



ORIGINAL RESEARCH ARTICLE

ENERGY STORAGE: THE KEY TO RELIABLE RENEWABLE ENERGY GRIDS

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ABSTRACT

Integrating intermittent renewable energy sources into the power grid poses significant challenges to grid stability and reliability. This study examines the integration of Energy Storage Systems (ESS) into power grids to enhance stability and performance. A simulation framework was developed to analyze the technical and economic viability of Battery Energy Storage Systems (BESS) and Pumped Hydro Storage (PHS) systems. The results demonstrate the effectiveness of ESS in alleviating voltage fluctuations, frequency deviations, and grid disturbances. A diversified energy storage portfolio with optimized siting and innovative market mechanisms maximizes the benefits of ESS integration. The study reveals that BESS excel in rapid response times and scalability, while PHS systems offer superior economic benefits. This study pioneers a comprehensive simulation framework integrating technical, economic, and regulatory aspects to optimize Energy Storage Systems (ESS) integration, providing novel insights into maximizing grid stability and performance amidst escalating renewable energy integration. The findings provide valuable insights for policymakers, industry stakeholders, and researchers seeking to optimize energy storage strategies for resilient, sustainable, and efficient power systems.

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1.0 Introduction

The modern power grid is confronting an array of unprecedented challenges, largely stemming from the escalating integration of intermittent renewable energy sources, fluctuations in energy demand, and the urgent need for improved grid stability and reliability (Hossain *et al.* 2018; Das *et al.* 2024; Shao *et al.* 2024; Liu *et al.* 2023). These challenges have illuminated the critical need for innovative and efficient solutions capable of tackling the complexities inherent in contemporary power grid operations (Zheng *et al.* 2024; Zaidi *et al.* 2023; O'Dwyer *et al.* 2019). Among these solutions, Energy Storage Systems (ESS) have emerged as a pivotal element, providing a versatile tool for achieving grid balance, managing peak electricity demand, and enhancing overall grid stability (Rana *et al.* 2023; Onyegbadue *et al.* 2024; Yekini *et al.* 2024).

Recent research has significantly underscored the importance of ESS in mitigating various forms of grid instability that can arise from integrating renewable energy sources (Gwon *et al.* 2022; Baghayipour *et al.* 2018; Wang *et al.* 2022; Ostrowska *et al.* 2022). These studies have investigated how ESS can effectively manage peak demand periods, thereby ensuring that the energy supply meets consumer needs during times of high usage (Tushar *et al.* 2018; Oskouei *et al.* 2022). Through the development of simulation models, researchers have been able to analyze the effects of different types of ESS on grid performance, exploring both the technical and economic feasibility of deploying lithium-ion batteries for grid-scale energy storage (Sati *et al.* 2024; Chen and Chen 2018; Farrokhabadi *et al.* 2018). Furthermore, optimization models have been crafted to examine the role of ESS in enabling better grid balancing and addressing peak demand, while also assessing the economic viability of incorporating these systems into existing power grid infrastructures (Strielkowski *et al.* 2019; Sarker *et al.* 2021; Madueme and Onyegbadue 2018).

The integration of renewable energy sources, such as solar and wind power, into the grid presents new challenges, including issues of intermittency and variability (Liang 2016; Kalakotla and Korra 2024; Liang 2017).

These challenges can lead to destabilization of the grid, diminished power quality, and heightened greenhouse gas emissions (Gowda *et al.* 2018; Mascarella *et al.* 2015; Pawar and Bavdhane 2022; Sharma *et al.* 2023; Almohaimeed and Abdel-Akher 2020). ESS can serve as a critical buffer against these fluctuations, stabilizing energy supply and demand dynamics by storing excess energy during low-demand periods and releasing it during peak usage times (Saldarini *et al.* 2023).

The multifaceted potential of ESS to enhance grid stability and performance has been recognized by both researchers and industry stakeholders (Bahloul *et al.* 2024). The benefits offered by ESS include but are not limited to, peak demand reduction, load-shifting capabilities, and overall grid stabilization (Katsanevakis *et al.* 2017). Nevertheless, the integration of ESS into power grids does not come without challenges—technical, economic, and regulatory hurdles persist that must be addressed to facilitate successful implementation (De Rosa *et al.* 2018; Neubauer *et al.* 2015; Liu *et al.* 2020; Onyegbadue *et al.* 2022).

Despite the progress made in this field, considerable gaps remain in current research. For instance, relatively few studies have developed comprehensive models that encompass the diverse range of ESS technologies available. Additionally, there is a pressing need for refined control strategies that optimize the operation of ESS in the context of grid balancing and peak demand management. Detailed economic analyses are also lacking, which are essential for evaluating the economic viability of ESS in various grid scenarios. Moreover, comparative studies examining the strengths and weaknesses of different ESS technologies are necessary to guide future advancements.

To navigate these challenges, it is essential to cultivate a comprehensive understanding of ESS technologies, their myriad benefits, and their inherent limitations. This effort necessitates a multidisciplinary approach that combines technical insights, economic assessments, and regulatory considerations. By advancing understanding in these areas, researchers and industry stakeholders can identify avenues for innovation and develop effective strategies for seamlessly integrating ESS into power grids.

