Review of Battery Energy Storage Systems: Challenges, Strategies and Applications

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***Abstract*—The rapid advancement and adoption of Battery Energy Storage Systems (BESS) have emphasized the importance of understanding their essential terms and concepts, along with the integration topologies that optimize their use. This technical paper examines the role of comprehensive energy management, Battery Management Systems (BMS), and power conversion systems in the effective deployment of BESS. Discussing the critical control architectures, we explore different charging and discharging techniques, and the control and monitoring systems employed to ensure efficient operation. The paper delves into the techno-commercial factors, addressing market analysis and cost considerations, applications of BESS in power systems. Emphasis is placed on the challenges and limitations in BESS deployment, strategies for performance optimization, and safety measures. The insights provided contribute to enhancing the understanding of BESS, fostering more resilient and efficient energy storage solutions across diverse scenarios.**

***Keywords*—Battery Energy Storage System (BESS), Battery Management Systems (BMS), power conversion System, challenges and strategies**

I. INTRODUCTION

The escalating urgency to mitigate carbon emissions and achieve net-zero targets has intensified the global search for sustainable energy solutions [1]. To meet these ambitious targets, a transformative shift towards renewable energy sources like solar and wind has emerged as essential alternatives to fossil fuels. The electric transformation is driven, in part, by the substantial growth in global wind and solar power generation capacity, the International Renewable Energy Agency (IRENA) reported that at the end of 2022, the global renewable generation capacity amounted to 3,372 Gigawatts (GW), with solar and wind power being the largest contributors [2]. The global acceleration in 2023 is primarily fueled by the substantial year-on-year growth in China's booming solar photovoltaic sector which saw growth rates exceeding 100% and wind capacity, surpassing 50% growth in the market share. By 2028, renewable energy sources are projected to account for 42% of global electricity generation, with wind and solar photovoltaic (PV) contributing 25% of this total [3]. This growth is driven by lower generation costs compared to both fossil and non-fossil alternatives in most countries, along with ongoing policy support. In this context, Battery-Based Energy Storage Systems (BESS) emerge as a critical enabler for a cleaner and more resilient power infrastructure [3]. Battery-based energy storage systems are designed to store electrical energy and release it when required, thereby bridging the gap between energy supply and demand [4]. However, the integration of BESS into the electricity grid is not just a technical challenge; it involves a complex interplay of economic, regulatory, and market factors [5]. The objective is to achieve zero emissions by 2050, with an estimated 10–13 TWh reaching 100% renewable energy use for cell production and recycling [6]. 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 [7]. The future of BESS is promising, with ongoing research and development aiming to overcome existing limitations and unlock new capabilities [8]

BESS plays a crucial role in addressing the operational and computational challenges presented by the increasing integration of renewable energy into global power grids. The importance of battery development cannot be overstated, as advancements in this area are crucial for facilitating the transition to cleaner and more sustainable energy systems. Moreover, the increasing interest in BESS has drawn professionals from diverse fields such as engineering, environmental science, economics, and policy-making. This interdisciplinary collaboration enhances our collective understanding of the technology, allowing stakeholders to play a pivotal role in advancing energy storage solutions since it bridges the gap between power generation and utilization across various sources and applications. By highlighting these areas, this review paper aims to provide readers with a comprehensive understanding of the evolving field.

II. LITERATURE REVIEW

Energy can be classified according to several criteria, including the form of energy stored, the response time, the duration of storage, and the application [9]. ESS is categorized [10] according to the various forms of energy stored, such as thermal (Sensible heat storage system, Latent heat storage system, Thermochemical energy storage), mechanical (Pumped hydro energy storage, Gravity energy storage, Compressed air energy storage (Adiabatic/diabatic), Flywheel energy storage), chemical (Hydrogen energy storage, Solar fuel (water & CO_2), Ammonia storage, Synthetic Natural Gas (SNG) Storage), electrical (Electrostatic Energy Storage, and Magnetic Energy Storage (SMES)), electrochemical (Paper battery & Flexible battery, Flow battery energy storage, Classic Battery energy storage). This paper will exclusively examine battery-based energy

