

Research Article

Renewable Energy Integration in Power Systems: Optimal Dispatch, Battery Storage, and Operational Performance

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Abstract

The increasing penetration of renewable energy sources, particularly solar and wind power, introduces significant operational challenges for modern power systems due to their variability and uncertainty. This study presents and evaluates a modelling and optimization framework to investigate the effects of renewable energy penetration on operating costs, carbon emissions, transmission losses, renewable energy curtailment, thermal generation requirements, and system flexibility. The framework is applied to a modified IEEE 39-bus test system incorporating conventional generating units, solar and wind generation, and a battery energy storage system (BESS). A multi-period optimal power flow model is used to evaluate four renewable energy penetration scenarios (0%, 20%, 35%, and 50%) over a 24-hour period. The optimization aims to minimize daily operating costs and carbon emissions while satisfying power balance, generator operating limits, ramp-rate constraints, transmission-line limits, and battery state-of-charge (SOC) constraints. The results indicate that daily operating costs decrease by 51.05%, from USD 1.898 million to USD 0.929 million, as renewable energy penetration increases from 0% to 50%. Daily carbon dioxide emissions decrease from 19.689 to 5.562 kilotonnes, while peak thermal generation decreases by approximately 38.81%. The 35% penetration scenario achieves the lowest transmission losses, with renewable energy curtailment limited to 2.65%. At 50% penetration, curtailment increases to 14.56%, primarily due to network congestion, minimum-generation constraints, and insufficient system flexibility. Optimized battery operation further reduces renewable energy curtailment, peak thermal generation, and the maximum thermal-generation ramp rate. These findings highlight the importance of coordinated energy storage, flexible generation, and transmission network enhancements in managing the operational challenges associated with high renewable energy penetration.

Keywords: Renewable Energy Integration; Power-System Optimization; Solar Energy; Wind Energy; Battery Energy Storage System; Optimal Power Flow; Renewable Curtailment; Carbon Emissions; Transmission Losses; IEEE 39-Bus System.

INTRODUCTION

The global energy sector is undergoing a significant transformation driven by decarbonization targets, technological advances, declining renewable energy costs, and the increasing electrification of energy end uses. Solar photovoltaic (PV) and wind power have

become central components of this transition. Continued reductions in the costs of solar PV, wind generation, and battery energy storage have strengthened the economic competitiveness of renewable energy technologies and accelerated their deployment. According to the International Renewable Energy Agency (IRENA), global renewable power capacity increased by a record 582 GW in 2024, with solar PV accounting for approximately 452 GW of new installations [1, 2]. In addition, the global installed cost of utility-scale battery energy storage systems declined by 93% between 2010 and 2024, reaching USD 192/kWh. These developments demonstrate that the transition towards renewable electricity systems is driven not only by environmental objectives but also by improving economic competitiveness and the potential to enhance energy security.

Despite these advantages, wind and solar technologies impart many challenges to the operation of traditional power systems using fossil fuels. Unlike dispatchable thermal generators, solar and wind energy generation is dependent on weather events and therefore tends to be unpredictable, intermittent and uncertain to forecast. High penetration of renewable energy may cause rapid changes in net load, counter flows of power, voltage fluctuations for facilities and the system as a whole, network congestion and high demand for operational reserves [3, 4]. These effects are vital during the distribution and transmission stages, especially when renewable output clusters at electricity weak nodes or where the transport capacity of existing networks is troubled in having this ability to transfer renewably-generated power from generation zones to main demand hubs. Research on machine-learning improve forecasting and smart control techniques is gaining impetus to mitigate uncertainty; yet forecasting errors cannot be completely eliminated and must therefore be incorporated into planning and operational optimization methods [4].

One major consequence of the variable nature of renewable energy generation is the increased need for flexibility in power systems. In electricity, flexibility is all about the ability of a power system to adjust to variable generation and consumption consistent with technical, reliability and cost constraints. Horizontally, traditional generating units can provide flexibility through ramping and spinning reserve services; however, their minimum generation limits, startup restrictions and ramp-rate limitations may reduce the potential of renewable energy penetration. As the penetration rate increases, there are cases where extreme wind or solar generation is higher than what either grid and conventional producers can respond to, causing curtailment of renewable generation. Previous studies have shown that curtailment can be an important factor of systems with high shares of variable renewable energy unless some combination of storage, improved transmission, flexible supply or demand-side resources are used; therefore, simply adding renewables capacity does not necessarily imply more use of renewable energy [5, 6].

This is why optimal power flow (OPF) has emerged as the vital mathematical tool for evaluation of renewable integrated power systems. The OPF determines the optimal operational point financially or technically under power-balance calculations, generator constraints, voltage limits and line transfer limits. However, the integration of renewables

renders the OPF problem much more complex as it must now also consider renewable variability, temporal constraints, energy storage, multiple objectives and network nonlinearities [7, 8]. Traditional OPF models have been so recently extended to account for stochastic renewable generation, energy storage management, carbon emissions with curve analysis and renewable curtailment with security restrictions [7–9]. Multi-objective Optimal Power Flow is particularly relevant because only minimizing generation costs; one can face operational results that may be environmentally unsustainable or technically rigid. Economic, environmental, and security metrics should be assessed together.

Modern renewable-integrated systems require optimization over multiple time intervals rather than just at discrete steady-state operational conditions. Multi-period scheduling directly links generator ramp rates, hourly demand variations, renewable availability, reserve requirements and battery charge limits over multiple time horizons [10–12]. This time-dependent representation is important because an excess of solar generation at noon may serve to change generator schedules and hours of energy storage later in the day. Not surprisingly, evening power might need to rise rapidly if solar energy generation drops quickly, too. Flexibility should be incorporated directly into unit scheduling and dispatch problem, rather than being treated only as a post-optimization performance metric for power systems [11–13].

One of the most promising developments addressing these operational issues is energy storage. Energy storage systems (ESS), including battery energy storage systems (BESSs) hold electricity when renewable energy is excessive and provide the power whenever demand is higher or availability of renewable resources reduce. In addition to energy arbitrage, batteries help frequency management, operating reserves, peak shaving applications; and renewable energy smoothing and congestion relief and voltage support. Storage is much more than just battery chemistry; even the same type of storage technology can have very different efficacy depending on the power, energy, and charge/dispatch configurations [14–17]. Recent optimization studies suggest that synchronizing Battery Energy Storage Systems (BESS) may reduce renewable energy curtailment and operational costs in grids with high renewable generation penetration. The scale of storage also needs to be weighed against generation and system operating costs because too much battery deployment could increase capital expenditure but without commensurate benefits on the operational side.

