A Simulation Study of Energy Storage Systems for Renewable Energy Integration

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Abstract—**The integration of renewable energy sources into modern power systems is constrained by their inherent variability, necessitating effective energy storage solutions to ensure stability, reliability, and economic efficiency. This study develops a comprehensive simulation-based framework to evaluate the technical and economic performance of Energy Storage Systems (ESS) in hybrid photovoltaic (PV)–wind configurations under Indian grid and climatic conditions. Using hourly meteorological and load data from the National Institute of Wind Energy (NIWE), Indian Meteorological Department (IMD), and Central Electricity Authority (CEA) for Jaisalmer, Rajasthan (2022), the research models multiple system configurations in HOMER Pro and analyzes results using IBM SPSS Statistics. Key performance indicators include renewable penetration, storage utilization, curtailment rates, Levelized Cost of Energy (LCOE), Net Present Cost (NPC), and dispatch strategy effectiveness. Findings reveal that renewable penetration increases from 63.7% to 84.9% with larger generation and storage capacities, but marginal benefits diminish beyond an optimal threshold. Market-responsive dispatch strategies outperform load-following and cycle-charging approaches, achieving the lowest LCOE (₹4.97/kWh) and highest penetration (79.6%). Seasonal analysis underscores the influence of monsoon-induced variability, while tariff sensitivity analysis highlights the role of supportive regulatory frameworks. The results bridge existing literature gaps by integrating technical, economic, and operational perspectives using real Indian data, offering actionable insights for policymakers, utilities, and investors to optimize ESS deployment for large-scale renewable integration.**

Index Terms—**Energy Storage Systems, Renewable Energy Integration, Hybrid PV-Wind Systems, Techno-Economic Simulation, Indian Power Sector, Market-Responsive Dispatch**

I. INTRODUCTION

The transition from fossil fuel–based power generation to renewable energy systems represents one of the most critical challenges and opportunities in the 21st century. Global electricity demand is projected to rise by over 25% by 2040, with renewable energy expected to supply nearly half of the increase (International Energy Agency, 2023). Solar photovoltaic (PV), wind, and emerging marine energy technologies have witnessed rapid deployment due to declining technology costs and supportive policies. However, their inherently intermittent and variable nature poses significant challenges to power system stability, reliability, and economic operation (Amrouche, Rekioua, & Rekioua, 2016). In this context, Energy Storage Systems (ESS)—encompassing electrochemical, mechanical, and thermal storage technologies—are increasingly recognized as key enablers for large-scale renewable integration.

Simulation studies have become indispensable tools for assessing the operational and economic performance of ESS in renewable energy systems. For instance, Talaat et al. (2019) demonstrated that hybrid systems integrating solar, wind, and wave power require dynamic storage control strategies to maintain voltage stability under variable load and generation conditions. Likewise, Buonomano et al. (2018) developed a dynamic simulation of a wind–PV hybrid system with battery storage, revealing that optimal sizing of storage capacity can enhance renewable penetration by up to 35% while reducing curtailment losses.

The role of ESS is not limited to balancing generation and demand but extends to providing ancillary services such as frequency regulation, voltage support, and black start capabilities (Datta, Kalam, & Shi, 2021). Large-scale deployment of ESS could, therefore, support a global shift toward a decarbonized, resilient, and flexible power system. However, the cost-effectiveness, lifecycle environmental impact, and integration strategies of ESS remain highly context-dependent and must be evaluated through simulation-based approaches tailored to specific grid architectures and renewable generation profiles (Ölmez, Ari, & Tuzkaya, 2025).

Despite substantial research, several gaps persist in the simulation-based evaluation of ESS for renewable energy integration. First, much of the existing work has focused on either single renewable sources (e.g., PV-battery systems) or simplified load profiles, limiting the applicability of results to complex, real-world scenarios (Nair & Garimella, 2010). Additionally, while advanced optimization methods have been applied to hybrid systems (Jafarian et al., 2024), these models often neglect dynamic grid conditions such as rapid frequency deviations, stochastic renewable generation variability, and market price fluctuations. Long-term seasonal storage solutions, including hydrogen and pumped hydro, have been comparatively underexplored in integrated simulation environments despite their potential to address extended periods of low renewable generation (Elberry, Thakur, & Veysey, 2021). Moreover, most studies prioritize technical performance metrics without adequately incorporating economic and environmental trade-offs. This lack of holistic assessment can lead to suboptimal policy and investment decisions, especially in contexts where renewable deployment is accelerating but financial resources are constrained. Lastly, there remains a shortage of studies that integrate market-responsive storage dispatch algorithms into renewable-ESS simulations. Considering that electricity market structures significantly influence ESS operations, the absence of such models in simulation studies leaves a critical research gap (Ölmez et al., 2025).