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storage systems as shown in the Fig. 1, providing a comprehensive analysis of their characteristics, functionalities, and applications

Classic Battery Energy Storage includes non-rechargeable primary batteries [11] like zinc-carbon, alkaline, and lithium primary cells, and rechargeable secondary batteries [12] like lead-acid are cost effective, they pose environmental concerns; nickel-cadmium offer, sodium-sulfur, and nickel-metal hydride batteries [13]. Lithium and Sodium -ion batteries represent a significant advancement in energy storage technology, largely due to their high efficiency, adaptability and scalability [14]. Furthermore, the suitability assessment is based on technology characteristics in terms of system size, discharge duration and response time, with the exception of seasonal storage, where lithium battery technology is more suitable for most of the grid application segments [15].

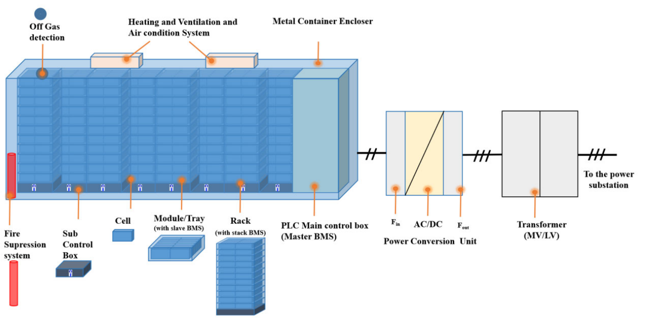

Fig. 1. Components of a BESS.

A Battery Management System (BMS) is an integral component of a BESS, connected to the battery cells and modules in many layers through a network of sensors and control units to ensuring the safe and efficient operation. It acts as primary control is pivotal for the immediate, local management of the battery system, ensuring safety and operational stability. These sensors monitor various parameters such as voltage, current, temperature, and State of Charge (SoC) of individual cells and the entire battery pack [16]. The BMS communicates with the BESS's central controller to provide real-time data and enable precise management of the energy storage process.

[Battery Module] -- [Battery Module]... --[Rack-Level BMS]

[Rack-Level BMS] → [Central BMS Controller] → [Master Controller] → [SCADA]

The rack-level BMS units communicate with the central BMS, providing detailed information on the status of each module and the overall rack. This data is used for monitoring, control, and optimization of the BESS [17]. The BMS must be capable of interfacing with various communication protocols and standards to ensure seamless operation within the broader energy network [18]. These features prolong the life of the batteries in BESS, reducing the frequency of replacements and lowering overall operational costs [19].

The Power Conversion System (PCS) is a critical component of BESS, responsible for converting electrical energy between the battery and the grid. The PCS is connected to the BESS via bidirectional inverters, which allow for both the charging and discharging of the battery, effectively managing the flow of energy in and out of the system [20].

[Battery Module] → [Inverter] → [Transformer] → [Switchgear] → [Grid]

The PCS ensures this conversion (AC/DC) happens efficiently, minimizing energy losses and maintaining power quality [21]. PCS systems are equipped with advanced filtering techniques and rapid-response control algorithms to minimize harmonic distortion and ensure a stable sinusoidal output [22]. There are various topologies of PCS used in BESS, each with its own advantages and applications: Single-Stage PCS: Single-stage PCS topology integrates the inverter and DC-DC converter into a single conversion stage [23]. Two-Stage PCS: The first stage involves a DC-DC converter that manages the battery voltage, while the second stage involves a DC-AC inverter that interfaces with the grid [24]. And a modular PCS consists of multiple smaller PCS units operating in parallel. Each module can independently convert power between the battery and the grid [25].