Geographical location and coordinated energy storage management are also important factors in renewable energy integration. As discussed by [18], the functional requirements and capacity needs of energy storage systems can vary considerably depending on whether they are located near renewable energy resources, conventional generation units, or demand centers. Similarly, coordinated operation of renewable generation and energy storage, together with appropriate energy management strategies, can significantly affect annual power losses and network operating performance [19]. These findings highlight that renewable energy integration involves more than simply increasing generation capacity; it requires coordinated optimization of generation, transmission networks, and

energy storage. Various mathematical, metaheuristic, and hybrid optimization methods have been investigated to address these challenges, as documented in recent reviews [20–24]. These methods include mixed-integer programming (MIP), particle swarm optimization (PSO), genetic algorithms (GA), the non-dominated sorting genetic algorithm II (NSGA-II), grey wolf optimization (GWO), and approaches augmented with machine learning.

Recent developments continually emphasize that future optimization approaches need to combine economic efficiency, environmental targets, flexibility, deteriorating storage system and limitations renewable energy sources with network security seamlessly. Grid-scale BESS investigations highlight the relevance of state-of-charge regulation, power-conversion approaches, up-scaling methods, and types of market structures [25–27]. Moreover, the 2026 study finds that in high-renewables systems curtailment indeed is an important wind-curtailment or solar-curtailment planning parameter, as those systems are likely to have very large installed renewable capacities but at the same time may experience significant renewable rejection and security challenges. Network limitations must be taken into account in the optimization, as distributed renewables can also incur voltage fluctuations, reverse currents or equipment overloads [28].

The main objective of this study is to provide a simulation and multi-objective optimization framework-based analysis for the integration of solar photovoltaic, wind energy and battery storage technologies into an updated IEEE 39-bus power system. The study investigates four renewable-energy availability scenarios throughout a 24-hour operational period with renewable availability of 0%, 20%, 35% and 50%. The framework simultaneously optimizes generation costs, carbon emissions, curtailment of renewables, line losses, limits for units on/off and ramp-rates, bus-voltage constraints and capacities of lines and reserves in addition to state-of-charge dynamics for batteries. An adaptive particle swarm optimization approach is employed to determine feasible schedules, and conduct economic–environmental trade-offs associated with better renewable penetration. In contrast, the proposed methodology provides a holistic analysis of their effects on operational costs, cost of CO₂ emissions, necessary thermal generation to meet demand and serve reserves, flexibility provisioning by flexible power plants versus storage technologies and usable renewables as well as grid performance in terms of overall utilization efficiency. This study not only aims to determine the maximum level of renewables that can be integrated, but also what level and manner of integration achieves an appropriate balance in economic viability, environmental improvement, grid resilience, and operating flexibility.

Research Gap

Despite rapid progress in renewable energy technology and the wider use of battery energy storage systems in modern-day electricity systems, there are however constraints to such existing work. The vast majority of current literature focuses on partially developing renewable integration, either as some combination between minimizing operational costs, emissions and power-system operation or storage scheduling. Many

studies investigate these goals separately, but the interaction among renewable integration, network losses, renewable curtailment, thermal generation flexibility and battery operation is often overlooked. Hence, it is still difficult to know whether the penetration level of renewables that provides best economic performance also provides the best technical performance.

The most important shortcomings relate to the nonlinear reaction of the power system when renewable integration increases. Increasing solar and wind generation alone does not necessarily mean that the network will be able to capture the same fraction of renewables. Transmission restrictions, minimum thermal generation requirements, reserve requirements, and battery operational characteristics may all increase curtailment and change power flows at these higher penetration levels. Thus, a higher percentage of renewables could reduce costs and carbon emissions but might increase transmission losses or require greater operational flexibility. In research that focuses only on renewable capacity or generation costs, this tradeoff is not often analyzed rigorously.

Battery energy storage generates another research gap. BESS is widely recognized as a powerful solution to reduce renewable curtailment and enable flexible operation, but its role in many technical metrics remains ambiguous. Charging and discharging batteries can reduce peak thermal generation, while battery dispatch can also alter power flows and transmission losses across the network. Therefore, the standalone impact of storage on renewable output, network efficiency, operational expenses, emissions and thermal generation needs must be evaluated.

In addition, many renewable integration assessments utilize single-period or stylized steady-state evaluations when the effect of consecutive operational hours is key to true system operation. Temporal interdependencies created with tight physical limits in generator ramp-rates, variability of hourly demand, intermittent nature of renewables and battery charge levels/discharge regimes will not be handled properly using independent hourly assessments for electricity generation. We therefore require a multi-temporal framework that can evaluate how foundational decisions taken in one hour affect the operational state of our systems at other times.

To address the identified research gap, this study proposes a multi-period assessment framework for evaluating the economic, environmental, and technical implications of renewable energy integration over a 24-hour period. The framework is applied to a modified IEEE 39-bus test system under four renewable energy penetration scenarios: 0%, 20%, 35%, and 50%. The analysis simultaneously evaluates operating costs, carbon dioxide emissions, transmission losses, renewable energy curtailment, thermal generation requirements, and the operational behaviour of conventional generators and battery energy storage systems. This integrated assessment enables comparisons of the economic and environmental benefits of different renewable energy penetration levels while identifying the associated technical challenges and operational trade-offs.

DATA AND METHODOLOGY

Dataset

Electrical network parameters used in this study were taken from IEEE 39-bus New England test system from MATPOWER. Such as active and reactive bus loads, generator limitations, voltage limits, transmission line reactance's, transformer parameters and network configuration are also provided by the benchmark for power-flow as well which we have seen in [29, 30]. The MATPOWER case39 provides the New England 345 kV transmission network and extracts fundamental system information from the classical benchmarking described in [31].

The hourly demand profile used in this simulation was generated by scaling (up or down) the original IEEE 39-bus demand according to a typical 24 h-a-day load curve and keeping the original spatial distribution of demand among the buses unchanged. The maximum load of 6254.23 MW is used as a benchmark simulation value rather than as measured data from a specific electricity market. Open Power System Data [32] is cited as a supporting source for typical hourly demand, wind, and solar profiles.

The solar and wind power profiles were generic renewable energy profiles created for regulated scenario assessment. The total daily output from all plants was scaled to match 20%, 35% or 50% of the daily electricity demand met by renewables for consideration. ERA5 [33] and the National Solar Radiation Database (NSRDB) [34] are cited as supporting data sources; the renewable profiles used in this study were normalized scenario profiles.

