling, and frequency regulation, and the Supervisory Control and Data Acquisition (SCADA) system, which provides real-time monitoring and control, collecting data from sensors and control units to execute automated control actions.

At the highest level, tertiary control involves the strategic and economic optimization of the BESS over longer time horizons, integrating with grid markets and making high-level decisions to maximize economic benefits and support grid stability.

Tertiary Scope: BESS → Grid integration & markets predictive → Analytics & forecasting → Grid

This includes components like grid integration and market participation, managing interactions with the grid and participating in energy markets for services such as frequency regulation and demand response, and predictive analytics and forecasting, which employs advanced algorithms to predict load demands, renewable generation, and market conditions to optimize BESS operation.

4. Deployment of BESS

BESS are crucial for stabilizing power systems with significant generation variability due to intermittent renewable energy sources like Photovoltaic and wind with the conventional power grid. Considering the current scope of deployment and growth as shown in Figure 4, it covers all the major grid utilization, integration, flexibility, real-time response and supporting grid services.

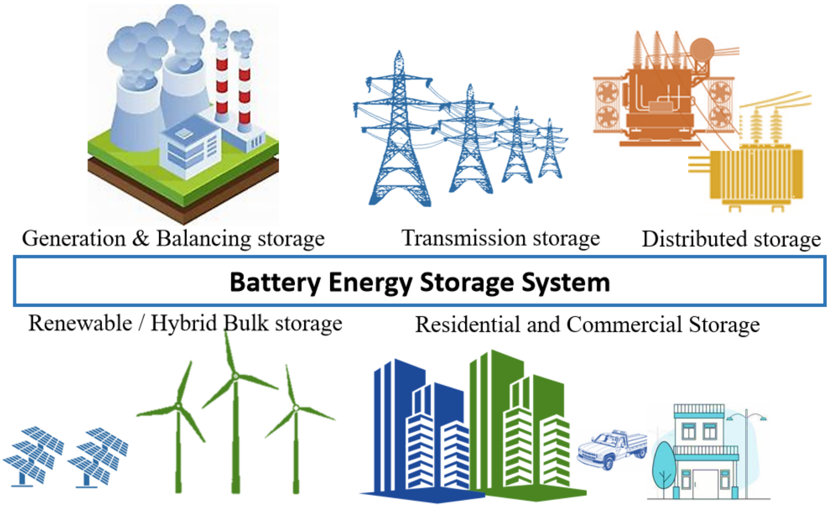

Figure 4. BESS Deployment across the electrical power system.

Standalone Battery Energy Storage Systems (SBESS): Operating independently, SBESS is used for backup power, off-grid supply, and peak shaving. They enhance energy security and reliability, especially in areas with unstable grids, with efficiencies of 85-95% and simplified maintenance. Recent technological advancements have improved their economic viability [4, 33].

Residential Battery Energy Storage Systems (RBESS): Contribute significantly to energy independence and cost savings by capturing surplus energy generated from residential photovoltaic panels or utilizing off-peak grid electricity. Typically, these systems operate within a power range of 5 kW to 20 kW and achieve efficiencies of approximately 85-95% [34]. They predominantly employ lithium-ion batteries, which are favored for their high energy density and extended cycle life. Furthermore, RBESS integrates advanced smart energy management systems and bi-directional inverters, enhancing both efficiency and user experience [35].

Community Energy Storage Systems (CES): CES stores energy from distributed generation sources like community solar farms, providing local energy resilience and grid stability [36]. Typically ranging from 100 kW to 5 MW with 85-95% efficiency, they reduce grid strain during peak periods and integrate advanced monitoring systems and IoT devices to optimize energy distribution [37, 38].

Commercial Battery Energy Storage Systems (CBESS): Specifically designed to optimize energy consumption in commercial buildings by effectively managing demand charges and providing backup power during outages

[39]. These systems achieve efficiencies ranging from 85% to 95% and commonly utilize lithium-ion batteries due to their superior energy density and longevity. Additionally, CBESS seamlessly integrates with building energy management systems and Internet of Things (IoT) devices, enabling real-time data collection and enhancing overall system reliability [40].