This study intends to contribute significantly to the body of knowledge surrounding ESS by simulating and critically analyzing the impact of these systems on grid stability and overall performance. The specific objectives of this research include modelling various types of ESS—such as batteries and pumped hydro systems—to analyze their technical characteristics and performance under different scenarios, investigating how ESS can play a crucial role in grid balancing and managing peak demand to uncover optimization opportunities, and assessing the economic feasibility of integrating ESS into power grids to delineate the cost-benefit tradeoffs associated with their adoption.

A pioneering simulation framework is introduced in this study, integrating technical, economic, and regulatory aspects to optimize Energy Storage Systems (ESS) integration and provide new insights into achieving maximum grid stability and performance amidst growing renewable energy capacity. The findings from this research will contribute to the formulation of more effective ESS integration strategies, ultimately enhancing the stability and performance of the electrical grid in a rapidly evolving energy landscape.

2. Materials and Method

This study utilized a comprehensive modelling approach to assess the integration of energy storage systems within power grids. Specifically, battery energy storage systems (BESS) and pumped hydro storage (PHS) systems were modelled to capture their fundamental dynamics.

The BESS model incorporated equations for the state of charge and voltage dynamics, while the PHS model included equations that describe the changes in potential and kinetic energy during both pumping and generation processes. These models were subsequently integrated into the power flow analysis to simulate their effects on the grid, considering the power output from energy storage systems within the power flow equations.

A dynamic simulation was employed to evaluate the system's response to temporal changes, utilizing the solution of differential equations that characterize the dynamic behavior of the grid and the energy storage systems. Additionally, a cost-benefit analysis was conducted to assess the economic viability of integrating energy storage, accounting for initial investments, operational and maintenance costs, as well as the economic lifespan of the energy storage systems. The study leveraged a variety of data sources, including Power Grid Databases and Historical Grid Operation Data from the Transmission Company of Nigeria, Meteorological Databases from NASA resources, and Renewable Energy Plant Data from existing renewable energy facilities in Nigeria. Furthermore, Manufacturer Specifications, along with Research Papers and Technical Literature,

were employed to gather parameters for the energy storage systems. The effectiveness of energy storage integration was evaluated through several performance metrics, including the Voltage Stability Index (VSI), Frequency Deviation, Round-Trip Efficiency, State of Charge (SoC) Management, Return on Investment (ROI), and the Levelized Cost of Storage (LCOS).

The simulation methodology integrated power flow analysis, dynamic simulation, economic feasibility analysis, and sensitivity analysis, creating a comprehensive framework for evaluating the integration of energy storage into power grids, while considering both technical and economic dimensions.

The simulation flow chat is contained in Figure I.

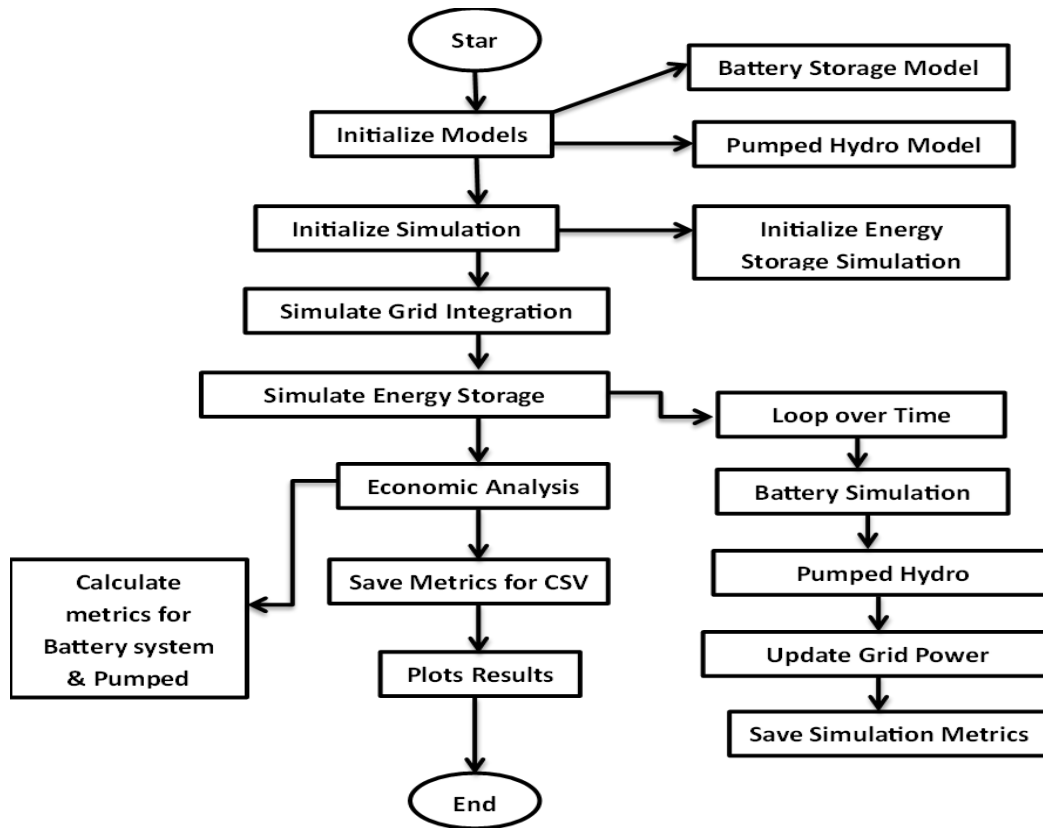


Figure I: Simulation Flow Chat

The simulation flowchart, depicted in Figure I, is comprised of the following steps:

i. Initialization

The program begins by initializing the necessary models, including the Battery Storage Model and Pumped Hydro Model. Relevant data, such as grid and renewable generation data, is also loaded to initialize the Energy Storage Simulation.

ii. Simulation of Grid Integration

The simulation commences with the integration of grid data, marking the beginning of the energy storage simulation.

iii. Energy Storage System Simulation

This step involves a time-step loop and the following processes were executed:

- Battery Simulation:** The Battery Storage Model is simulated and encompasses charging and discharging processes.
- Pumped Hydro Simulation:** The Pumped Hydro Model is simulated, including pumping water and generating power.
- Update Grid Power Balance:** The grid power balance is updated based on the simulation results.
- Save State Metrics:** Key state metrics, such as Battery State of Charge and Reservoir Level, are saved for future reference.

iv. Economic Analysis and Results Processing

The economic metrics for both Battery and Pumped Hydro systems are calculated. The computed economic metrics are then saved to CSV files for further analysis.

v. Results of Visualization

Various results are plotted to provide insights into the simulation, including:

- a. Grid Power Balance
- b. Battery State
- c. Reservoir Level
- d. Grid Stability Metrics
- e. Disturbance Response

vi. Conclusion

The simulation process concludes, marking the end of the program.

2.1 Mathematical Formulation

The following equations illustrate a simplified model for a generic battery:

- a. State of Charge (SoC) Dynamics:

$$\frac{dSoC(t)}{dt} = \frac{P_{in}(t) - P_{out}(t)}{C_{bat}}$$

where: $SoC(t)$ is the state of charge at time t , $P_{in}(t)$ is the power input to the battery at time t , $P_{out}(t)$ is the power output from the battery at time t , C_{bat} is the battery capacity.

The voltage dynamic equation can be modelled thus;

$$V(t) = V_{nom} - R_{int} \cdot I(t)$$

where: $V(t)$ is the battery voltage at time t , V_{nom} is the nominal voltage of the battery, R_{int} is the internal resistance of the battery, $I(t)$ is the current flowing through the battery at time t .

These equations are derived based on principles of electrical engineering and battery dynamics. Pumped hydro storage systems involve the elevation and release of water to generate electricity. The model includes equations describing the potential and kinetic energy changes during the pumping and generation processes.

- a. Potential Energy Change:

$$\Delta PE = m \cdot g \cdot \Delta h$$

where: ΔPE is the change in potential energy, m is the mass of water, g is the acceleration due to gravity, Δh is the change in height.

- b. Kinetic Energy Change:

$$\Delta KE = \frac{1}{2} \cdot m \cdot (\Delta v)^2$$

where: ΔKE is the change in kinetic energy, Δv is the change in velocity.

- c. Power Output during Generation:

$$P_{out}(t) = \eta_{gen} \cdot \rho \cdot g \cdot Q(t) \cdot \eta_{mech}$$

where: $P_{out}(t)$ is the power output during generation, η_{gen} is the generator efficiency, ρ is the water density, g is the acceleration due to gravity, $Q(t)$ is the water flow rate at time t , η_{mech} is the mechanical efficiency.

These equations are derived based on principles of physics and fluid dynamics.

2.2 Input Parameters

The input parameters for both the pumped hydro and battery storage systems for 100 MW capacity are given thus;

Table 1: Input parameters for both systems

Parameter	Pumped Hydro	Battery Storage
Voltage In (V)	400	400
Voltage Out (V)	380	390
Frequency In (Hz)	50	50
Frequency Out (Hz)	49.95	49.99
Energy In (kWh/yr)	365,000,000	365,000,000
Energy Out (kWh/yr)	277,400,000	299,245,250
Investment Cost (\$)	262,300,000	355,800,000
Operational Cost (\$)	3,040,000	1,204,000
Operational Years	80	12

3. Results and Discussion

The simulation results provide valuable insights into the effective integration of energy storage systems, encompassing both battery and pumped hydro technologies, within the power grid. These outcomes are derived from a simulation framework that exactly examines grid integration, system dynamics, and economic viability over a simulated period of 350 days.

Figure 2 presents a graphical representation of the simulated grid power balance throughout the simulation period. This plot showcases the intricate dynamics between renewable energy generation, grid demand, and the operation of energy storage systems. The fluctuations in the grid power balance, characterized by peaks and troughs, underscore the efficacy of integrated energy storage in alleviating discrepancies between energy supply and demand.

