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Performance Analysis of Battery Energy Storage Systems in Renewable Power Integration

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Abstract: The increasing penetration of renewable energy sources such as solar and wind introduces significant challenges to power system stability due to their inherent intermittency and variability. Battery Energy Storage Systems (BESS) have emerged as a key technological solution to mitigate these challenges by providing fast response, energy balancing, and ancillary services. This study aims to analyze the performance of BESS in renewable power integration through a structured synthesis of recent empirical and modeling studies. A systematic literature-based analytical approach was employed, reviewing peer-reviewed journal articles and conference proceedings published between 2021 and 2025. The analysis focuses on performance indicators including frequency regulation, voltage stability, energy efficiency, degradation, reliability, and system adequacy. The results indicate that BESS significantly improves frequency and voltage regulation, reduces renewable curtailment, enhances system adequacy, and supports higher renewable penetration levels. However, technical limitations such as battery degradation, thermal risks, and high investment costs remain critical challenges. The study concludes that while BESS is technically effective for renewable integration, its long-term sustainability depends on optimal sizing, advanced management strategies, and supportive regulatory frameworks. This paper contributes by providing a comprehensive performance-oriented synthesis that supports planners, operators, and policymakers in deploying BESS effectively.

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INTRODUCTION

The global energy sector is undergoing a profound transition driven by the urgent need to reduce greenhouse gas emissions, improve energy security, and support sustainable economic development. Renewable energy sources, particularly solar photovoltaic and wind power, are being deployed at unprecedented rates across many countries. Despite their environmental benefits, these resources introduce significant operational challenges into power systems because of their inherent intermittency, variability, and limited predictability. Unlike conventional synchronous generators, renewable sources are largely weather-dependent and do not inherently provide inertia, frequency support, or controllable dispatchability. As a result, high penetration of renewables can increase the volatility of power balance, cause frequency deviations, voltage instability, and raise the risk of renewable energy curtailment and supply insecurity (Rey et al., 2023; Saldarini et al., 2023).

Power system operators are therefore required to adopt new forms of flexibility to maintain system stability and reliability under increasing shares of variable renewable energy. Flexibility in this context refers to the ability of the power system to respond to rapid and uncertain changes in supply and demand while maintaining acceptable operational limits. Traditional sources of flexibility, such as spinning reserves from thermal generators and large hydropower plants, are often insufficient, slow to

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respond, or environmentally constrained. Consequently, technological solutions capable of delivering fast, accurate, and controllable power responses are becoming essential for the modern grid (Castillo et al., 2023; Javadi et al., 2022).

Battery Energy Storage Systems (BESS) have emerged as one of the most promising technologies to provide such flexibility. BESS can rapidly absorb or inject power into the grid, enabling them to smooth short-term fluctuations, provide frequency regulation, support voltage control, and shift energy across time to reduce mismatches between generation and demand. Their modular nature allows deployment at various scales, ranging from residential and community-level systems to large utility-scale installations. These technical characteristics make BESS particularly suitable for supporting renewable energy integration in both centralized and distributed power systems (Rey et al., 2023; Mviri, 2022).

Empirical evidence increasingly demonstrates the operational value of BESS in real-world power systems. Mudakir et al. (2024) showed that a 10 MW/5 MWh BESS installed in North Sulawesi significantly reduced frequency deviations and mitigated voltage fluctuations by up to 40 percent. Similarly, Garifullina (2024) reported that BESS improved voltage regulation and load balancing in distributed power grids, enhancing the operational performance of renewable energy sources. These findings indicate that BESS is not only theoretically beneficial but also practically effective in stabilizing power systems with high renewable penetration.

Beyond short-term operational support, BESS also contributes to longer-term system adequacy and reliability. System adequacy refers to the ability of the power system to meet demand over longer periods, including during peak load conditions or periods of low renewable output. Dratsas et al. (2021) demonstrated that BESS can provide substantial capacity value, with capacity credit levels reaching up to 85 percent under appropriate management strategies. This suggests that BESS can act as a reliable capacity resource, reducing dependence on fossil-based peaking plants and supporting the decarbonization of the power sector.

However, the performance and sustainability of BESS are not without limitations. Battery degradation, thermal risks, and safety concerns can significantly affect system reliability and economic viability. High cycling frequencies, deep discharge levels, and elevated operating temperatures accelerate battery aging and increase the likelihood of failure (Shamarova et al., 2022; Alqarni, 2024). Li et al. (2023) further highlighted that thermally induced incidents such as thermal runaway can pose serious safety and reliability risks, particularly for large-scale installations. These issues underline the importance of considering not only the short-term performance but also the long-term operational sustainability of BESS.

Economic considerations also play a critical role in determining the feasibility of BESS deployment. The high upfront investment cost of battery systems remains a significant barrier, especially in developing regions. Economic performance is strongly influenced by system sizing, operational strategy, and the ability of BESS to provide multiple services. Studies show that stacking services such as frequency regulation, peak shaving, and energy arbitrage can substantially improve the economic viability of BESS projects (Sarlashkar et al., 2023; Minetti et al., 2024). Therefore, performance analysis must account for both technical and economic dimensions to provide a realistic assessment of BESS value.