Industrial Battery Energy Storage Systems (IBESS): IBESS are engineered to meet the high-power demands typical in industrial settings, providing essential functions such as peak shaving and load leveling. These capabilities not only help improve operational efficiency but also lead to significant cost savings and enhanced productivity. With efficiencies ranging from 80% to 90% [26], IBESS commonly utilizes both lithium-ion and flow batteries. Furthermore, these systems incorporate advanced diagnostics and predictive maintenance tools, which are crucial for ensuring reliability and safety in their operation [41].

Mobile Battery Energy Storage Systems (MBESS): It offers a versatile solution for providing portable energy in temporary and remote applications, such as disaster recovery operations and construction sites [42]. With efficiencies ranging between 80% and 90%, these systems primarily utilize advanced lithium-ion batteries, which are well-known for their performance and reliability. Recent developments in MBESS focus on improving efficiency through modular designs for scalability and implementing real-time monitoring systems to optimize energy management and performance [43].

Aggregated Battery Energy Storage Systems (ABESS): ABESS consolidates multiple distributed battery units into a virtual power plant for enhanced grid flexibility and operational efficiency. They support grid services such as frequency regulation and demand response, employing advanced aggregation algorithms for optimized dispatch and economic benefits [44].

Virtual Energy Storage Systems (VESS): VESS uses software algorithms to manage dispersed energy storage resources, balancing supply and demand without large-scale physical storage. To improve grid reliability and efficiency, VESS relies on software updates and cybersecurity, integrating advanced analytics and AI for optimization [45, 46].

Dual Battery Energy Storage Systems (DBESS): DBESS integrates two battery types to leverage their complementary strengths, optimizing performance and extending battery lifecycle. With advanced control strategies and battery management systems, they ensure efficient operation and reliability [47].

Hybrid Energy Storage Systems (HESS): HESS has developed a system that combines batteries, supercapacitors, and flywheels into a single unit, thereby exploiting the respective advantages of each component to achieve enhanced efficiency. Such systems are well-suited to applications that require a rapid response and an extended discharge period, and which integrate advanced real-time optimization algorithms [48].

Multi Energy Storage Systems (MESS): MESS integrates thermal, mechanical, and chemical systems, and batteries for enhanced adaptability and reliability. Suitable for complex applications in large industrial complexes and microgrids, MESS achieves high efficiency through coordinated operation and advanced control systems [49].

Classification based on integration: Integrated Energy Storage Systems (IESS) are classified into five categories: Centralized Integration, Distributed Integration, Hybrid Integration, Grid-Interactive Integration, and Behind-the-Meter Integration. These classifications categorize how energy storage systems are integrated into larger energy frameworks, reflecting various deployment strategies and operational functionalities within energy networks.

Centralized BESS Integration: Centralized Battery Energy Storage Systems (BESS) are large-scale installations co-located with generation plants or substations, offering grid stabilization and energy arbitrage [40]. They benefit from economies of scale, streamlined maintenance, and centralized control, achieving high efficiency through optimized power conversion and predictive maintenance [50]. An example is a 100 MW centralized BESS in Texas, which provides frequency regulation and reduces dependence on peaking power plants.

Distributed BESS Integration: Distributed BESS is deployed across various sites, enhancing grid resilience and flexibility through decentralized structures [40]. This approach optimizes local energy consumption, minimizes transmission losses, and improves stability, although it poses challenges in coordination and cybersecurity. Maintenance involves managing multiple dispersed units with advanced analytics to ensure efficiency. Distributed BESS supports peak shaving, and demand response services, and reduces costs for consumers and utilities [51].

Hybrid BESS Integration: Hybrid integration is a strategy that unites distributed and centralized battery energy storage (BESS) systems. It does so by capitalizing upon the unique strengths of each approach, thereby enhancing overall flexibility, resilience, and efficiency [40]. Advanced energy management systems dynamically allocate resources, optimizing performance based on real-time conditions. This improves grid stability, reduces energy costs, and supports comprehensive grid services by integrating utility-scale and distributed residential systems [52].