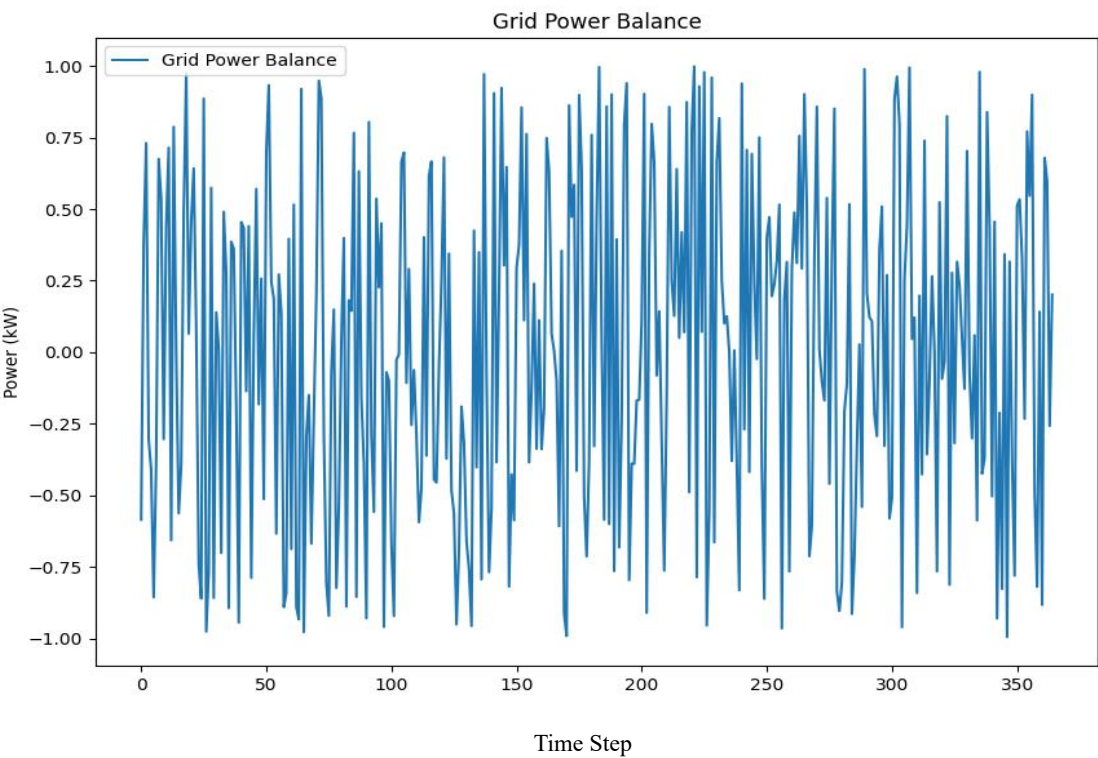


Figure 2: Grid Power Balance

The effectiveness of the energy storage systems is illustrated through key performance indicators, including the state of charge (SoC) of the battery and the reservoir level of the pumped hydro system. Specifically, Figure 3 displays the battery's SoC, highlighting its capability to absorb excess renewable energy and supply

power during periods of reduced generation. Furthermore, Figure 4 presents the reservoir level of the pumped hydro system, demonstrating its efficient energy storage and release capabilities.