The battery energy storage system was designed for a maximum capacity of 500 MW/2000 MWh, indicating that it is sized to provide up to four hours of storage time, and a round-trip efficiency factor of 90%. These features are chosen as representational utility-scale storage metrics for scenario analysis instead of being based on an exact operational battery system. This is primarily the four-hour duration lithium-ion systems that are included in NREL Annual Technology Baseline, which provides performance and cost data for utility-scale battery systems covering a 2–10-hour storage durations.

The data on generator operational expenses, levels of renewable integration, battery timetables, curtailment, transmission inefficiencies, operational costs & carbon emission outcomes in this study were analysed and quantified independently from the optimization model. Therefore, the reported numerical values should be interpreted as benchmark simulation results. Costs and performance characteristics of technologies may also be compared against the NREL Annual Technology Baseline, which provides data-driven estimates for technology costs, capacity factors, operating expenses (O&M), and other key characteristics of wind, solar PV, thermal generating, and battery storage technologies [35].

The overall procedure used to evaluate the integration of renewable energy within the modified IEEE 39-bus system is illustrated in Figure 1. The process consists of data preparation, renewable integration scenarios, optimization modelling and limitations on the system. All scenarios are modelled and evaluated according to unscheduled generation costs, CO₂ emissions, transmission loss, renewable curtailment and peak thermal

production. A final assessment is made to determine the best plan for renewable energy integration.

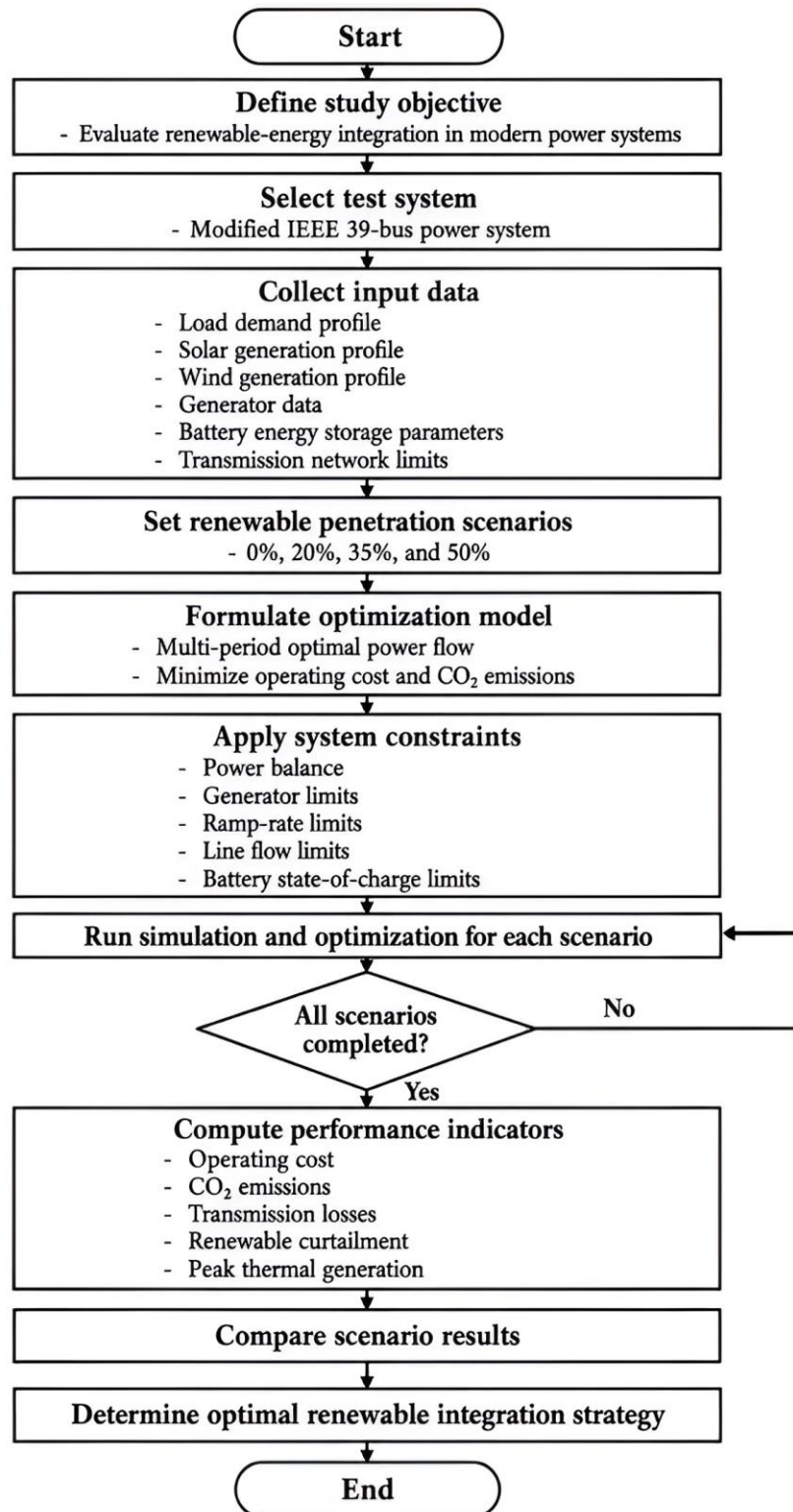


Figure 1. Flowchart of the Proposed Simulation and Optimization Framework for Renewable Energy Integration.

IEEE 39-Bus Test System

The altered IEEE 39-bus network is selected as it has a reasonably complex transmission system to study renewable penetration, yet computationally simple enough. It represents the New England power system with 39 busses, together with 10 traditional producing units and interconnected transmission lines.

The first batch of bus thermal and voltage limits, generator bounds, line specifications, voltage requirements and net topology was obtained from IEEE 39-bus benchmark used in MATPOWER. The overall system active power demand was approximately 6254.23 MW.

Bus 21 was connected to a battery energy storage system. These sites were leveraged to investigate the opportunities, and cost savings, due to renewable generation and storage across their local, regional and even national scale electricity transmission network.

Hourly Load Modelling

The original IEEE 39-bus test system contains static demand values. Therefore, the loads were converted into hourly demand values using a normalized 24 h demand profile. The profile represented typical daily operation, with relatively low demand during early morning hours, increasing consumption during daytime, and an evening peak.

The active power demand at each bus was calculated as:

$$P_{i,t}^D = P_i^{D,peak} \lambda_t \quad (1)$$

where $P_{i,t}^D$ is the demand at bus i during hour t , $P_i^{D,peak}$ is the corresponding peak demand, and λ_t is the hourly load factor.

The same normalized pattern was applied across buses while maintaining the original spatial distribution of system demand. Reactive-power demand was scaled proportionally to preserve approximately the same power factor as the original benchmark network.

The resulting daily system demand was approximately 126.6 GWh, with the maximum hourly value corresponding to the benchmark peak load.