While ESS technologies have been proven to enhance renewable energy integration, the optimal configuration, control, and economic viability of these systems in diverse power system contexts remain insufficiently understood. Simulation-based studies exist but are often narrow in scope, either excluding key operational variables or focusing on isolated renewable-storage combinations without considering the complex interactions within hybrid systems. This lack of comprehensive simulation frameworks leads to uncertainty in system planning, investment decisions, and policy formulation for renewable integration with ESS.

The primary aim of this study is to develop a simulation-based framework for analyzing the technical and economic performance of ESS in hybrid renewable energy systems. The objectives are:

1. To simulate multiple hybrid renewable configurations incorporating ESS under varying resource availability and load demand conditions.
2. To evaluate system performance metrics, including renewable penetration, storage utilization, curtailment rates, and operational costs.
3. To assess the economic viability of different ESS technologies under market-driven and technical operation strategies.
4. To identify optimal control and dispatch strategies for ESS that enhance system reliability while minimizing costs.

By addressing the identified gaps, this study contributes to the growing body of knowledge on renewable integration by providing a comprehensive, scenario-based simulation approach. Unlike prior studies focusing on either purely technical or purely economic assessments, this work integrates both domains, enabling stakeholders—including utilities, policymakers, and investors—to make informed decisions.

Furthermore, by simulating market-responsive storage dispatch in hybrid renewable contexts, this research aligns technical solutions with real-world economic incentives, thereby improving the practical relevance of its findings. The results are expected to assist in designing robust ESS investment strategies for future low-carbon power systems, with potential implications for global climate change mitigation targets.

II. LITERATURE REVIEW

This section organizes and critically analyzes prior studies on simulation-based assessment of energy storage systems (ESS) for renewable energy integration, structured thematically to align with our research objectives:

1. Simulation and Modeling Approaches for ESS in Hybrid Renewable Systems
2. Optimization Strategies for ESS Sizing and Control
3. Technological Perspectives and Functional Roles of ESS
4. Integration of ESS in Microgrids and Small-Scale Systems

A. Simulation and Modeling Approaches for ESS in Hybrid Renewable Systems

Several studies have developed simulation models to evaluate hybrid renewable systems coupled with ESS. Buonomano et al. (2018) constructed a dynamic simulation of a hybrid wind–solar system integrated with battery storage, analyzing performance under varying load and weather profiles. Using TRNSYS and MATLAB, they quantified energy balance, renewable penetration, and economic metrics, concluding that optimal sizing of storage can reduce energy curtailment by 20–35%.

Bussar et al. (2016) conducted a sensitivity study on large-scale renewable integration for the European power system of 2050, using the REMix simulation platform to assess storage demand under high renewable penetration scenarios. They found that long-term storage capacity requirements could reach 67 TWh depending on spatial distribution of renewable generation.

Weitemeyer et al. (2015) evaluated the role of storage in integrating variable renewable energy sources, using a simplified power system model to determine critical storage size thresholds for system stability. Their simulations indicated that beyond a certain renewable share (~70%), storage becomes essential to maintain supply reliability without excessive curtailment.

Etxeberria et al. (2010) reviewed hybrid energy storage systems (HESS) for renewable integration, providing simulation results for systems combining batteries with supercapacitors to enhance both energy and power performance. Their study highlighted that hybrid configurations can extend storage lifespan by 15–30% compared to single-technology systems.

B. Optimization Strategies for ESS Sizing and Control

Jafarian et al. (2024) proposed a novel optimization and dynamic evaluation framework for integrating ESS with renewable sources in hybrid systems. Their model, developed in MATLAB/Simulink and optimized via multi-objective genetic algorithms, demonstrated that integrating ESS increased renewable fraction by up to 42% while minimizing levelized cost of energy (LCOE).

Rahbar et al. (2014) focused on real-time energy storage management for renewable integration in microgrids. They employed an offline optimization strategy to derive optimal dispatch rules, which were then validated in simulation using stochastic renewable generation profiles. The results showed that optimized ESS operation reduced operational costs by 12% and improved reliability indices significantly.

Bussar et al. (2015) further refined simulation optimization by applying the GENESYS model to determine optimal allocation and sizing of renewable generation and storage capacities across Europe, emphasizing the interplay between spatial generation patterns and storage placement.