Grid-Interactive BESS Integration: Grid-interactive BESS integrates storage technologies with real-time communication and control capabilities, optimizing operations based on data, market signals, and predictive analytics [40]. They enhance demand response, load flexibility, ancillary services, and grid reliability while achieving high efficiency through optimized power flow and real-time service provision. Maintenance leverages AI-driven algorithms and advanced grid management software for maximal performance and economic benefits [53].

Behind-the-Meter BESS Integration: Behind-the-Meter (BTM) BESS manages energy use directly on the consumer's side of the meter, aiding in cost reduction through peak shaving, load shifting, and enhanced self-consumption of renewable energy [40]. With efficiencies around 85-95%, BTM systems reduce transmission losses and improve interaction with the grid through smart grid technologies and demand response programs. Integration with other smart technologies enhances user experience and system efficiency [54].

4.1 Classification Based on Coupling Method

AC coupling: AC coupled configurations are commonly used for integrating battery storage with existing solar photovoltaic (PV) systems, facilitating easier retrofitting. These systems necessitate an additional inverter to convert solar electricity from AC to DC for battery charging, allowing the BESS to operate independently from the PV system. AC coupling connects the BESS to the AC side of the system via an inverter, enabling straightforward integration with existing AC infrastructure [55]. This method is versatile and suitable for various applications, including residential, commercial, and industrial settings [56]. While AC coupling offers flexibility in system design and expansion, its efficiency is generally lower than DC coupling due to additional conversion losses [57].

DC coupling: DC coupling in Battery Energy Storage Systems (BESS) involves directly connecting the storage system to the DC side of the power system, such as solar PV arrays or DC loads, minimizing conversion losses and enhancing overall system efficiency, particularly for integrating renewable energy sources [58]. Advances like maximum power point tracking (MPPT) for optimizing PV performance and sophisticated battery management systems further improve system efficiency and longevity [59]. This approach is prevalent in new solar PV plus battery installations, where direct charging from solar panels to batteries enhances performance and reduces energy losses, where DC coupling effectively integrates solar energy with efficient BESS solutions [60].

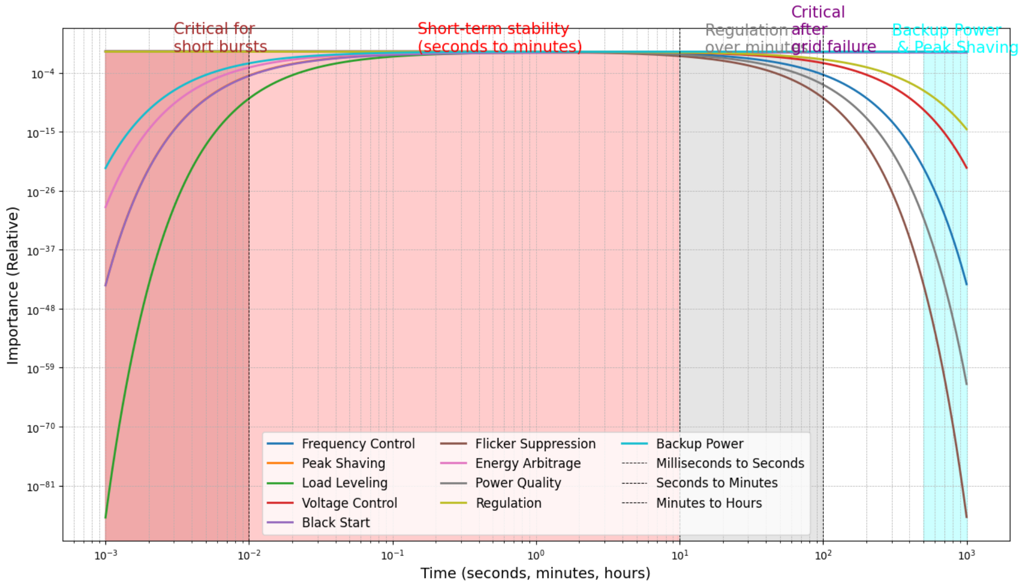

Figure 5. Time-dependent Importance of BESS Applications in Grid Operations.