The architecture of an EMS encompasses a broad spectrum of functionalities, including data acquisition, state estimation, control strategy implementation, and user interface provisions [26]. At its core, the EMS is underpinned by advanced algorithms that facilitate real-time decision-making, predictive analytics, and adaptive control [27] as mentioned in the Fig. 2.

Communication protocols form an integral part of the EMS, enabling seamless interaction with Distributed Energy Resources (DERs) and grid operators [28]. Furthermore, the incorporation of machine learning and artificial intelligence techniques has paved the way for the development of fully autonomous EMS capable of predictive maintenance, fault detection, and dynamic optimization [29]. The performance and reliability of BESS are dependent on the efficacy of the EMS [30].

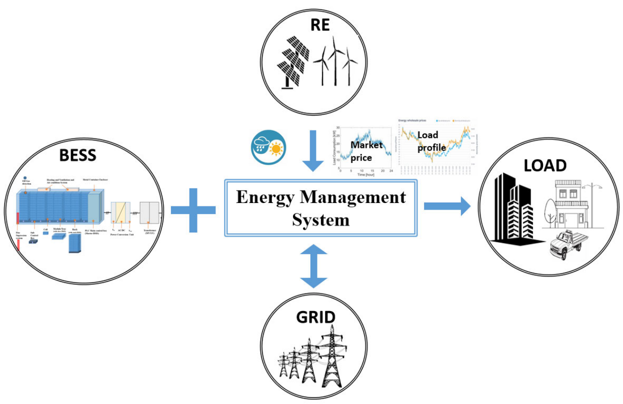

Fig. 2. Schematic of an energy management system for BESS.

[Central BMS Controller] → [Master Controller] → [SCADA System] → [Cloud Platform]

Furthermore, the effective reduction of peak demand and the balancing of load levels enabled by the EMS can result in significant cost savings for utility operators, as it may obviate the necessity for infrastructure upgrades [31]. Another significant concern is cybersecurity, it is imperative that future research prioritize the advancement of cybersecurity protocols in order to safeguard EMS against potential threats [32].

III. BESS Deployment and Market Analysis

Considering the current scope of deployment and growth as shown in the Fig. 3, it requires a robust framework of standardized regulations to ensure safety and interoperability [9].

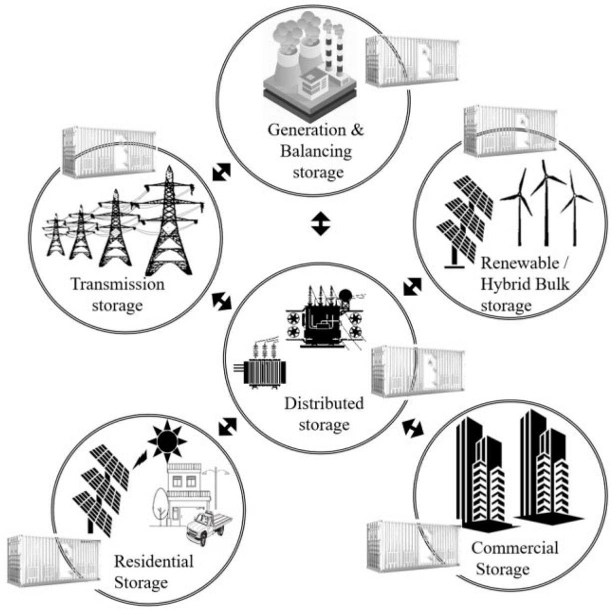

Fig. 3. BESS deployment across the electrical power system.