C. Technological Perspectives and Functional Roles of ESS

The functional roles of ESS in renewable integration extend beyond simple energy shifting. Datta et al. (2021) reviewed key ESS functionalities, including frequency regulation, voltage stabilization, black start, and peak shaving, supported by simulation-based performance evaluations. They emphasized that battery control strategies significantly influence system-level benefits.

Amrouche et al. (2016) provided a comprehensive overview of various storage technologies, their costs, and technical parameters. Their work synthesized simulation studies across lithium-ion, lead-acid, and flow batteries, showing that choice of technology directly affects operational strategy, especially in multi-renewable contexts.

Nair and Garimella (2010) assessed battery ESS for small-scale renewable integration from an environmental and technical perspective, using HOMER software to simulate performance. Their findings indicated that battery efficiency and depth-of-discharge strongly influence the system's life cycle emissions and cost.

D. Integration of ESS in Microgrids and Small-Scale Systems

Etxeberria et al. (2010) examined hybrid storage solutions in microgrid contexts, particularly for wind–PV–ESS configurations. Simulation analysis indicated that hybridizing storage (e.g., batteries plus ultracapacitors) can reduce short-term fluctuations and extend storage life.

Rahbar et al. (2014) provided operational insights into microgrid ESS management, where simulation-based optimization enhanced system flexibility during islanded operation.

Weitemeyer et al. (2015) discussed small-scale ESS integration, noting that localized storage can alleviate distribution network constraints and enable higher penetration of rooftop solar PV without grid reinforcement.

While the reviewed studies have advanced our understanding of ESS simulation for renewable integration, several notable gaps remain. Most existing works focus on either technical optimization or economic evaluation, with few integrating both into a unified simulation framework. Furthermore, seasonal and market-driven dispatch strategies are underrepresented, despite their growing importance in systems with high renewable penetration. Long-term storage technologies, such as hydrogen or compressed air energy storage, have received limited attention in dynamic simulation contexts, especially in hybridized configurations. Additionally, many studies rely on idealized renewable and load profiles, which may not accurately reflect real-world variability and operational uncertainties. This study addresses these gaps by developing a simulation framework that integrates technical, economic, and operational perspectives of ESS in hybrid renewable systems, incorporating market-responsive dispatch and stochastic resource modeling. By bridging this methodological divide, the research aims to provide more robust, actionable insights for policymakers, system planners, and investors.

III. RESEARCH METHODOLOGY

A. Research Design

This research adopted a simulation-based quantitative design to analyze the technical and economic performance of Energy Storage Systems (ESS) integrated into hybrid renewable energy systems under Indian grid and climatic conditions. The approach combined real-world meteorological and load data with hybrid system modeling to evaluate renewable penetration, storage utilization, curtailment rates, operational costs, and optimal dispatch strategies.

The simulation framework was scenario-driven, where each scenario represented a different configuration of photovoltaic (PV), wind generation, and lithium-ion battery ESS under varying resource availability and demand conditions. The methodology was designed to address the identified literature gap by integrating both technical and economic performance metrics within a unified model.

B. Data Source

A single authoritative source was selected to ensure data reliability: National Institute of Wind Energy (NIWE) and Indian Meteorological Department (IMD) Renewable Resource Dataset, integrated with state-level demand data from the Central Electricity Authority (CEA).

The location chosen was Jaisalmer District, Rajasthan, a region with high solar irradiance and moderate wind potential, making it ideal for testing hybrid ESS configurations under Indian conditions.

Table 1. Data Source Specifications for Simulation Study

Data Attribute	Description
Source Name	NIWE–IMD Renewable Resource Dataset & CEA State Load Data
Data Type	Hourly time-series data for renewable resources and electricity demand
Geographical Location	Jaisalmer District, Rajasthan, India
Time Span	January 1 – December 31, 2022

Variables Included	Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Wind Speed (m/s), Ambient Temperature (°C), State-level Demand (kWh)
Data Resolution	1-hour intervals
Data Format	CSV format, NIWE and IMD processed data
Access Method	Official NIWE Solar & Wind Resource Assessment Platform and IMD Climate Data Portal; CEA Monthly Demand Reports
Data Validation	Cross-verified with MNRE (Ministry of New and Renewable Energy) renewable performance benchmarks
Relevance to Study	Provides real-world Indian renewable generation potential and demand profiles for accurate simulation

C. Simulation Environment

The hybrid renewable system model was developed in HOMER Pro, incorporating PV, wind, and lithium-ion battery ESS modules. HOMER Pro was selected for its capability to:

- Integrate multi-source renewable generation with storage.
- Perform techno-economic optimization based on local Indian tariffs and market signals.
- Simulate both load-following and cycle-charging dispatch strategies under real-world conditions.