Backup power solution: BESS for Backup Power provides backup power by instantly supplying energy during grid failures, ensuring uninterrupted operations for critical infrastructure [61]. Backup power BESS is typically designed with a robust Battery Management System (BMS) that can switch seamlessly from grid power to battery power within milliseconds. By storing excess energy generated during periods of high production and low demand, BESS ensures a steady energy supply [62]. In residential and commercial applications, BESS configurations are often used to provide power during outages, leading to increased energy security and reliability [63]. Industries with critical processes, like manufacturing and data centers, rely on BESS to prevent costly downtime and equipment damage during power interruptions [64]. In microgrid applications, BESS plays a crucial role by balancing loads and ensuring consistent power supply during islanded operations. This is particularly beneficial for remote areas that are not connected to the main grid [65].

Frequency control: When there is a sudden imbalance between electricity supply and demand, the system frequency can deviate, BESS can quickly inject power into the grid (if frequency drops) or absorb power (if frequency rises) to counteract these deviations. This rapid response helps to stabilize the frequency almost instantaneously, maintaining it within acceptable limits [66]. Once the primary control actions stabilize the frequency, secondary control mechanisms act to restore the frequency to its nominal value. BESS can participate in this process as well by adjusting their charge and discharge cycles over a longer timescale compared to primary control [67]. BESS can both generate and absorb energy, providing flexibility in frequency management, and holding a bidirectional capability [68] further by smoothing out frequency variations caused by intermittent renewable sources like solar and wind, BESS aids in the integration of more renewables into the grid [69].

Peak Shaving: Peak shaving is an important power system management strategy that aims to reduce electricity demand at times when network capacity is stressed. This technique is essential for deferring investments in network expansion or reinforcement and allows utilities to meet demand without relying on expensive peaking generators, promoting long-term savings and efficiency [70]. BESS is particularly effective for peak shaving because it stores energy during off-peak, low-cost periods and discharges it during high-demand, high-cost periods, relieving pressure on the grid and significantly reducing energy costs [67]. The technical implementation of BESS for peak shaving involves sophisticated load management and control strategies. BESS systems discharge stored energy during peak demand periods, effectively reducing the load on the grid [71]. Advanced algorithms and predictive analytics within the BMS optimize discharge schedules, ensuring financial benefits and operational efficiency [72]. The use of BESS represents a forward-looking, technologically advanced approach to managing peak demand, ultimately contributing to a more sustainable and resilient energy grid [73].

Load leveling: One way to achieve grid stability and efficiency is through load leveling, which involves distributing electrical demand more evenly throughout the day. This can help reduce the strain on the grid during peak load periods and prevent blackouts. By smoothing out the demand curve, load leveling can also improve the integration of renewable energy sources, such as solar and wind power, into the grid, maximizing their potential contribution to the overall energy mix [74]. Energy storage systems can also help reduce peak demand charges for utilities by providing stored energy during peak times. Integrating smart grid technologies can further enhance grid efficiency and optimize power flow through automatic monitoring and control. Implementing energy management strategies can also help grid operators improve load leveling and balance energy supply and demand more effectively. By utilizing advanced forecasting techniques, operators can better anticipate fluctuations in energy demand and adjust energy generation accordingly [74].

Voltage control: Voltage control is crucial for maintaining the power quality and stability of an electrical grid. Voltage deviations can cause inefficient operation of equipment and may even lead to equipment damage or grid instability [75]. BESS can provide both active power and reactive power support, which are essential for voltage regulation. BESS can provide reactive power to help maintain voltage levels within desired limits, especially during peak demand periods or when there are significant inductive loads [76]. During instances of voltage sags or surges, BESS can inject or absorb active power to stabilize the voltage [77].