The commonly available deployment across the electrical power system [5, 10, 15] as Standalone Battery Energy Storage System, Residential Battery Energy Storage System, Community Energy Storage, Commercial Battery Energy Storage System, Industrial Battery Energy Storage System, Mobile Battery Energy Storage System, Aggregated Battery Energy Storage System, Virtual Energy Storage System, Dual Battery Energy Storage System, Hybrid Energy Storage System, Multi Energy Storage System, Based on integration [24] (Centralized BESS Integration, Distributed BESS Integration, Hybrid BESS Integration, Grid Interactive BESS Integration, Behind-the-Meter BESS Integration), Coupling method [21] (DC-Coupled, AC-Coupled, based on Load profile [20] (Peak Shaving, Load Leveling, Backup Power, Frequency Regulation, Black Start Capability, Voltage Control, Flicker Suppression, Energy arbitrage, Power quality, Regulation. Modernizing the grid to integrate BESS involves hardware and software upgrades. Additionally, economic incentives and continuous research are essential for driving innovation and improving the efficiency and affordability of the BESS systems.

Techno-Commercial: The Levelized Cost of Storage (LCOS) quantifies the discounted cost per unit of discharged electricity for a specific storage technology and application [33]. The LCOS incorporates all elements required to determine the full lifetime cost of an electricity storage technology: investment, Operation and Maintenance (O&M), charging, and end-of-life cost divided by electricity discharged during the investment period [33]. It assumes all investment costs are incurred in the first year and sums ongoing costs in each year (n) up to the system lifetime (N), discounted by the discount rate (r). LCOS provides an all-encompassing cost per unit measure, critical for assessing long-term economic viability. Similarly Annuitized Capacity Cost (ACC) divides all costs incurred during the lifetime of a storage system by its power capacity and lifetime (USD/kW-year). ACC helps to annualize the capital cost for easier comparison and financial planning [33].

According to BloombergNEF, the average cost of lithium-ion battery packs fell to around $137/kWh in 2020, and projections indicate it could reach approximately $100/kWh by 2024. By 2030, current battery technologies are projected to be prioritized within the circular economy, with an anticipated capacity of 4.7 TWh at a cost of $80 per kilowatt-hour [34]. The cost of PCS is typically measured in dollars per kilowatt ($/kW). As of recent market data, the cost of PCS for lithium-ion BESS ranges from $150/kW to $250/kW, depending on the system's size and specific requirements. This cost includes the inverter, transformer, control systems, and necessary protections. The battery price is a significant portion of the total ESS cost. It is typically measured in dollars per kilowatt-hour ($/kWh). The cost of enclosures is typically measured in dollars per kilowatt ($/kW) and the price for enclosures for lithium-ion BESS ranges from $50/kW to $100/kW. Battery technologies exhibit the highest probability of the lowest LCOS in most applications beyond 2025. Projecting future LCOS based on investment cost reductions indicates that lithium-ion batteries become cost-competitive for low discharge duration applications [33].

List of Li-Ion BESS projects executed by around the world Installed and Costs: Moss Landing Battery Storage, California, USA-$500 million [35], Hornsdale Power Reserve, South Australia-$116 million [36], Hokkaido Battery Storage, Hokkaido, Japan-$278 million [37], Manatee Energy Storage Center, Florida, USA-$350 million [38], Victorian Big Battery, Victoria, Australia-$104 million [39], Abu Dhabi Al Dhafra Solar Project, Abu Dhabi, UAE-$150 million[40], Ravenswood Battery Project, New York, USA-$1.5 billion [41], Bungama Battery, Bungama, South Australia-$163 million [42], CEP Energy-Kurri Kurri Battery Energy Storage, Kurri Kurri, NSW, AUS-$1.57 billion [43], Morro Bay BESS, Morro Bay, California, USA-$1 billion [44], Sunnica Solar-plus-BESS, Suffolk and Cambridgeshire, UK-$750 million [45], Liddell Battery, Liddell, NSW, AUS-$114 million [46], Gnarwarre Battery, Gnarwarre, Victoria, AUS-$114 million[47], Hopeland Battery, Hopeland, Queensland, AUS-$114 million [48], Blyth Battery, Blyth, South Australia, AUS-$114 million [49], Mortlake Battery, Mortlake, Victoria, AUS-$114 million [50], Mount Fox Battery, Mount Fox, Queensland, AUS-$114 million [51], Pilbara Generation Project BESS, Pilbara, Western Australia-$163 million [52], Fredericia Energy Island Project, Denmark-$108 million [53], Svevind's Markbygden 1101 Project, Sweden-$216 million [54], Baltic Battery Storage Project, Estonia-$54 million [55], Wallonia BESS, Belgium-$32 million [56], and Slate Project, California, USA-$500 million [57]