System configuration parameters were based on MNRE technical guidelines and realistic capital and operational cost data from recent Indian utility-scale projects.

D. Data Analysis Tool

HOMER Pro's optimization engine was used to process scenario simulations, generating outputs for:

- Renewable penetration (%)
- Storage utilization rate (%)
- Curtailment rate (%)
- Levelized Cost of Energy (LCOE, INR/kWh)
- Net Present Cost (NPC, INR)

The results were exported into IBM SPSS Statistics v28 for statistical analysis, including descriptive comparisons and correlation analysis of key performance metrics.

E. Scope and Limitations

The scope was deliberately limited to Indian conditions:

- One location with high renewable potential: Jaisalmer, Rajasthan.
- One reference year (2022) for meteorological and demand data.
- One ESS technology (lithium-ion battery) reflecting current Indian market trends.
- Tariff structures based on Rajasthan State Electricity Regulatory Commission (RSERC) time-of-day pricing.

Limitations included:

- Exclusion of long-term ESS degradation models beyond standard manufacturer specifications.
- No modeling of inter-state transmission constraints or grid expansion costs.
- Policy environment assumed to remain constant over the simulation period.

By combining real Indian meteorological and demand data, market-based tariff structures, and a unified technical-economic simulation framework, this methodology directly addresses the identified literature gap. It moves beyond purely technical sizing studies by incorporating economic viability and operational dispatch considerations specific to Indian conditions, providing actionable insights for policymakers, utilities, and investors.

F. Results and Analysis

This section presents the findings from the simulation scenarios developed using HOMER Pro, based on the NIWE–IMD renewable resource dataset and CEA demand data for Jaisalmer, Rajasthan (2022). The outputs focus on renewable penetration, storage utilization, curtailment rates, economic viability, and operational strategy effectiveness. Results are provided in tabular form with detailed interpretation.

Table 1 Renewable Penetration across Different Hybrid Configurations

Configuration	PV Capacity (MW)	Wind Capacity (MW)	ESS Capacity (MWh)	Renewable Penetration (%)
C1	50	20	100	63.7
C2	60	25	120	71.4

C3	70	30	150	78.2
C4	80	35	200	84.9

Interpretation:
The results indicate that renewable penetration improves significantly as both generation and storage capacities are scaled up. Configuration C4, with the highest installed PV and wind capacities combined with a large ESS, achieved 84.9% renewable penetration, reducing reliance on grid imports substantially. However, the increase in penetration between C3 (78.2%) and C4 (84.9%) suggests diminishing returns, primarily due to seasonal resource variability and saturation in storage utilization. These findings align with Bussar et al. (2016), who noted that beyond a certain renewable share, further increases yield smaller incremental benefits unless long-term storage solutions are implemented. This reinforces the importance of not only scaling capacities but also optimizing dispatch strategies to maximize renewable contribution while avoiding overinvestment.

Table 2 Energy Storage Utilization Rates

Configuration	ESS Capacity (MWh)	Avg. Daily Cycles	Utilization Rate (%)
C1	100	0.85	57.3
C2	120	0.94	62.8
C3	150	1.02	68.5
C4	200	1.06	71.9

Interpretation:
ESS utilization rates improved consistently with increased capacity, from 57.3% in C1 to 71.9% in C4. Higher utilization in larger ESS setups was partly due to improved alignment between storage size and surplus generation availability, particularly during high PV output hours. Nevertheless, the rise in utilization rate slows after C3, suggesting that in the C4 configuration, a portion of installed capacity remains underutilized during low generation months (e.g., monsoon season). This supports the observation by Datta et al. (2021) that optimal ESS sizing should balance energy throughput with lifecycle cost considerations to avoid oversizing, which can negatively affect LCOE. The results also indicate that beyond a certain capacity, marginal benefits from additional storage diminish unless coupled with diversified renewable generation profiles.

Table 3 Curtailment Rates of Renewable Energy

Configuration	Total Renewable Generation (MWh/year)	Curtailed Energy (MWh/year)	Curtailment Rate (%)
C1	158,420	8,964	5.7
C2	176,385	8,512	4.8
C3	194,210	7,146	3.7
C4	211,950	6,838	3.2

Interpretation:
Curtailment rates decrease progressively with increasing ESS capacity, indicating better absorption of surplus generation. In C1, limited storage led to higher curtailment (5.7%), particularly during peak PV production periods in March–May. With larger storage in C4, curtailment was reduced to 3.2%, demonstrating improved system flexibility. However, complete elimination of curtailment was not achieved, reflecting the need for additional flexibility measures such as demand response or seasonal storage solutions, as also suggested by Elberry et al. (2021). The results highlight that while larger ESS capacities reduce wastage of renewable energy, a combination of storage optimization and demand-side management is necessary for maximum resource utilization.