Renewable-Energy Generation Profiles

Instead of using continuous generation from solar and wind energy sources, we used normalized hourly production profiles. This method allowed the action of generators, operation of batteries, loading of lines and renewable reductions to be determined by the variability in renewables.

Solar power generation ceased overnight, increased after sunrise, peaked around midday, and then declined as dusk approached. Wind power generation exhibited a similar temporal pattern but was considerably higher during the night and evening than during daylight hours.

For each renewable scenario, the available solar and wind resources were extended to 20%, 35% or 50% beyond daily electricity demands. In the simulation, 55% of renewable energy resources consisted of solar energy and 45% of wind.

Renewables were considered inexpensive megawatts, resulting in their prioritization by the optimizer. However, this renewable energy data can be limited when its optimal

deployment is hampered by network congestion, minimum conventional generation mandates, reserve constraints or battery limitations.

The peak curtailment was computed in the manner described above, and it is presented as a percent of the renewable output lost under non-peaking operation.

$$R_{curt} = \frac{E_{available}^{RE} - E_{used}^{RE}}{E_{available}^{RE}} \times 100\% \quad (2)$$

where $E_{available}^{RE}$ is the total available renewable energy and E_{used}^{RE} is the renewable energy actually delivered to the system.

Conventional Generation Model

The conventional generators provided the controllable base load needed to balance generation and use of the power. Each unit was characterized by the minimum and maximum active power, reactive power limits, ramping capability and generating costs.

A traditional quadratic cost function was demonstrated to show the cost of generation. The optimization instead selected the combined operation of all thermal units over this 24h window rather than the individual reduced costs down through each generator.

Ramp-rate limitations for generators were particularly impactful in renewable integration scenarios. The thermal units must modify their output in a limited time due to the fast variations of solar and wind energy shape. A generator's power generation at time t , one hour, was related to its power generation in the previous hour.

Linking these two temporally prevented unrealistic changes in heat generation from being made while at the same time making the simulated dispatch more representative of real power-system operation.

Battery Energy Storage System

The BESS has a 500 MW peak power and 2000 MWh energy storage capability, i.e. about four hours of operation at full power. The round-trip efficiency was modelled to be 90%. The battery is responsible for two main jobs. It initially absorbed excess renewable generation whenever the solar or wind energy exceeded what the network could realistically absorb directly. Second, it discharged energy on high-demand or low-renewable generation days.

The state of accumulated battery energy was calculated using the following relation at average time period:

$$E_t = E_{t-1} + \eta_{ch} P_t^{ch} \Delta t - \frac{P_t^{dis} \Delta t}{\eta_{dis}} \quad (3)$$

where E_t is the battery energy at hour t , P_t^{ch} and P_t^{dis} are the charging and discharging powers respectively, η_{ch} , η_{dis} are efficiencies.

A maximum charge level was limited to approximately 10–90% of the respective energy capacity so that a full charge and total discharge would be avoided. In addition, simultaneous charging and discharging were not allowed. This was used to limit the ultimate battery condition near its initial value and prevent the optimizer from driving

down the daily operational cost of a storage system model by balancing it all out at zero with no energy being available in storage each day at the end simulation.

Multi-Period Optimal Power-Flow Formulation

A multi-period optimal power-flow model was applied over all 24 operating hours. This formulation connected successive periods using state of charge and thermal-generator ramp rates instead of distinct hourly power flows.

The cumulatively produced power for 1 hour, including battery drain, was needed to provide the electricity demand and battery charging needs while taking into account transmission losses. The fundamental power balance equation is given by:

$$\sum P_{g,t} + P_t^{PV} + P_t^W + P_t^{dis} = P_t^D + P_t^{ch} + P_t^{loss} \quad (4)$$

The terms represent classical generation, solar generation, wind generation, battery discharging, demand (load), charging of the battery and energy losses on the grid.

The model also imposed limits on generator output, voltage limits, thermal line capacity, ramp-rate constraints on transmission lines and generators, fuel availability for renewable resources. wind generation or battery charge level; reserve requirements are met by the system.

AC power-flow analyses were used to demonstrate standards compliance, ensuring every possible operating state satisfied bus-voltage and transmission-network performance criteria. Penalties were imposed on options leading to unacceptable voltage oscillations or line overloading during optimization steps.

Objective Function

The optimization was made to balance economic efficiency, ecological effectiveness, use of renewable resources, and network performance. Thus, the overall objective function can be stated as:

$$\min F = w_1 C_{op} + w_2 E_{CO_2} + w_3 E_{curt} + w_4 E_{loss} + \Phi \quad (5)$$

where C_{op} is the operating cost, E_{CO_2} represents carbon emissions, E_{curt} represents curtailed renewable energy, E_{loss} represents transmission losses, and Φ is a penalty applied when operational constraints are violated.

To obtain the overall average of these components, the individual variables were standardized away to prevent them from overshadowing one another when optimizing, solely due to their respective unit.

This included traditional generating costs, and the operating costs associated with battery cycling. Emissions from carbon were based on the output from traditional thermal generators while solar and wind resources had assumed no direct operating emissions.

Optimization Procedure

A metaheuristic for adaptive particle swarm optimization was then used to determine the most practical operation schedule. The proposed systems showed the hourly output of

thermal generators, solar generation and wind generation with included charging or discharging from batteries for a 24-h period.

To ensure computational feasibility and strict adherence to physical network bounds, the multi-period optimal power flow problem was evaluated using full AC power-flow equations via MATPOWER's power-flow kernel at each iteration. Non-linear AC inequality constraints including bus voltage limits ($V_{\min} \leq V_i \leq V_{\max}$) and transmission line thermal limits ($S_{ij} \leq S_{ij,\max}$) were enforced using quadratic penalty functions incorporated into the composite objective function term Φ in equation (5). Candidate solutions violating voltage or branch constraints were heavily penalized, guiding the APSO search strictly toward feasible operating regions.

The search was initialized using a population of feasible candidate schedules. At each iteration, every candidate solution was evaluated using hourly power-flow analyses that determined their operational costs, emissions, curtailments, losses and constraint violations.

The search was conducted for a maximum of 4000 iterations. During the earliest stages, a wider exploration capability was retained to investigate multiple regions of the solution space. The optimization progressively became more concentrated on the best paths.

The objective function was verified by showing that optimization had converged. The final solution was ratified immediately after all the operational limitations had been satisfied and additional iterations added little improvements.

Performance Evaluation

The final scenarios were analysed in terms of daily operational costs, CO₂ emissions, energy losses in the transmission system, renewable energy consumption, renewable energy curtailment, peak thermal generation capacity; maximum hourly thermal ramp rate and battery throughput.