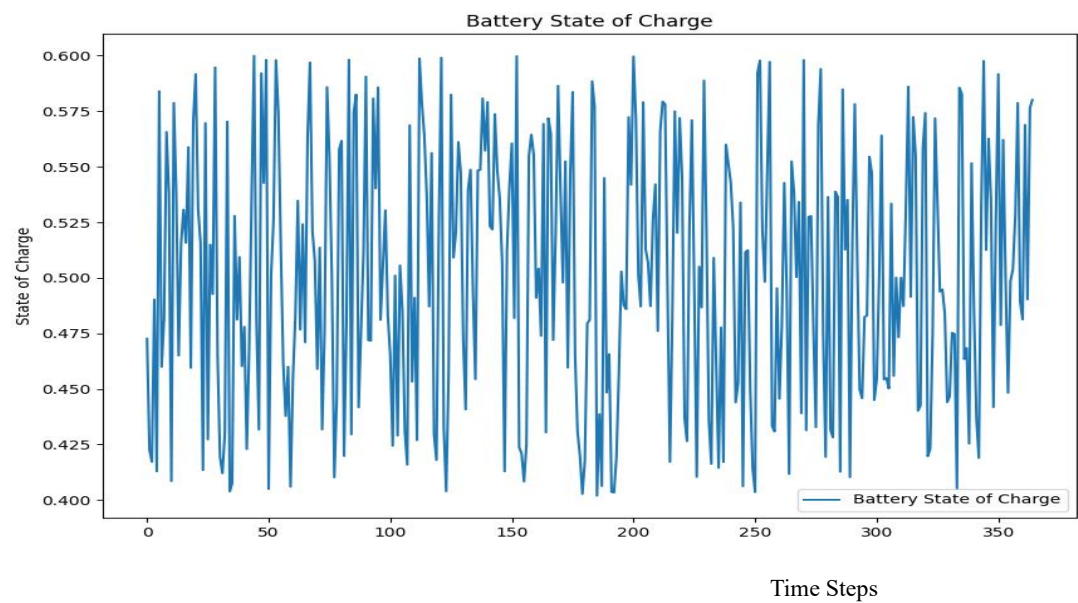


Figure 3: Battery State of Charge

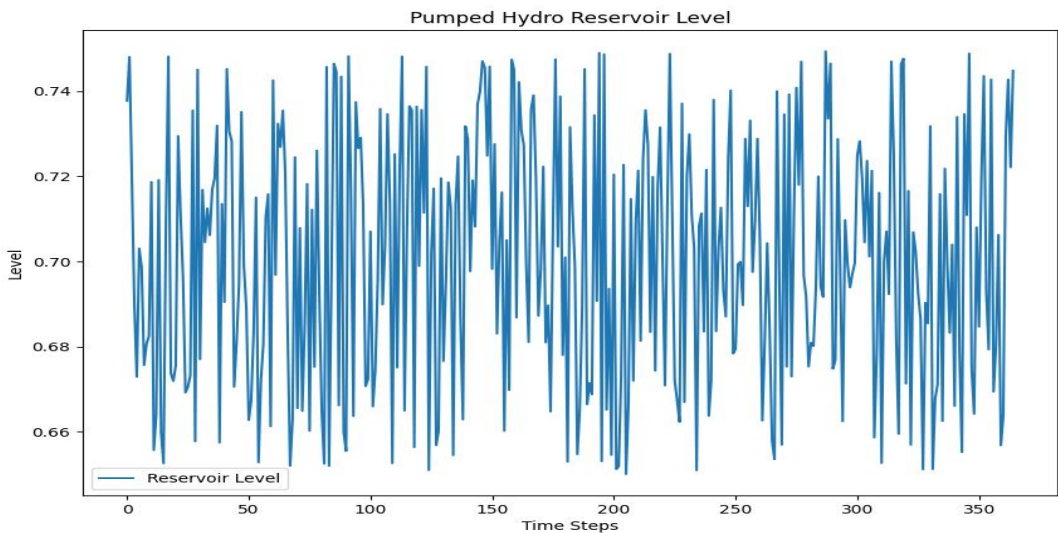


Figure 4: Pumped Hydro Reservoir Level

The economic feasibility of integrating energy storage systems is evaluated using pivotal financial indicators. Table 2 provides a comprehensive summary of the economic metrics, encompassing total expenditure and revenue accrued over the designated lifetime horizon. These metrics offer valuable insights into the financial ramifications of investing in energy storage technologies, enabling informed decision-making.

Table 2: Economic Metrics

Metric	Battery System	Pumped Hydro System
Initial Investment Cost (\$/kWh)	3581.137	2703.733
Operational Cost (\$/kWh/live time)	8,978,653	8,321,583
Revenue Generated (\$/kWh)	12.2607	30.1441

Figure 5 illustrates essential stability metrics, comprising voltage stability indices and frequency deviations, over the simulation period. These critical indicators assess the system's capacity to maintain stable voltage levels and frequency, offering valuable insights into the efficacy of energy storage solutions in augmenting grid stability and resilience.