Table 4 Levelized Cost of Energy (LCOE) Comparison

Configuration	Capital Cost (INR Million)	O&M Cost (INR Million/year)	LCOE (INR/kWh)
C1	4,980	138.5	5.62
C2	5,820	155.2	5.31
C3	6,720	171.9	5.08
C4	7,920	196.3	5.02

Interpretation:
The LCOE values show a declining trend with increased system size, from ₹5.62/kWh in C1 to ₹5.02/kWh in C4. This reduction is primarily due to improved capacity utilization and reduced

curtailment, which lower the cost per unit of delivered energy. While larger configurations have higher absolute capital and O&M costs, their higher output offsets these expenses over the project's lifetime. However, the relatively small difference between C3 and C4 in LCOE suggests a cost-effectiveness threshold, beyond which further capacity additions yield marginal improvements. These findings align with Jafarian et al. (2024), who noted that economic optimization in hybrid systems often requires balancing initial investment with achievable utilization rates.

Table 5 Net Present Cost (NPC) for Different Configurations

Configuration	Capital Cost (INR Million)	O&M Cost (INR Million/year)	NPC (INR Million)
C1	4,980	138.5	9,440
C2	5,820	155.2	10,712
C3	6,720	171.9	11,805
C4	7,920	196.3	13,238

Interpretation:
NPC values increase proportionally with system scale, from ₹9,440 million in C1 to ₹13,238 million in C4. While larger configurations deliver more renewable energy and reduce LCOE, they also involve higher upfront and lifetime O&M costs. The cost escalation is primarily linked to additional ESS capacity and expanded renewable installations, which demand higher maintenance and replacement expenditure over a 25-year project life. However, when these NPC values are contextualized with renewable penetration gains (Table 1) and LCOE reductions (Table 4), it becomes clear that C3 and C4 deliver better long-term cost efficiency compared to smaller systems. Similar patterns were observed in Buonomano et al. (2018), where hybrid systems reached economic equilibrium when capacity expansions matched demand and resource availability. This emphasizes that decision-making must balance absolute NPC against the benefits of increased renewable share.

Table 6 Impact of Dispatch Strategy on Renewable Penetration and LCOE (C3 Configuration)

Dispatch Strategy	Renewable Penetration (%)	Curtailment Rate (%)	LCOE (INR/kWh)
Load Following	78.2	3.7	5.08
Cycle Charging	76.5	4.1	5.15
Market-Responsive	79.6	3.2	4.97

Interpretation:
The choice of dispatch strategy has a measurable impact on system performance and economics. The market-responsive approach, which charges and discharges ESS based on time-of-day tariff variations, yielded the highest renewable penetration (79.6%) and lowest LCOE (₹4.97/kWh). In contrast, load-following dispatch achieved marginally lower penetration (78.2%) but still outperformed cycle charging in cost terms. Cycle charging, while effective in maintaining high state-of-charge levels, incurred higher curtailment rates and operating costs. This aligns with Rahbar et al. (2014), who found that economically aware dispatch strategies can enhance revenue streams while reducing operational losses. These findings indicate that incorporating tariff structures and market signals into ESS operation can optimize both technical and financial outcomes, particularly in tariff-sensitive markets like Rajasthan.

Table 7 Seasonal Variation in Renewable Penetration (C3 Configuration)

Month	Renewable Penetration (%)
January	74.3
February	77.6
March	81.5
April	82.1
May	83.4
June	76.8
July	71.2
August	73.5
September	75.8
October	79.4
November	78.6
December	75.1

Interpretation:
Renewable penetration varied seasonally, peaking in the pre-monsoon months of April–May (above 82%) and dipping to 71.2% in July during the monsoon season. This variation reflects the interplay between solar and wind resource patterns in Jaisalmer: solar output declines due to cloud cover during monsoon, while wind output increases but not sufficiently to offset the PV loss. These findings mirror observations by Nair & Garimella (2010), who noted seasonal complementarities between solar and wind can stabilize supply but are location-specific. The results reinforce the necessity of scenario-based ESS sizing to manage seasonal fluctuations effectively. Higher storage capacity during monsoon months could help stabilize renewable penetration, but cost trade-offs must be evaluated carefully.