IV. Challenges and Strategies

BESS are increasingly recognized for their pivotal role in stabilizing power grids and supporting renewable energy integration. However, several challenges and limitations hinder their widespread adoption.

A. Policy and Incentives

A significant strides in BESS development through various policies and initiatives aimed at enhancing renewable energy integration and grid stability. Asia's ESS development is driven by Japan and China's strategic energy plans and supportive policies, focusing on market development, grid management, and financial assistance to achieve clean energy targets. The Asian Development Bank (ADB) has raised $600 million through a 7-year green bond to finance climate change mitigation and adaptation projects [58]. By 2030, annual BESS market installation will hit 110 GW, 58% of which will be developed in Asia with a Projected 60 plus GWh of BESS installations across Asia by 2030 [59]. In the United States, policies to promote ESS through investments, tax incentives, and subsidies. Notable initiatives include the American Energy Innovation Act, the Farm Bill, and various state-level mandates like California's Bill AB2514 and New Jersey's A3723. Europe's approach to ESS involves EU-wide support for clean energy generation, with countries like Germany offering low-interest loans for ESS through the KfW Bank. However, barriers exist in countries like the Netherlands and Italy due to a lack of specific ESS policies. The Australian Renewable Energy Agency (ARENA) has been instrumental in funding and supporting BESS projects [60]. The Australian Capital Territory's goal of achieving 100% renewable energy by 2025 relies heavily on battery ESS, supported by programs like Next Generation Renewables and the Renewable Energy Industry Development Strategy [61].

B. Environmental Challenges

The production and disposal of batteries involve hazardous materials that can lead to soil and water contamination. Improper recycling of degraded batteries, which contain toxic chemicals, can result in severe environmental concerns [62]. The mining of raw materials such as lithium, cobalt, and nickel also has significant environmental and social impacts, including soil degradation and water resource depletion. Ethical sourcing and the development of sustainable practices for battery production, recycling, and disposal are crucial to minimize these impacts [63]. According to a study by the National Renewable Energy Laboratory (NREL), the annual degradation rate for lithium-ion batteries ranges from 0.5% to 2% per year, depending on operating conditions. Accurate degradation modeling can significantly impact the total cost of ownership by optimizing the usage and extending the battery life [64]. Developing sustainable and environmentally friendly battery technologies, along with appropriate recycling facilities provided by manufacturers, is essential for reducing the environmental footprint of BESS [65]. Recycling facilities must comply with local and international regulations such as EU Directive 2006/66/EC on batteries and accumulators, ensuring proper disposal and recycling of BESS components to minimize waste generation and maximize resource recovery [66].

C. Cycling Performance of BESS

Typical lithium-ion batteries have a cycle life of 5,000–10,000 cycles, equating to roughly 10–15 years of operational life [67]. Additionally, optimizing the charging and discharging processes is essential to improve battery longevity and operational efficiency. Battery lifetime, measured as calendric and cyclic degradation, reflects the total number of cycles a battery can sustain, with calendric degradation based on temperature and voltage, and cyclic degradation dependent on the charging/discharging rate [68]. Thermal management is critical for optimizing operational conditions, as extreme temperatures can adversely affect performance and accelerate degradation. Smart control algorithms are essential for regulating ambient conditions and improving battery health [69]. Effective Battery Management Systems (BMS) are crucial for monitoring these variables, employing adaptive algorithms and data-driven techniques for accurate assessments [70]. Comprehensive modeling ensures reliable power supply and effective integration of BESS, characterized by fast charging, slow discharging, and delayed degradation to maximize lifespan [63].