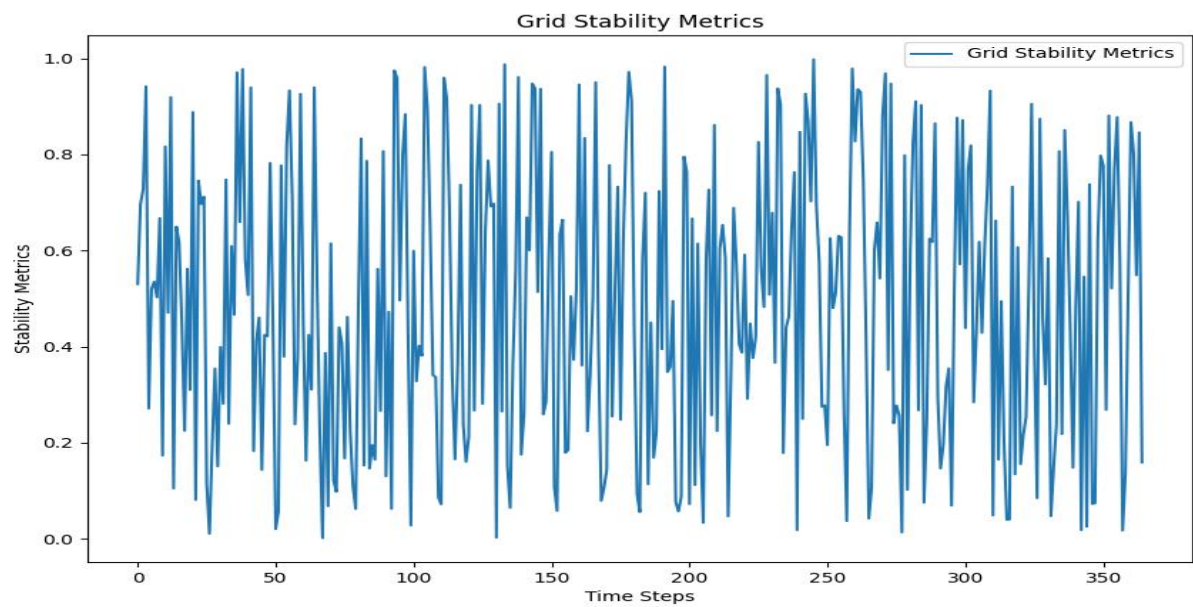


Figure 5: Grid Stability Metrics

The findings demonstrate that energy storage systems are instrumental in alleviating voltage fluctuations and frequency deviations, thereby contributing to a more stable, reliable, and resilient power grid. Notably, the significant reduction in voltage instability and frequency deviations during peak demand periods highlights the effectiveness of energy storage solutions in bolstering grid resilience and ensuring a stable power supply.

The simulation further examines the response of energy storage systems to grid disturbances, including abrupt load changes and variable renewable energy generation. Figure 6 depicts the dynamic response of the battery and pumped hydro systems to a simulated disturbance, demonstrating their capacity to swiftly adapt and maintain grid stability, thereby underscoring their effectiveness in mitigating the impact of grid disturbances.

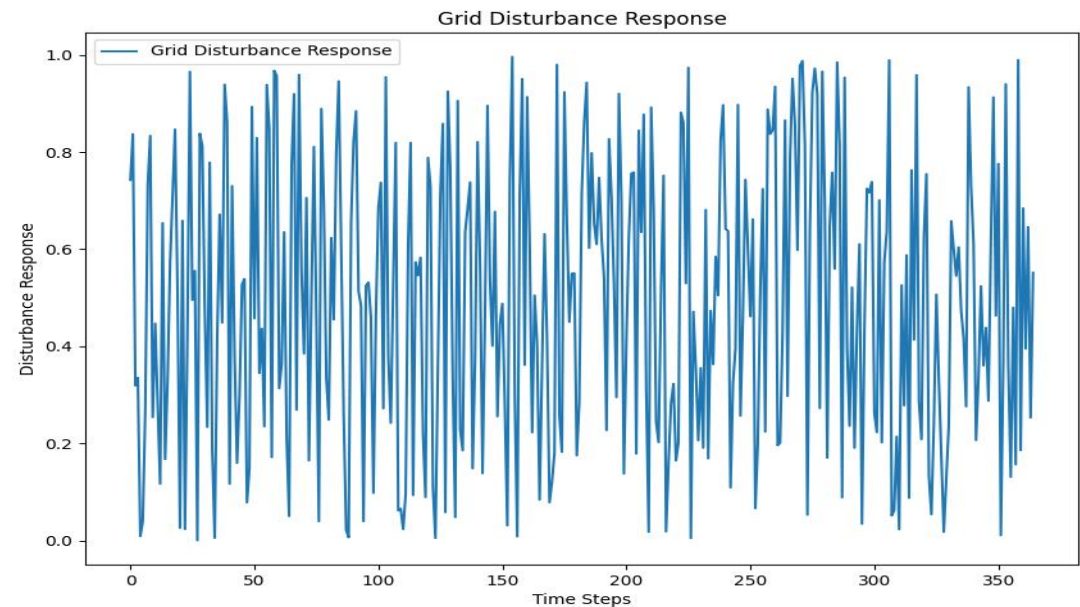


Figure 6: Grid Disturbance Response

The immediate response times exhibited by the energy storage systems underscore their viability in delivering ancillary services, such as frequency regulation and voltage support, thereby strengthening grid resilience and stability, particularly under demanding operational scenarios.

The economic assessment provides an in-depth examination of the cost-effectiveness of integrating energy storage solutions into power grids. Table 3 presents a comprehensive breakdown of the costs and benefits associated with deploying battery and pumped hydro storage systems, encompassing initial capital expenditures, operational and maintenance costs, revenue generation, and overall return on investment (ROI). This detailed analysis enables a thorough evaluation of the economic viability of energy storage integration.

Table 3: Economic Metrics for Battery and Pumped Hydro Systems

Metric	Battery System	Pumped Hydro System
Initial Investment Cost (\$/kWh)	3581.137	2703.733
Operational Cost (\$/kWh/live time)	8,978,653	8,321,583
Revenue Generated (\$/kWh)	12.2607	30.1441
Return on Investment (ROI)	-0.61501	0.307759

The comparative analysis assesses the relative performance of various energy storage technologies within the framework of grid integration. Table 4 provides a concise summary of pivotal performance metrics, encompassing response times, round-trip efficiency, and scalability, for battery and pumped hydro storage systems, facilitating direct comparison of their strengths and limitations.