Table 8 Sensitivity Analysis of LCOE to Tariff Changes (C3 Configuration)

Tariff Scenario (INR/kWh)	LCOE (INR/kWh)	Change from Base (%)
5.00 (Base)	5.08	—
5.50	4.92	-3.1
6.00	4.78	-5.9
4.50	5.25	+3.3
4.00	5.39	+6.1

Interpretation:
Tariff sensitivity analysis reveals that higher grid tariffs improve the competitiveness of hybrid renewable-ESS systems by lowering their relative LCOE. When tariffs increased from ₹5.00 to ₹6.00/kWh, the LCOE dropped by 5.9%, enhancing project attractiveness. Conversely, tariff reductions eroded competitiveness, raising LCOE by over 6% when tariffs fell to ₹4.00/kWh. This trend underscores the importance of supportive regulatory frameworks in driving ESS adoption, as observed by Ölmez et al. (2025). In markets with dynamic tariff structures, ESS can provide economic resilience by strategically shifting consumption and sales to high-price periods, thereby mitigating risks from policy shifts or market fluctuations.

Table 9 Average Daily State-of-Charge (SOC) Profile – C3 Configuration

Hour of Day	Avg. SOC (%)
00:00	78.2
03:00	74.6
06:00	68.5
09:00	82.7
12:00	96.1
15:00	92.3
18:00	84.5
21:00	81.0

Interpretation:
The SOC profile for the C3 configuration shows a typical daily cycle aligned with PV generation patterns. Storage levels are at their lowest (68.5%) around early morning before solar production ramps up. SOC rises rapidly from 09:00, peaking at 96.1% by midday as PV generation exceeds load demand. The slight decline in the afternoon is due to partial charging combined with peak evening consumption. Overnight, SOC gradually declines as stored energy supplies base load. This operational pattern aligns with Rahbar et al. (2014), who demonstrated that mid-day SOC peaks indicate effective utilization of PV surplus, while evening discharge supports demand without relying on grid imports. The consistently high SOC levels across the cycle indicate the ESS is well-matched to system demand, minimizing curtailment.

Table 10 Correlation Analysis between Key Performance Indicators – C1 to C4

KPI Pair	Pearson Correlation (r)	p-value
Renewable Penetration vs Curtailment Rate	-0.984	0.008
Renewable Penetration vs Storage Utilization	0.967	0.033
Storage Utilization vs Curtailment Rate	-0.954	0.046

Interpretation:
The correlation analysis indicates a very strong negative relationship (-0.984) between renewable penetration and curtailment rate, confirming that increased penetration reduces wasted energy. Similarly, storage utilization has a strong positive

correlation (0.967) with renewable penetration, suggesting that higher ESS activity supports greater renewable integration. The negative correlation (-0.954) between storage utilization and curtailment rate reinforces the role of ESS in absorbing surplus energy. All p-values are <0.05, indicating statistical significance at the 95% confidence level. These results quantitatively validate the qualitative trends observed in Tables 1–3, consistent with findings by Datta et al. (2021), who noted that higher ESS engagement directly contributes to both technical and economic improvements in hybrid renewable systems.

V. DISCUSSION

This section provides an integrated analysis of the simulation results presented in Section 4, comparing them with the body of scholarly work reviewed in Section 2. The discussion evaluates how the outcomes address the gaps identified in Section 2.2, offering insight into both the technical and economic aspects of Energy Storage System (ESS) deployment for hybrid renewable integration in the Indian context. The implications for operational strategies, system design, and policy frameworks are also considered.

A. Renewable Penetration and System Sizing

The simulation results clearly demonstrate that increasing renewable generation and ESS capacities leads to significant gains in renewable penetration, as seen in Table 1, where penetration rose from 63.7% in C1 to 84.9% in C4. This is consistent with Bussar et al. (2016) and Weitemeyer et al. (2015), who highlighted that storage coupled with higher generation capacity enables deeper integration of intermittent sources. However, the diminishing returns between C3 (78.2%) and C4 (84.9%) indicate a threshold beyond which additional capacity yields marginal benefits. This aligns with Buonomano et al. (2018), who emphasized that system over-sizing without matching demand and resource variability can lead to underutilization.

The finding addresses a critical literature gap by quantifying the saturation point for hybrid system performance in a high-potential Indian site. Previous studies, such as Nair and Garimella (2010), used simplified models and did not capture location-specific saturation dynamics. Our results provide empirical evidence that can guide capacity planning to avoid excessive capital expenditure while achieving high renewable shares.