D. Lack of Regulatory Barriers to Clarify the Role of BESS

The deployment and operation of BESS face significant challenges due to the lack of clear regulatory frameworks, which hinders their ability to provide multiple grid ancillary services [71]. Network providers and market operators may hesitate to deploy BESS for these services in the absence of explicit regulations, legislation, or guidelines that authorize such use, given in Table 1 [72]. Additionally, without assurances of reimbursement for BESS projects dedicated to ancillary services, storage owners and system operators may be reluctant to make the necessary capital investments [73]. The lack of consistent regulatory support further complicates the landscape, as some regions do not have supportive policies, and fluctuations in raw material prices can affect project attractiveness [74]. The regulatory environment governing BESS is often fragmented and unclear, posing barriers to their deployment and operation. Clear regulations defining the ownership, operation, and market participation of BESS are essential to provide certainty to investors and operators [75]. Policies must address grid interconnection standards, market access, and revenue models to create a conducive environment for BESS adoption [7].

E. Safety

Securing the grid system is a key priority for the government to support national economic growth and social stability [76]. Deploying early warning systems like smoke detectors, thermal imaging cameras, and gas detection sensors can significantly reduce fire-related damages [77]. In the event of an accident involving BESS, prompt response protocols are crucial to mitigate potential risks to personnel and the environment. Rapid deployment of fire suppression systems, such as dry chemical agents or water mist, is essential to contain thermal runaway events [78]. Advanced fire suppression systems, such as clean agents (e.g., FM-200, Novec 1230) and inert gases (e.g., IG-541), are designed to rapidly extinguish fires without damaging sensitive electronic equipment [79]. The use of thermal barriers and insulation materials helps prevent the spread of heat and flame between battery cells [80]. Over 100 BESS facilities worldwide incorporate automated fire suppression systems to enhance safety [81] but the cause of the fire remains unknown in most of the cases. A fire incident occurred at a 30 MW/120 MWh Battery Energy Storage System (BESS) facility in Escondido, California [82] and in another incident, on July 20, 2024, a fire spread rapidly at a photovoltaic plant in Trebach, Althofen, with a total capacity of 7.3 MWp, due to the heat and dry vegetation surrounding the solar farm [83].

Table 1. Recommended standards/regulations/govt policies [84, 85]

Energy Storage System Components	UL 489/810A/1642/1741/1973
Energy Storage System Type	IEC 62897/62932-2-2; IEEE 519/1547; NFPA 791- 2014; UL 9540
Energy Storage Installation	UN 38.3; IEC 62281/61850; NFPA 1/13/15/101/790/850/851/ 5000
Energy Storage Operations & Maintenance	NFPA 70B/400
Energy Storage Commissioning	NFPA 3; ICCC1000
Incident Preparedness	NFPA 50/704/921/1001/1006/1500; IEEE979

F. Monitoring and Control Systems in BESS Using Digital Twin and AI Approach

Fuzzy Logic Control (FLC) and Model Predictive Control (MPC) have emerged as two pivotal methods for effective management of complex and nonlinear systems has led to the development of sophisticated control strategies. Fuzzy Logic Control (FLC) and Model Predictive Control (MPC) FLC is composed by a knowledge base where its parameters can be determined without an exact model of the system favorable for complex nonlinear systems or even non-analytic ones [86]. Model Predictive Control (MPC) is a control method which provides the sequence of optimal control variables over a finite time horizon by solving an optimization problem [86]. Digital twin technology, allowing real-time monitoring and simulation of operational behaviors [87]. Each component within the BESS, from individual modules to the entire system, was replicated as a digital twin. These virtual models were continuously updated with real-time operational data, providing a dynamic simulation of the physical system's behavior. AI algorithms, integrated into the digital twins, processed vast amounts of data to optimize charging and discharging schedules based on grid demand patterns, weather forecasts, and historical operational data [88]. This approach enable to achieve precise control over BESS operations, ensuring efficient energy storage and distribution [89].