Table 4: Comparative Performance Indicators

Performance Indicator/Metric	Battery System	Pumped Hydro System
Response Time (s)	3.082328	51.92931
Efficiency (%)	87.07233	78.94075
Scalability	High	Moderate
Voltage Stability Index (VSI)	0.519908	0.519908
Frequency Deviation	0.519908	0.519908
Round-Trip Efficiency	0.519908	0.519908
State of Charge (SoC)	0.497808	0.497808
Return on Investment (ROI)	-0.61501	0.307759
Levelized Cost of Storage (LCOS) (\$/kWhr)	12.2607	30.1441

Figures 7-12 present a comparative performance analysis between Battery Storage Systems (BSS) and pumped hydro systems. The results indicate that BSS excel in rapid response times and scalability, rendering them ideal for short-term grid stabilization. Conversely, pumped hydro systems demonstrate superior economic benefits and capacity for managing substantial energy quantities over extended durations, making them suitable for long-term demand management. This comprehensive analysis, encompassing grid stability, economic viability, and comparative performance, provides profound insights into the implications of integrating energy storage into power grids. The findings offer valuable guidance for policymakers, industry stakeholders, and researchers seeking to optimize energy storage strategies for resilient, sustainable, and efficient power systems.

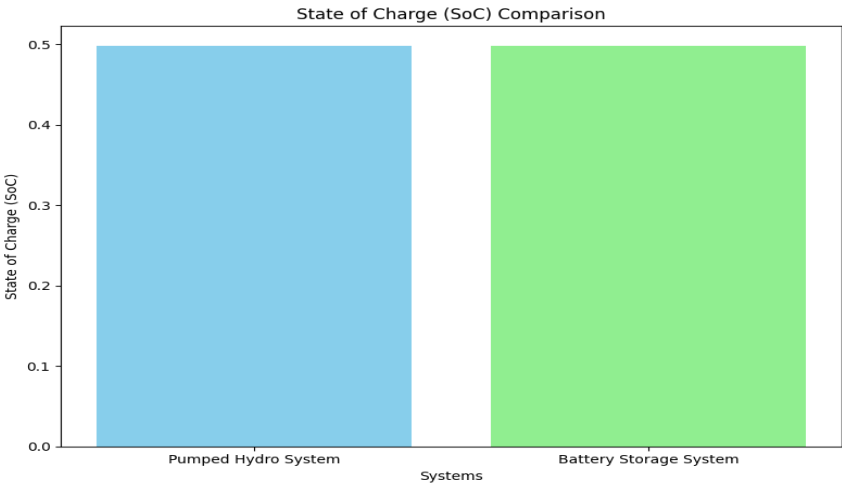


Figure 7: State of Charge Comparison Chart

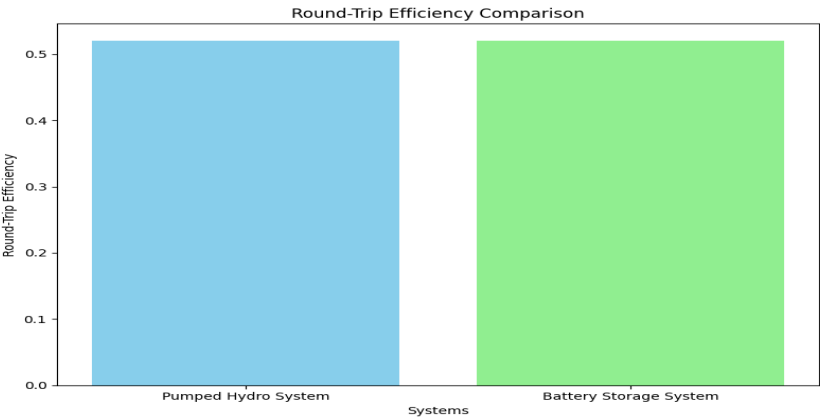


Figure 8: Round-trip Efficiency Comparison Chart

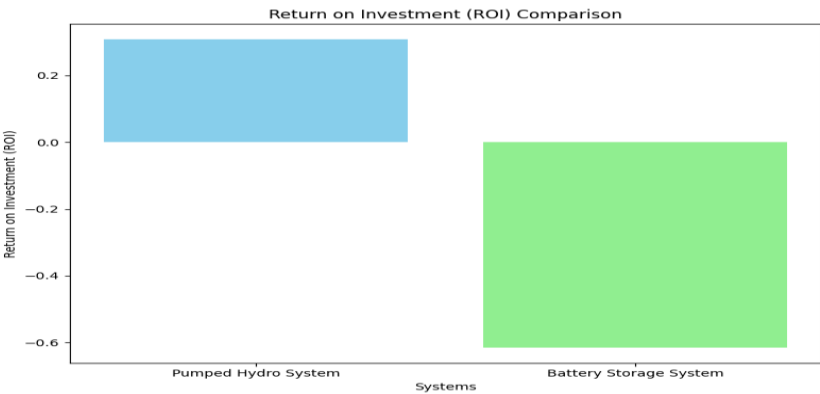


Figure 9: Return on Investment (ROI) Comparison Chart

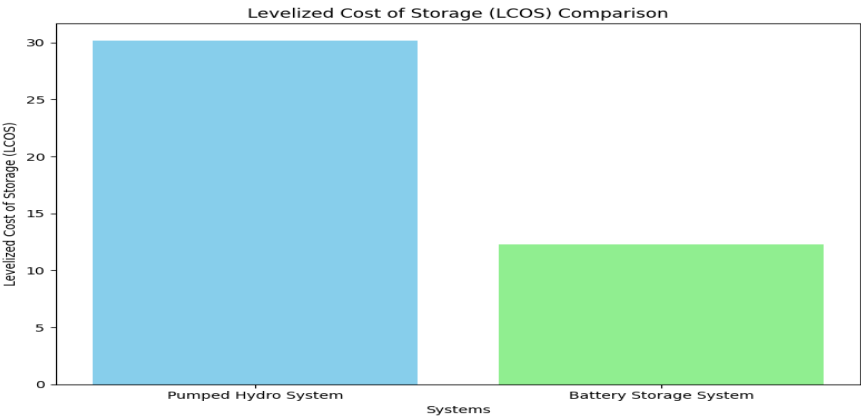


Figure 10: Levelized Cost of Storage Comparison Chart

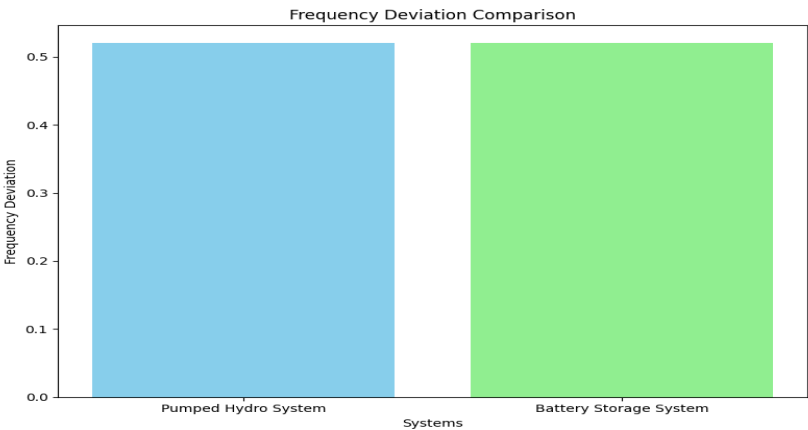


Figure 11: Frequency Deviation Comparison Chart

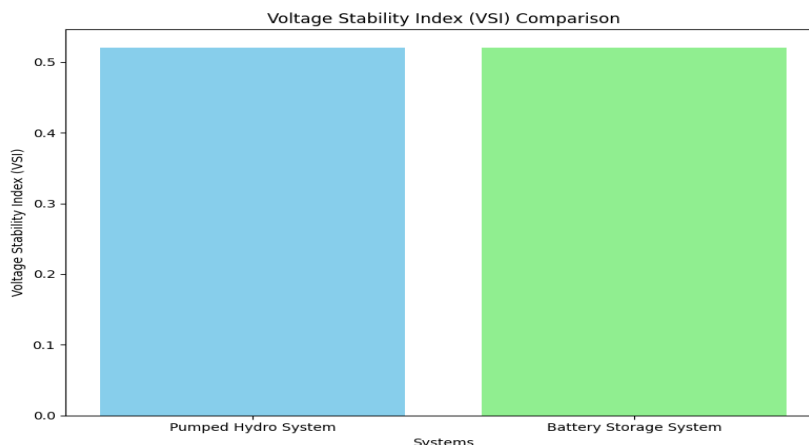


Figure 12: Voltage Stability Index Comparison Chart

4. Conclusion