The percent change over the standard reference scenario using:

$$Improvement(\%) = \frac{Y_o - Y_s}{Y_o} \times 100\% \quad (6)$$

where Y_o is the performance measure for the 0% renewables scenario and Y_s is the corresponding value for scenario s .

This comparison method allows one to evaluate if adding renewables continually benefits system efficiency or if at some point due to technological limitations almost any added renewable capacity will have limited value. This has largely fed into the balance of low operational costs and emissions vs increased renewable curtailment (and need for network flexibility).

RESULTS

The results suggest a significant reduction on operational costs and CO₂ emissions in the case of integrating high renewable energy levels with the IEEE 39-bus system. The 35% scenario- which very little curtailment and lower transmission losses suggested the

optimal technical balance, but the economic and ecological advantages were most significant in the 50% scenario. The addition of battery storage increased renewable use and reduced thermal ramping, but more renewables led to greater curtailment.

The main attributes of the testing system utilized in the simulation are summarized in Table 1 present the IEEE 39-bus New England system, which is a modified version of the original day with complex network transmission to study renewable energy power-flow, generator placement, and network constraints was selected. It consists of 39 busses and 10 conventional generators and the simulations were held for a time horizon of 24 hours called hourly resolution.

The actual maximum demand of the system peaked at approximately 6254.23 MW, which corresponds to a daily power consumption of 126.6 GWh. Geographically dispersed generation was illustrated by incorporating renewable energy sources at some substations. Photovoltaic solar energy was connected to Bus 4, wind power was incorporated at Bus 16, and battery storage was set up at Bus 21. The battery had a nameplate capacity of 500 MW/2000 MWh with 90% round-trip efficiency from SOC range of NEW NMC 10%-90%. The battery was set up to absorb excess renewable power and help the system through peak demand periods using these benchmarks. The system response to increased solar and wind integration was then investigated in four scenarios of renewable energy integration.

Table 1. Main Parameters of the Modified IEEE 39-Bus Test System

Parameter	Value/Description
Test system	Modified IEEE 39-bus New England system
Number of buses	39
Conventional generators	10
Simulation period	24 h
Time resolution	1 h
Peak system demand	6254.23 MW
Approximate daily energy demand	126.6 GWh
Solar PV location	Bus 4
Wind farm location	Bus 16
Battery location	Bus 21
Battery power rating	500 MW
Battery energy capacity	2000 MWh
Battery round-trip efficiency	90%
Battery SOC limits	10–90%
Renewable scenarios	0%, 20%, 35%, and 50%

The impact of different levels of renewable energy integration on system performance was assessed using the renewable energy scenarios presented in Table 2. Scenario S0 represents the reference case, in which electricity demand is met entirely by conventional generation technologies. Scenario S1 assumes that renewable energy sources supply 20%

of daily electricity demand. In this scenario, all available renewable energy is utilized, and no renewable energy curtailment is required.

The actual amount of renewable energy contributing truly to the system at 35% was in fact only 34.07%, while only 2.65% of the available renewable energy would have to be curtailed. This means that the system has plenty of flexibility to keep successfully transmitting most of the additional solar and wind energy generation. However, with 50% renewable availability, the actual renewable contribution decreased to 42.72%, while curtailment increased to 14.56%. This divergence indicates that thermal-limited generators may hit maximum capacities which reduce the possible rate of renewables inclusion at high penetration levels. This means that, as the chart shows, installed capacity for renewables doesn't always correlate with actual usage.

Table 2. Renewable-Energy Penetration Scenarios

Scenario	Available Renewable Energy	Renewable Energy Utilized	Renewable Curtailment	Main Description
S0	0%	0.00%	0.00%	Conventional reference system
S1	20%	20.00%	0.00%	Moderate renewable integration
S2	35%	34.07%	2.65%	High renewable integration
S3	50%	42.72%	14.56%	Very high renewable integration with BESS

The main technical, economic and environmental indicators are compared for all renewable energy scenarios in Table 3. The reference scenario caused highest operational costs, most CO₂ emissions, largest transmission losses, and highest peak thermal-generation requirement of 6254.23 MW. As renewable energy sources became a larger share of the system, it provided less bluster from conventional generation and many benefits both economically and ecologically.

At 20% integration of renewable energy, the daily operating costs reduced to USD 1.260 million/day and CO₂ emissions decreased to 6.688 kilotons per day. 35% penetration improved progress, with operating costs reduced to USD 1.038 million/day and transmission losses limited to 1101.29 MWh/day. The maximum renewable capacity, along with operating cost (USD 0.929 million/day) and emissions (5.562 kt/day), were decreased at their peak values. Maximum thermal output steadily decreased, arriving at 3826.97 MW in the 50% scenario. Results show that high diffusion of renewable energy greatly reduces dependence on conventional generation, but at the same time it is not always true that when renewable penetration rises higher, network losses decline too.

Table 4 presents the percentage improvement of each renewable-energy scenario relative to the 0% renewable baseline. Such representation, allows for a better understanding of the magnitude of the changes when only assessing absolute numbers.

Operational cost savings were approximately 33.61%, and CO₂ reduction of about 66.03% with the deployment of renewable energy, at 20% renewable integration. It enables

the conclusion that even only a small deployment of renewable resources could provide massive ecological benefits. Thus, the 35% renewable scenario resulted in a decrease of operational cost by 45.31%, emissions by 69.88%, and transmission losses by an average of 18.14%. This context resulted in the largest improvement in transmission loss.

Table 3. Overall Performance of the Renewable-Energy Scenarios

Renewable Penetration	Operating Cost (million USD/day)	CO ₂ Emissions (kt/day)	Transmission Losses (MWh/day)	Peak Thermal Generation (MW)
0%	1.898	19.689	1345.36	6254.23
20%	1.260	6.688	1203.31	4829.74
35%	1.038	5.931	1101.29	4335.04
50%	0.929	5.562	1192.59	3826.97

The reduction in operating cost was 51.05%, and also led to a 71.75% reduction of CO₂ emissions at the penetration rate of 50%. Peak thermal generation decreased by about 38.81%. However, the reduction in transmission loss was not as significant as it would be worked out for any similar scenario of 35 %. This confirms that minimizing the integration cost of renewables is not in general the optimal outcome for each actual technical performance indicator.

Table 4. Percentage Improvement Relative to the Conventional Scenario.

Renewable Penetration	Cost Reduction (%)	CO ₂ Reduction (%)	Transmission-Loss Reduction (%)	Peak Thermal-Generation Reduction (%)
20%	33.61	66.03	10.56	22.78
35%	45.31	69.88	18.14	30.69
50%	51.05	71.75	11.36	38.81

Table 5 presents the performance analysis of the battery energy storage system under the challenging renewable power scenario. So, the analysis made the comparison between the 50% renewable scenario with inactive BESS dispatch and the same case with optimized BESS operation.