G. Performance Enhancement Strategies and Efficiency Optimization Techniques

BESS achieves enhanced frequency response by utilizing fast-response control algorithms within the Battery Management System (BMS). These algorithms enable rapid adjustments in charge and discharge rates to stabilize grid frequency within milliseconds [90]. Frequency containment reserve involves pre-programmed responses to grid frequency deviations, ensuring grid stability during sudden load changes or disruptions [91]. Efficiency is optimized through precise energy forecasting and real-time monitoring of grid conditions [92]. By accurately predicting frequency variations, BESS minimizes energy losses and maximizes response accuracy. Advanced power electronics and optimized cycling algorithms also contribute to maintaining high round-trip efficiency during frequent charge-discharge cycles [93].

Frequency Restoration Reserve: BESS provides frequency restoration reserve by quickly injecting stored energy into the grid following major disturbances like generator or transmission line failures. This rapid response stabilizes frequency deviations and restores grid integrity, preventing cascading outages and ensuring system reliability [94]. Efficiency in frequency restoration is optimized through automated grid monitoring and response systems. BESS integrates with grid management software to detect frequency anomalies and dispatch stored energy instantly [95]. Dynamic charge-discharge control algorithms adjust energy flow rates to minimize losses and maximize response speed, thereby enhancing overall grid resilience [96].

Energy Shifting: Energy shifting optimizes BESS by storing surplus energy during off-peak periods and discharging it during peak demand hours. This strategy helps in reducing electricity costs for consumers and supports grid stability by balancing supply and demand fluctuations [63] Efficiency in energy shifting is achieved through optimal charge and discharge scheduling based on energy price forecasts and demand patterns. BESS utilizes advanced forecasting models and predictive analytics to determine optimal charging times and discharge strategies [91]. EMS ensure seamless integration with grid operations, optimizing energy utilization and minimizing peak-time electricity purchases [91]

Load Leveling: Load leveling involves smoothing out fluctuations in electricity demand by storing excess energy during periods of low demand and releasing it during peak hours. BESS stabilizes grid load profiles, reducing strain on generation plants and improving overall grid reliability [31]. Efficiency in load leveling is optimized through precise load forecasting and real-time demand response capabilities. BESS employs sophisticated EMS and BMS algorithms to forecast load variations and adjust energy dispatch accordingly [93]. By reducing peak demand spikes, BESS enhances grid efficiency and reduces operational costs associated with peak generation [97].

Self-Consumption (Residential & Small Commercial) and Time-of-Use Management: In residential and small commercial settings, BESS enhances self-consumption of solar energy by storing surplus solar power for later use. Time-of-use management aligns energy consumption with tariff structures, optimizing energy savings and grid interaction [98]. Efficiency in self-consumption and time-of-use management is achieved through intelligent charge-discharge scheduling and integration with smart grid technologies. BESS utilizes AI-based algorithms to predict energy generation and consumption patterns, ensuring maximum utilization of self-generated solar energy [99].

Community Storage and Village Electrification: Community storage solutions utilize BESS to enhance microgrid stability and support localized energy independence. BESS integrates renewable energy sources and provides reliable power supply to communities, reducing dependency on centralized grids [63]. Efficiency in community storage and village electrification is optimized through scalable BESS configurations and adaptive control strategies. AI-driven energy management platforms optimize energy dispatch, ensuring continuous and reliable electricity supply while maximizing renewable energy utilization [100].

Increase of Power Quality: BESS improves power quality by mitigating voltage fluctuations, reducing harmonics, and enhancing grid stability. It provides reactive power support and voltage regulation, ensuring consistent and reliable electricity supply for sensitive industrial processes and electronic equipment [101].