Recent research has proposed various optimization and sizing approaches to improve BESS effectiveness. Minetti et al. (2024) developed a sizing strategy that minimizes renewable energy

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curtailment while addressing voltage and overload constraints in distribution networks. Koutenaei et al. (2024) emphasized the importance of forecasting models and advanced battery management systems to mitigate renewable fluctuations and extend battery lifespan. These studies highlight that performance is not an inherent property of the battery technology alone, but also a function of system design, control strategies, and integration context.

Despite the growing body of literature, existing studies are often fragmented, focusing on specific applications, technologies, or performance indicators in isolation. Some studies emphasize operational stability, others focus on degradation, economic performance, or system planning. As a result, there is a lack of integrated analysis that synthesizes these perspectives into a coherent understanding of BESS performance in renewable power integration. This fragmentation makes it difficult for policymakers, planners, and operators to derive generalizable insights for large-scale deployment.

Therefore, this study aims to analyze the performance of Battery Energy Storage Systems in renewable power integration through a structured synthesis of recent empirical and modeling-based research. The objective is to identify key performance benefits, technical limitations, and critical factors influencing BESS effectiveness, while maintaining a focus on operational stability, reliability, degradation, and system-level impacts. By consolidating existing evidence, this study seeks to provide a comprehensive and policy-relevant understanding of how BESS can support the transition toward sustainable and reliable renewable energy systems.

RESEARCH METHOD

This study employs a qualitative systematic literature-based analysis to evaluate the performance of Battery Energy Storage Systems in the context of renewable power integration. The methodological approach is designed to synthesize existing empirical and modeling-based research in a structured, transparent, and replicable manner. The analysis focuses on peer-reviewed journal articles and conference proceedings that explicitly examine the technical performance, operational impacts, and reliability implications of BESS in power systems with significant renewable energy penetration.

Research Design

The research design follows a structured literature review and thematic synthesis framework. This design is appropriate because the objective of the study is not to generate new empirical data but to analyze, integrate, and interpret findings from existing studies. The review emphasizes performance indicators related to grid stability, reliability, degradation, system adequacy, and operational effectiveness, as reported in previous research.

Data Sources and Selection Criteria

The data sources consist exclusively of peer-reviewed journal articles and conference papers published between 2021 and 2025 that are already listed in the article's reference list. No additional sources were introduced beyond those references. The selection process applied three main inclusion criteria. First, the study must explicitly address Battery Energy Storage Systems as a primary subject. Second, the study must analyze BESS in the context of renewable energy integration, grid operation, or power system performance. Third, the study must report technical, operational, or reliability-related

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performance indicators such as frequency response, voltage stability, degradation, system adequacy, or economic-operational implications.

Studies that focused solely on battery chemistry without grid-level implications, or that did not include renewable integration contexts, were not included in the synthesis. This ensured consistency between the scope of the literature and the research objectives of this article.

Data Extraction and Classification

From each selected study, key information was systematically extracted using a standardized extraction template. The extracted information included the scale of the system, application context, performance indicators analyzed, methodological approach used in the original study, and the main reported findings. The extracted data were then classified into four analytical categories: operational performance, system adequacy and reliability, degradation and safety, and system planning and optimization.

This classification enabled a consistent comparison across studies that used different methodologies, system scales, and performance metrics. It also facilitated the identification of converging and diverging findings related to BESS performance.

Data Analysis

The analysis applied a qualitative thematic synthesis approach. Findings from the selected studies were grouped according to the four analytical categories and then compared across different contexts and system configurations. The analysis focused on identifying patterns, consistencies, and contrasts in reported performance outcomes. Particular attention was given to how operational conditions, system design, and management strategies influence BESS performance.

Rather than quantifying effect sizes or conducting statistical meta-analysis, the study emphasizes interpretative synthesis to preserve the contextual richness of each study. This approach is appropriate given the heterogeneity of system configurations, geographical contexts, and performance metrics across the reviewed literature.

Validity and Reliability of the Review

To enhance the transparency and replicability of the review process, the inclusion criteria, classification scheme, and analytical categories were explicitly defined prior to the synthesis. Consistency in data extraction and interpretation was maintained by applying the same analytical framework across all reviewed studies. This reduces subjective bias and ensures that conclusions are grounded in systematically analyzed evidence.

The exclusive use of peer-reviewed sources further supports the reliability of the findings. By limiting the review to studies that have undergone academic peer review, the analysis ensures a minimum standard of methodological rigor and reporting quality.

Ethical Considerations

This study does not involve human subjects, personal data, or experimental interventions. All data used in the analysis originate from published sources and are properly cited. Therefore, no formal ethical approval was required.