It reduced the day by day working expenses from USD 0.939 million per day to USD 0.929 million per day and diminished CO₂ emissions from 5.681 kilotonnes per day to 5.562 kilotonnes per day, respectively. Importantly, the amount of renewable energy used increased from 52,706.31 MWh to 54,102.46 MWh which means that the battery allowed the system to use renewable electricity that otherwise would have been wasted.

Renewable curtailment fell from 16.77% to 14.56%, a relative decrease of around 13.18%. The maximum thermal generation decreased by 3.55%, while the maximum thermal ramp reduced by 30.70%. This result is particularly relevant because fast generator ramping can arguably increase wear and tear, fuel consumption, and maintenance requirements.

Transmission losses increased slightly because battery charging and discharging changed power transfers in the network.

Figure 2 presents the hourly system demand against the thermal generation requirements at different degrees of renewable energy penetration. For the case with 0% renewable energy, thermal generation closely follows total system demand over the course of a day. The 35% renewable energy mixture in a capacity expansion scenario greatly reduces the thermal generation that is required during high-renewable generation. The scenario with 50% renewable energy + BESS produces the least need for thermal generation over most of the 24-h period. The figure shows that renewable generation and storage can reduce reliance on traditional thermal units while maintaining the generation–demand balance.

Table 5. Effect of Battery Energy Storage at 50% Renewable Penetration.

Performance Indicator	BESS Inactive	With Optimized BESS	Improvement
Operating cost	USD 0.939 million/day	USD 0.929 million/day	1.05% reduction
CO ₂ emissions	5.681 kt/day	5.562 kt/day	2.10% reduction
Renewable energy utilized	52,706.31 MWh	54,102.46 MWh	2.65% increase
Renewable curtailment	16.77%	14.56%	13.18% relative reduction
Peak thermal generation	3967.94 MW	3826.97 MW	3.55% reduction
Maximum thermal ramp	712.38 MW/h	493.67 MW/h	30.70% reduction
Transmission losses	1152.74 MWh	1192.59 MWh	3.46% increase
Battery discharge energy	0 MWh	1517.89 MWh	—

Figure 3 shows the hour-distribution of accessible solar energy, accessible wind energy and total harnessed renewable energy by the system. Solar energy generation rises quickly after sunrise, reaches a peak at noon, and falls to zero after sunset. There is also a unique wind energy generation profile, with relatively less output during the day and an increase at pre-dawn and post sunset; quite similar to solar generation. The used renewable-power curve shows combined input from different technologies, including restrictions on system operation and limitations of renewables.

The state of charge is shown in Figure 4, and it depicts the theoretical charging–discharging schedule associated with an energy storage system. A negative battery charge indicates that it is currently charging, predominantly at high renewable energy levels. It means that the battery charge level rises up to its maximum working limit coming nearer maximum conditions in hours of afternoons. While a positive battery power indicates a discharge during evening hours when demand picks up and renewable energy generation begins to drop off.