Efficiency in power quality enhancement is achieved through real-time monitoring of grid conditions and dynamic response capabilities. BESS integrates with grid voltage control systems to provide fast and accurate voltage support [93]. Advanced control algorithms optimize reactive power injection and voltage regulation, minimizing energy losses and enhancing overall grid performance [102].

Peak Shaving: Peak shaving involves reducing peak electricity demand through BESS by deploying stored energy during periods of high demand. This strategy reduces utility costs and supports grid stability by reducing peak load requirements. Efficiency in peak shaving is optimized through predictive load forecasting and demand response strategies. BESS systems use historical data and AI-based analytics to forecast peak demand periods accurately [103]. Automated charge-discharge management adjusts energy dispatch to coincide with peak load events, minimizing electricity purchases at peak rates and optimizing cost savings [104].

Nano- and Off-Grid Applications: In nano-grid and off-grid applications, BESS serves as a primary or backup power source, ensuring reliable electricity supply in remote areas or during grid outages. It integrates with renewable energy sources to support energy independence and sustainability goals [90] Efficiency in nano-grid and off-grid applications is optimized through hybrid renewable energy-BESS systems and intelligent energy management solutions. BESS systems employ autonomous operation modes and remote monitoring capabilities to maximize energy storage efficiency and minimize reliance on fossil fuels [105]. Real-time data analytics optimize energy dispatch and resource allocation, ensuring continuous and stable power supply in isolated environments [106].

Island Electrification: BESS facilitates island electrification by integrating renewable energy sources and stabilizing microgrid operations. It supports energy independence, reduces reliance on imported fuels, and enhances grid resilience against climatic disruptions [105]. Efficiency in island electrification is optimized through robust BESS configurations and grid integration strategies. BESS systems are designed with scalable capacity and modular flexibility to meet varying island energy demands [107]. AI-driven optimization algorithms monitor and control energy flows, maximizing renewable energy utilization and minimizing diesel generator operation. Real-time monitoring and predictive maintenance ensure high system reliability and efficiency, contributing to sustainable island electrification [106].

Solid-state batteries are poised to be the next significant advancement in energy storage technology, offering improved safety, energy density, and longevity compared to traditional lithium-ion batteries. There is a critical need for research and development of advanced control strategies to effectively coordinate BESS with distributed Renewable Energy Sources (RESs) for rapid and efficient ancillary support, which requires detailed analysis of BESS dynamics to assess battery degradation, converters, inverters, filters, and transformers to ensure optimal performance and reliability, while leveraging artificial intelligence, IoT, big data, and cybersecurity measures to provide robust, reliable, and intelligent scheduling solutions, thereby enhancing overall system efficiency and security

V. Conclusion

In conclusion, this review paper offers a comprehensive exploration of BESS, highlighting their critical role and potential within the contemporary energy landscape. By overviewing foundational concepts, integration topologies, and various energy storage technologies, it underscores the maturity and pivotal importance of BESS in addressing current energy market demands. The paper explores into the essential components of BESS deployment, including energy management, BMS, and power conversion systems, while detailing critical control architectures and safety measures. Additionally, it assesses the techno-commercial factors involved in BESS design, deployment, and market viability. Through its detailed analysis, the paper addresses the multifaceted applications of BESS in power systems and projects the significant impact of overcoming existing challenges and limitations. The insights provided are instrumental in advancing the understanding and adoption of efficient, safe, and cost-effective energy storage solutions, thus supporting the progression towards more resilient and sustainable energy systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yu was Responsible for gathering and summarizing relevant research on BESS challenges, strategies, and applications; Zhang focused on comparing case studies to identify patterns in BESS deployment and operational challenges; Singh coordinated feedback from co-authors and reviewers, integrating suggestions and preparing the final manuscript for submission; Lyu developed figures and tables that illustrate critical findings; Wu ensured the paper's coherence by reviewing each section and making necessary edits for flow and readability; Dong checked all references for accuracy, ensuring that all citations followed the required style and format; all authors had approved the final version.

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