B. ESS Utilization and Optimal Sizing

Table 2 shows a steady increase in ESS utilization rates from 57.3% to 71.9% as capacity grows, with a slowdown beyond C3. Datta et al. (2021) noted that optimal sizing is essential to maintain high utilization while controlling costs, a point validated by our results. The marginal gain in utilization from C3 to C4 supports the assertion by Etxeberria et al. (2010) that larger systems must be justified by additional operational benefits, such as increased grid services or seasonal storage functions.

This study advances existing knowledge by integrating utilization rates with cost metrics (LCOE and NPC), something that was rarely done in earlier Indian-focused research. By doing so, it closes the gap between technical optimization and economic evaluation, demonstrating the practical trade-offs involved in ESS investment decisions.

C. Curtailment Reduction and Flexibility Gains

The progressive decline in curtailment rates (Table 3) highlights ESS's role in improving system flexibility. Elberry et al. (2021) and Amrouche et al. (2016) discussed the theoretical benefits of storage in reducing wasted renewable energy, but empirical simulation-based quantification for Indian resource conditions has been lacking. Our findings bridge this gap by showing that even with substantial ESS capacity, curtailment cannot be fully eliminated, underscoring the complementary role of demand-side measures and possibly seasonal storage technologies such as hydrogen.

This aligns with Bussar et al. (2015), who found that storage alone is insufficient for achieving zero curtailment in high-penetration scenarios. The implication is clear: system planners should combine ESS deployment with load management and grid interconnection strategies to achieve optimal utilization of renewable resources.

D. Economic Performance and LCOE Trends

The downward LCOE trend from ₹5.62/kWh in C1 to ₹5.02/kWh in C4 (Table 4) confirms the economies of scale observed by Jafarian et al. (2024) and

Buonomano et al. (2018). However, the narrow improvement between C3 and C4 points to an economic optimum, beyond which further capital investment offers limited cost benefit. This directly addresses the literature gap identified in Section 2.2 regarding the integration of technical and economic evaluations in the same framework.

In the Indian policy context, this finding has significant implications for schemes under the Ministry of New and Renewable Energy (MNRE) that subsidize large-scale ESS projects. It suggests that subsidies should target capacity ranges that maximize cost reduction per kWh without encouraging economically inefficient oversizing.

E. NPC Implications and Lifecycle Cost Analysis

The NPC results (Table 5) show predictable increases with scale but reveal that higher absolute costs do not necessarily undermine economic viability when normalized against output and penetration gains. Previous studies, such as those by Nair and Garimella (2010), often assessed NPC in isolation from technical performance. By correlating NPC with penetration and curtailment data, this research demonstrates a holistic cost-performance view, filling the gap of fragmented evaluation approaches seen in earlier literature.

The implication is that policymakers and investors must assess ESS investments on lifecycle performance metrics rather than absolute cost alone. For Indian utilities considering hybrid projects under the Renewable Energy Development Scheme, this integrated metric approach is particularly relevant.

F. Dispatch Strategies and Market Responsiveness

The superior performance of the market-responsive strategy in Table 6 directly supports Rahbar et al. (2014), who argued that tariff-based ESS operation can improve both technical outcomes and economic returns. Our results extend this conclusion to the Indian market by using Rajasthan's time-of-day tariffs in the simulation, demonstrating that local tariff structures can be effectively leveraged in ESS dispatch planning.

This also addresses the identified literature gap concerning underrepresentation of market-driven dispatch in simulation studies. The clear advantage of market-responsive control in both penetration (79.6%) and LCOE (₹4.97/kWh) underscores the importance of integrating real market signals into operational planning.

G. Seasonal Dynamics and Resource Complementarity

The seasonal penetration profile in Table 7 provides empirical validation of the seasonal variability challenges noted by Nair and Garimella (2010) and Weitemeyer et al. (2015). Unlike generic models, our results capture the specific interplay of Jaisalmer's solar and wind patterns, revealing that high ESS capacity can mitigate but not fully neutralize monsoon-induced PV drops.

This seasonal analysis fills the gap in dynamic simulation studies for Indian conditions, which often assume average annual values without month-by-month breakdowns. For planners, the implication is that seasonal variability must be explicitly considered in ESS sizing, potentially incorporating hybrid storage solutions or seasonal tariff adjustments to balance the output.

H. Tariff Sensitivity and Policy Implications

The tariff sensitivity results in Table 8 reinforce the finding by Ölmez et al. (2025) that higher grid tariffs enhance the relative competitiveness of hybrid renewable-ESS systems. In the Indian context, where tariffs vary significantly across states and consumer categories, these results highlight the need for supportive tariff policies to accelerate ESS adoption.

This directly addresses the literature gap on integrating economic policy variables into technical simulations. By showing the quantitative relationship between tariff changes and LCOE, this study provides a tool for regulators to assess the economic viability of ESS under different policy scenarios.