Black start: Black start capability refers to the ability to restart a power station or a power grid without relying on the external electric power system. A review of the causes of blackouts revealed that a majority of them (69%) resulted from suboptimal protection and operational strategies. Over-demand and vehicle accidents were identified as the primary contributors in 18% and 7% of cases, respectively. Additionally, animal-related incidents and adverse weather conditions were found to be responsible for 6% of blackouts [78]. In order to achieve full power discharge in any state with a large area of active power shortage, emergency energy storage requires a millisecond-level quick response. BESS can provide the necessary power to restart generators and restore the grid following a blackout. BESS can immediately supply the necessary power to control systems and auxiliary equipment needed to restart conventional power plants [79]. Once the initial critical sections are powered, BESS can assist in gradually re-energizing other parts of the grid, ensuring a stable and controlled restoration process [80].

Flicker Suppression: A voltage flicker is a rapid and repeated change in the voltage magnitude that can cause light flicker and other disturbances in electrical equipment. This phenomenon is often caused by fluctuating loads such as industrial motors or wind turbines. BESS can mitigate flicker by quickly responding to these rapid voltage changes. BESS can rapidly inject or absorb power to smooth out these fluctuations, thereby reducing the impact of flicker [81]. For systems with high penetration of renewable like wind and solar, BESS can stabilize the output, minimizing the flicker caused by their intermittency [82]. Dynamic Response: BESS systems detect voltage deviations and rapidly inject or absorb power to counteract flicker. Smoothing Algorithms: Employ sophisticated algorithms to predict and mitigate flicker events in real time [83]. BESS ensures a stable and reliable power supply, minimizing disturbances caused by voltage flicker, and reducing flicker by up to 80% in comparison to traditional methods [83].

Energy arbitrage: Energy arbitrage with battery energy storage systems (BESS) involves storing energy when prices are low and discharging it during high-price periods to capitalize on price differentials [84]. Advanced Energy Management Systems (EMS) that optimize charging and discharging cycles via predictive algorithms [85]. This approach generates revenue by leveraging market volatility, with studies highlighting significant annual earnings and the potential for demand charge reduction, particularly in commercial settings where demand charges can comprise 30-70% of electricity bills [86]. However, the sustainability and efficiency of BESS in energy arbitrage require careful management of technical, economic, and regulatory factors.

Power quality: Power quality refers to the presence of harmonic signals in bus voltages and load currents, spikes, momentary low voltages, and other issues of distortion that can impact the performance of some sensitive pieces of equipment. Additionally, this could cause instability in transmission lines and result in loss of work output. For instance, in industrial firms, transient fluctuations in power can cause disruption in production processes. In order to mitigate the effects of power fluctuations, an electrical storage system can also be used.

Regulation: A deviation of the frequency from the normal designed frequency in the power plant can damage equipment. A rapid drop in the frequency could also cause tripping of generating units, shedding of loads, or even lead to a system collapse. This imbalance between generation and load can be reduced by using energy storage systems since the stored energy would be used to make up for a sudden reduction in supply. Frequency support requires power to be delivered for a very short duration. Many energy storage systems have characteristics that make them suitable for both regulation and power quality applications [87].

5. Conclusion

Battery Energy Storage Systems (BESS) are increasingly central to modern power systems, offering a range of solutions from grid stabilization and renewable energy integration to frequency regulation and peak shaving. As advancements in battery technologies, particularly lithium-ion systems, continue to drive down costs and enhance performance, the deployment of BESS is expanding across residential, commercial, and industrial sectors. This review has highlighted the broad applicability of BESS, demonstrating its role in enhancing grid flexibility and supporting energy transitions. However, the continued evolution of the sector will depend on further technological innovations, regulatory support, and economic incentives. The development of scalable solutions and the optimization of energy storage systems will be critical in addressing the growing energy demands and variability posed by renewable energy sources.

In summary, BESS represents a crucial component of the future energy landscape, enabling a cleaner, more resilient, and sustainable power grid. Continued research and development, alongside strategic investments, will be key to unlocking the full potential of these systems.

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