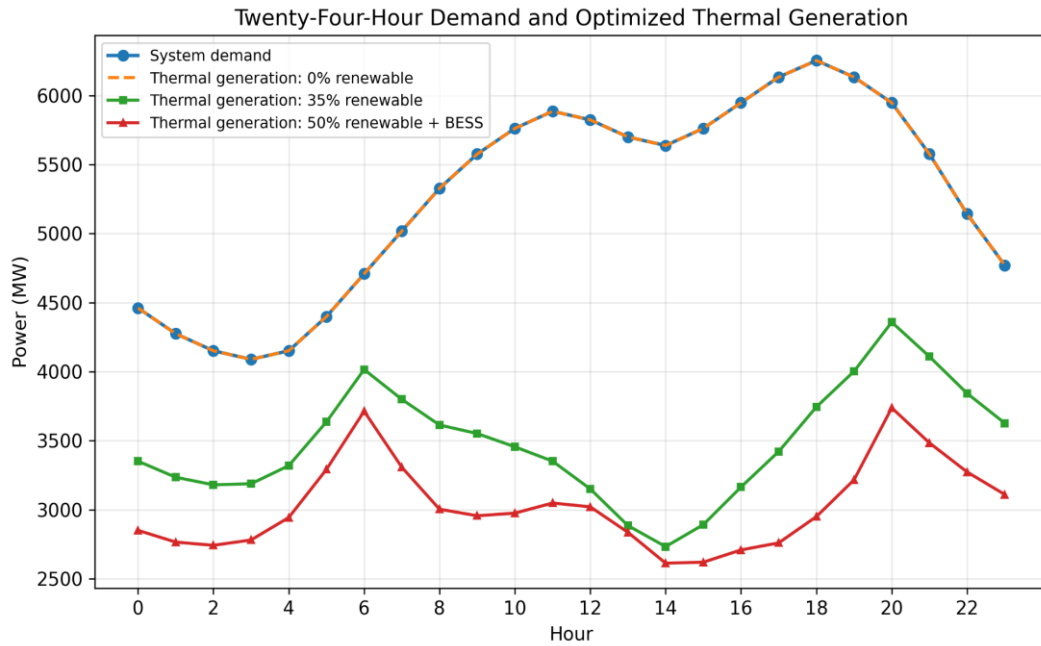


Figure 2. Twenty-Four-Hour Demand and Optimized Thermal Generation

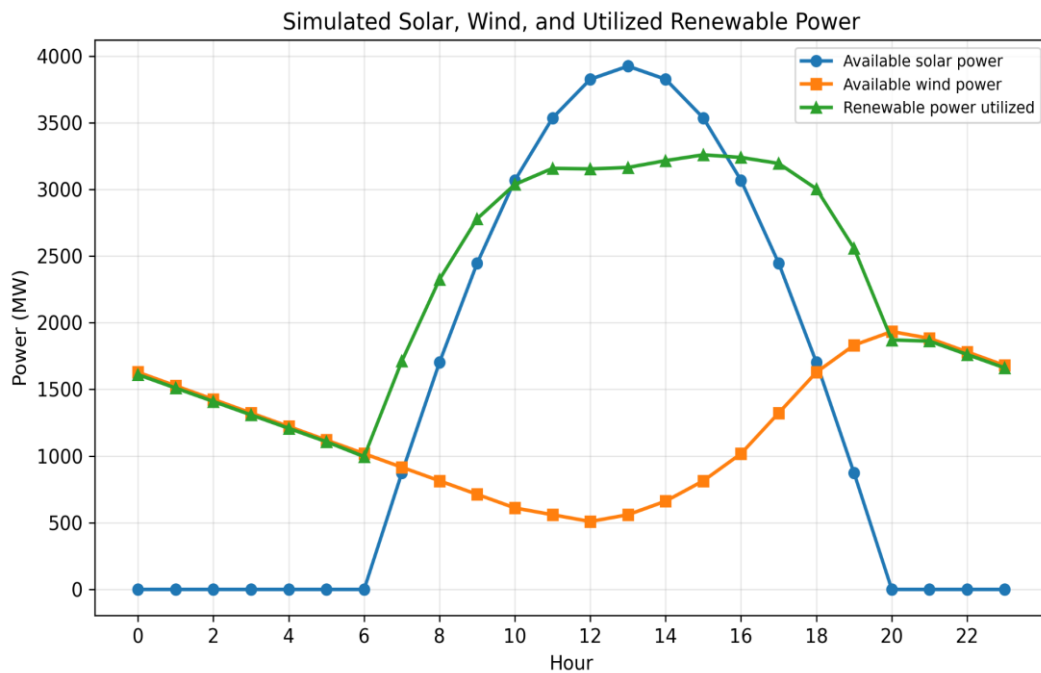


Figure 3. Simulated Solar, Wind, and Utilized Renewable Power

Figure 5 presents the convergence behaviour of four primary indicators during optimization process. Operating-cost objective approaches to 0.929 million USD per day in Figure 5(a), and CO₂ emissions evolve towards about 5.562 kt/day in Figure 5(b). In Figure

5(c) the x-axis shows how the transmission losses align at approximately 1192.59 MWh/day while Figure 5(d) indicates a useable increase in renewable curtailment of 14.56%.

In all cases, the smoothed trajectories progress towards a stable value with growing iteration counts. The patterns of persistence convergence show that the optimization technique realizes stable and almost optimal features of operational solutions.

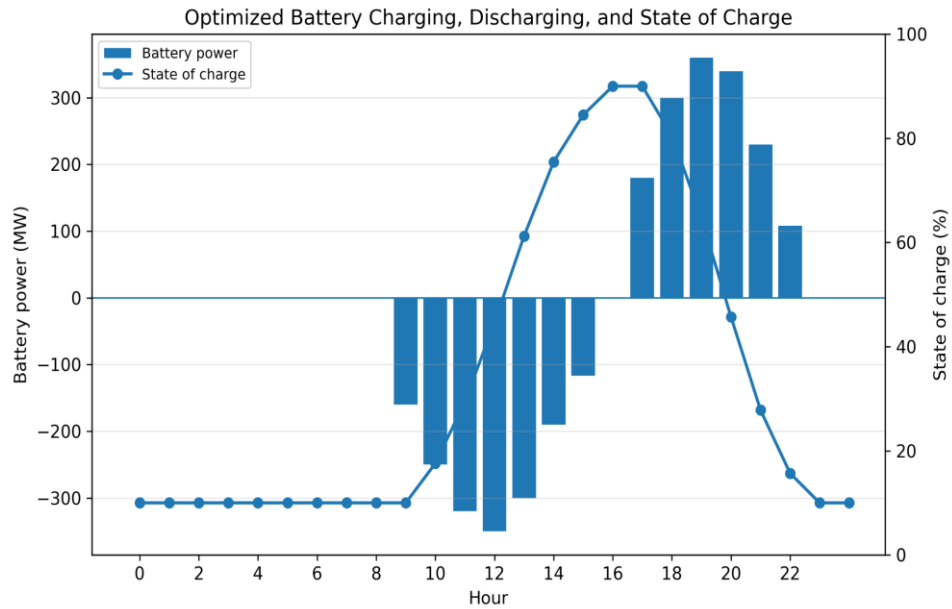


Figure 4. Optimized Battery Charging, Discharging, and State of Charge

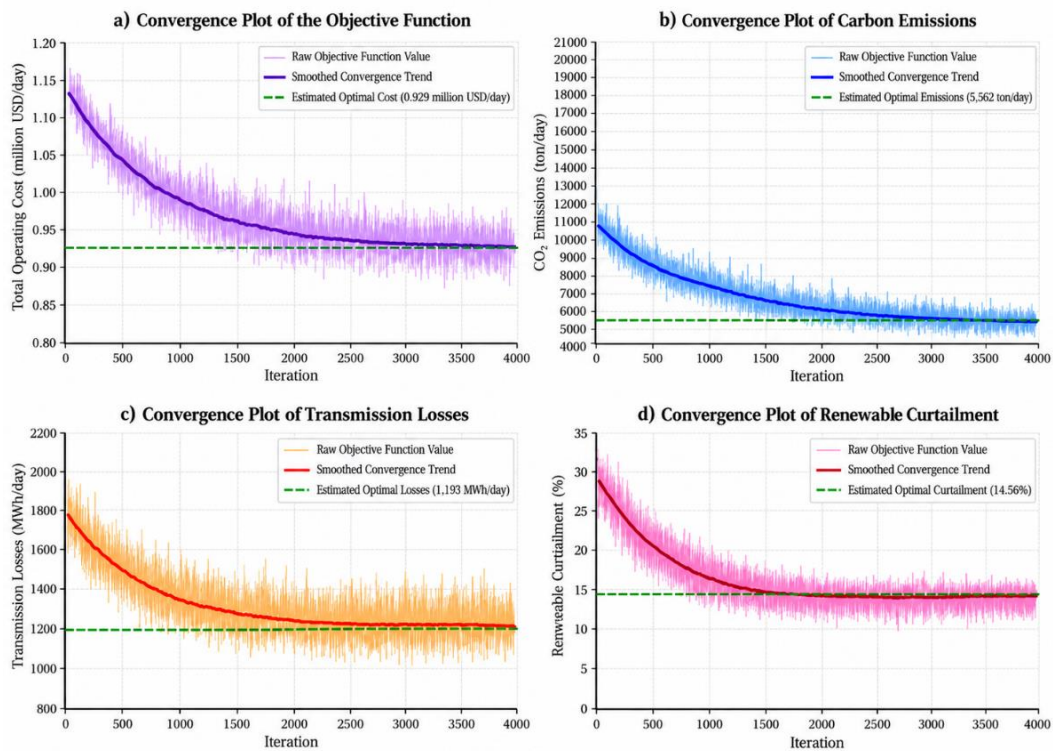


Figure 5. Convergence Behaviour of the Proposed Optimization Framework

The impact of increasing renewable penetration on operating cost, CO₂ emissions and transmission losses is outlined in Figure 6. In subfigure (a) shows that the daily operating cost decreases from USD 1.898 million/day without renewable integration to 0.929 million USD/day at 50% which represents a significant economic improvement. As part (b) shows, CO₂ emissions are only going down from 19.689 kt/day to 5.562 kt/day which proves the environmental benefits of replacement fossil power by renewables. Transmission losses drop from 1345.36 MWh/day to a low of 1101.29 MWh/day at 35% penetration and subsequently increase slightly to 1192.59 MWh/day at 50% as shown in Subfigure (c). The results indicate that higher levels of renewable energy integration led to greater economic and environmental benefits, though high levels of integration introduce additional problems concerning network flow and storage.