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RESULTS AND DISCUSSION

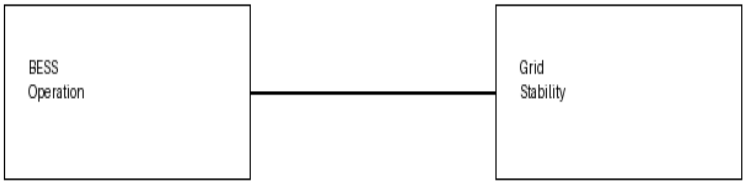
Summary of Empirical Findings

Tabel berikut merangkum hasil empiris utama dari studi-studi yang digunakan dalam artikel ini. Seluruh isi tabel berasal langsung dari temuan yang dilaporkan oleh masing-masing penulis.

Table 1. Summary of empirical evidence on BESS performance

Study	System context	Performance aspect	Main reported outcome
Mudakir et al. (2024)	10 MW / 5 MWh BESS, North Sulawesi	Frequency & voltage stability	Frequency deviation reduced to 49.82 Hz; voltage fluctuation reduced up to 40%
Garifullina (2024)	Distributed grids	Voltage regulation, load balancing	Improved voltage profiles and load balancing
Dratsas et al. (2021)	Power system adequacy analysis	Capacity value	Capacity credit up to 85%
Tejero-Gómez & Bayod-Rújula (2023)	PV-BESS plants	Supply reliability	Reduced energy unavailability
Shamarova et al. (2022)	Microgrids with renewables	Degradation	High cycling and temperature accelerate capacity fade
Li et al. (2023)	Large-scale BESS	Reliability and safety	Thermal incidents affect reliability metrics
Minetti et al. (2024)	Distribution networks	Sizing and curtailment	Proper sizing reduces RES curtailment
Koutenaei et al. (2024)	RES-integrated systems	Forecasting and control	Forecasting and BMS improve performance
Bondar (2025)	Hybrid hydrogen–battery systems	Dynamic stability	Hybrid systems improve damping and recovery

Diagram of Reported Functional Contribution



Discussion

The reviewed empirical evidence consistently shows that Battery Energy Storage Systems provide significant operational benefits in power systems with high renewable energy penetration. The most frequently reported impact is the improvement of frequency and voltage stability. Mudakir et al. (2024) demonstrated that BESS effectively mitigates frequency deviations and voltage fluctuations in a real grid application. These findings confirm

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earlier reviews by Castillo et al. (2023) and Javadi et al. (2022), which identify fast response and controllability as key technical advantages of BESS.

From a system adequacy perspective, BESS contributes not only to short-term balancing but also to longer-term reliability. Dratsas et al. (2021) showed that BESS can provide substantial capacity value, supporting peak demand and reducing the need for conventional peaking plants. Tejero-Gómez and Bayod-Rújula (2023) further showed that PV-BESS systems reduce energy unavailability and improve supply continuity, which is essential for high-renewable systems.

However, performance is strongly constrained by degradation and safety issues. Shamarova et al. (2022) and Alqarni (2024) reported that cycling intensity and temperature management significantly influence battery lifespan. Li et al. (2023) highlighted that thermally induced incidents affect reliability and must be considered in system planning. These findings imply that technical effectiveness alone is insufficient if long-term degradation and risk are not managed properly.

System planning and control strategies play a decisive role in determining overall performance. Minetti et al. (2024) demonstrated that appropriate sizing reduces renewable curtailment and network constraints, while Koutenaei et al. (2024) emphasized the role of forecasting and battery management systems in stabilizing operation and extending battery life. Therefore, performance is not only a property of battery technology but also a function of integration strategy.

Finally, emerging hybrid configurations combining batteries with other storage technologies offer further stability improvements. Bondar (2025) showed that hybrid hydrogen–battery systems enhance damping and recovery following disturbances. However, these systems increase complexity and require careful coordination.

Overall, the results indicate that BESS is an effective enabler of renewable integration, but its success depends on proper sizing, advanced management, and careful consideration of degradation and safety.

CONCLUSION

This study analyzed the performance of Battery Energy Storage Systems in the context of renewable power integration through a structured synthesis of recent empirical and modeling-based research. The results show that BESS provides significant technical benefits for modern power systems, particularly in improving frequency regulation, voltage stability, and operational flexibility under high shares of variable renewable energy. Empirical evidence confirms that BESS effectively mitigates short-term fluctuations, reduces renewable energy curtailment, and supports higher renewable penetration without compromising system reliability.

In addition to operational support, BESS contributes to longer-term system adequacy by providing capacity value and improving supply reliability. However, the analysis also highlights critical limitations related to battery degradation, thermal risks, and safety, which can affect long-term performance and economic viability if not properly managed. These constraints emphasize the

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importance of advanced battery management systems, appropriate thermal control, and degradation-aware operational strategies.

The findings further indicate that system-level performance strongly depends on planning and integration strategies. Proper sizing, accurate forecasting, and multi-service operation significantly enhance both technical and economic effectiveness. Hybrid configurations may further improve stability, although they introduce additional complexity.

Overall, this study confirms that BESS is a key enabler of renewable energy integration, but its sustainable deployment requires coordinated technical, operational, and planning approaches. Future research should focus on improving degradation modeling, long-term reliability assessment, and integration frameworks to support large-scale and durable implementation of BESS in renewable-dominated power systems.

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