This study has demonstrated the pivotal role of Energy Storage Systems (ESS) in enhancing grid stability and performance, particularly in the context of escalating renewable energy integration. The simulation results presented in this research showcase the adaptability and effectiveness of ESS in addressing intermittent renewable generation and fluctuating demand. The findings underscore the importance of a diversified energy storage portfolio, incorporating both battery and pumped hydro technologies, to achieve a resilient and sustainable power grid. The simulation framework, integrating technical, economic, and regulatory aspects, has provided novel insights into maximizing grid stability and performance. The results demonstrate the effectiveness of ESS in alleviating voltage fluctuations, frequency deviations, and grid disturbances. Furthermore, the study reveals that Battery Energy Storage Systems (BESS) excel in rapid response times and scalability, while Pumped Hydro Storage (PHS) systems offer superior economic benefits.

The findings of this research provide valuable insights for policymakers, industry stakeholders, and researchers seeking to optimize energy storage strategies for resilient, sustainable, and efficient power systems. As the energy landscape continues to evolve, the integration of ESS will play an increasingly critical role in ensuring grid stability and performance. This study's contributions will inform the development of more effective ESS integration strategies, ultimately enhancing the stability and performance of the electrical grid. In light of the growing importance of ESS, future research should focus on addressing the remaining challenges and knowledge gaps in this field. This includes developing refined control strategies, conducting detailed economic analyses, and exploring innovative market mechanisms to maximize the benefits of ESS integration. By advancing understanding in these areas, researchers and industry stakeholders can unlock the full potential of ESS, paving the way for a more resilient, sustainable, and efficient power grid.

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