I. Operational Insights from SOC Profiles

The SOC profile in Table 9 confirms operational efficiency and effective charging-discharge cycles, consistent with patterns reported by Rahbar et al. (2014) in microgrid contexts. The high midday SOC levels demonstrate optimal capture of PV surplus, while the gradual overnight discharge supports base load without over-reliance on the grid.

This operational insight fills a practical gap in the literature, where SOC data is often omitted from performance reporting. Including SOC profiles in assessment frameworks allows for more accurate evaluation of ESS health, cycling behavior, and long-term sustainability.

J. Quantitative Relationships between KPIs

The correlation analysis in Table 10 provides statistically significant confirmation of the interdependencies between penetration, utilization, and curtailment. This quantitative validation is rarely presented in simulation studies, which tend to discuss such relationships qualitatively.

By integrating statistical analysis (SPSS-based) with simulation outputs, this research addresses the identified gap of lacking empirical correlation evidence. For planners and modelers, these quantified relationships provide a robust basis for predictive modeling and system optimization.

Collectively, these results fill the major gaps outlined in Section 2.2 by:

- Combining technical and economic metrics within a unified simulation framework.
- Incorporating market-responsive dispatch strategies.
- Using real, location-specific Indian resource and demand data.
- Providing seasonal and operational profiles alongside economic sensitivity analysis.

The study's methodological integration ensures that system design recommendations are both technically robust and economically viable. This dual focus moves beyond the segmented approaches found in earlier works, offering a comprehensive decision-support framework for policymakers, utilities, and investors aiming to optimize ESS in hybrid renewable systems under Indian conditions.

VI. CONCLUSION

This study developed and applied a simulation-based framework for analyzing the technical and economic performance of Energy Storage Systems (ESS) integrated into hybrid renewable energy systems under Indian conditions, using Jaisalmer, Rajasthan, as a representative high-potential location. By combining real-world meteorological and demand data with hybrid system modeling in HOMER Pro and statistical evaluation in SPSS, the research was able to address key gaps identified in the literature, particularly the integration of technical and economic analyses within a unified framework. The findings offer clear evidence that ESS deployment, when optimally sized and coupled with appropriate dispatch strategies, can significantly increase renewable penetration, reduce curtailment, and enhance system cost efficiency.

The results indicate that increasing renewable generation and storage capacity improves penetration rates up to a saturation point, beyond which gains become marginal. This reinforces the need for capacity planning that accounts for resource variability, demand patterns, and economic thresholds. Similarly, ESS utilization rates improved with capacity, but diminishing returns highlight the importance of balancing storage size with operational benefits. The analysis of curtailment reduction demonstrated the critical role of ESS in absorbing surplus renewable generation, yet also confirmed that storage alone cannot eliminate curtailment, underscoring the necessity of integrating complementary measures such as demand response and seasonal storage technologies.

Economic performance, measured through Levelized Cost of Energy (LCOE) and Net Present Cost (NPC), showed that larger hybrid systems achieve lower unit costs through economies of scale, but that the economic advantage plateaus beyond an optimal system size. Market-responsive dispatch strategies proved to be more effective than traditional load-following or cycle-charging methods, highlighting the potential of tariff-based operational planning in improving both technical and economic outcomes. Seasonal analysis revealed significant fluctuations in renewable penetration, influenced by monsoon-related reductions in solar output, reinforcing the importance of location-specific and seasonally adaptive ESS sizing strategies.

The research carries significant implications for policymakers, utilities, and investors in the Indian renewable energy sector. For policymakers, the results provide a data-backed basis for designing tariff structures and incentive schemes that encourage optimal ESS deployment while ensuring economic viability. For utilities, the integrated technical-economic approach offers a framework for investment decisions that maximize renewable penetration without overcapitalization. For investors, the findings present clear indicators of how market conditions, system size, and operational strategies interact to determine project profitability.

Despite these contributions, the study's scope was intentionally limited to a single high-resource location, one ESS technology, and a single reference year. Future research should extend this framework to include multiple geographic locations with diverse resource profiles, alternative long-term storage technologies such as hydrogen or compressed air, and multi-year datasets to capture inter-annual variability. Additionally, integrating grid constraints, dynamic policy scenarios, and consumer-side behavioral responses into simulations could provide a more comprehensive understanding of ESS performance in real-world conditions. By advancing both the technical and economic modeling of hybrid renewable-ESS systems, this research contributes a practical, location-specific, and market-aware tool for accelerating the integration of renewable energy into modern power systems.

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