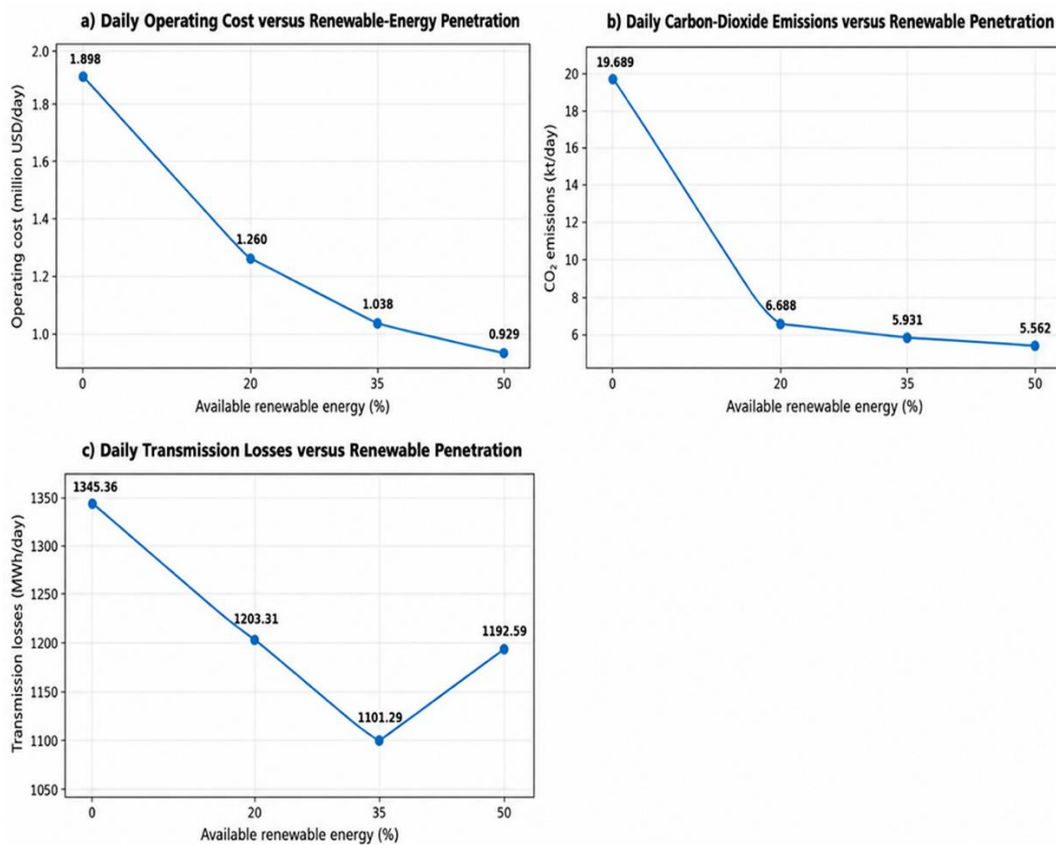


Figure 6. Effect of Renewable-Energy Penetration on System Performance.

SUMMARY AND CONCLUSION

This study developed and evaluated a modelling and optimization framework for integrating renewable energy sources into an interconnected power system. The proposed approach was demonstrated using a modified IEEE 39-bus system incorporating conventional thermal generation, solar photovoltaic (PV) generation, wind power generation, battery energy storage (BES), transmission network constraints, and multi-

period operation over a 24-hour scheduling horizon. Four renewable energy integration scenarios, corresponding to 0%, 20%, 35%, and 50% renewable energy availability, were evaluated in terms of operating costs, carbon emissions, transmission losses, renewable energy utilization and curtailment, thermal generation requirements, and system flexibility.

The simulation results demonstrated substantial economic and environmental benefits as renewable energy integration increased. Daily operating costs decreased from USD 1.898 million in the baseline scenario (0% renewables) to USD 1.260 million, USD 1.038 million, and USD 0.929 million in the 20%, 35%, and 50% renewable energy scenarios, respectively. The highest renewable integration scenario therefore achieved an operating cost reduction of approximately 51.05% relative to the baseline. Carbon emissions followed a similar trend, declining from 19.689 kt/day in the baseline scenario to 6.688 kt/day, 5.931 kt/day, and 5.562 kt/day, respectively. Overall, the 50% renewable energy scenario achieved a reduction in daily carbon emissions of approximately 71.75%, confirming the considerable environmental benefits of renewable energy integration.

The technical performance assessment revealed that the relationship between renewable energy penetration and transmission losses was not strictly linear. Daily transmission losses decreased from 1,345.36 MWh in the baseline scenario to 1,203.31 MWh and subsequently to a minimum of 1,101.29 MWh at 35% renewable integration. At 50% penetration, losses increased slightly to 1,192.59 MWh. This increase suggests that higher renewable penetration, together with additional battery charging and discharging operations, may alter power flow patterns and reduce the transmission efficiency achieved at intermediate penetration levels. Consequently, the 35% scenario provided the most favorable balance between renewable energy integration and transmission network performance among the evaluated scenarios.

Renewable energy curtailment emerged as another important indicator of system flexibility. At 20% renewable energy availability, all available renewable generation was utilized, resulting in zero curtailment. At 35% availability, curtailment remained relatively low at 2.65%, indicating that the system could accommodate most of the available solar and wind generation. However, at 50% availability, curtailment increased to 14.56%, highlighting the challenges associated with balancing high renewable generation during periods of limited demand and insufficient system flexibility. The effective renewable energy share reached approximately 42.72%, demonstrating that increased renewable energy availability does not necessarily translate into a proportional increase in renewable energy utilization.

Battery energy storage played a significant role in improving system performance under the 50% renewable energy scenario. Coordinated storage operation reduced renewable energy curtailment from 16.77% to 14.56% and increased renewable energy utilization from 52,706.31 MWh to 54,102.46 MWh. Furthermore, the maximum thermal generation ramp rate decreased from 712.38 MW/h to 493.67 MW/h, while peak thermal generation output declined from 3,967.94 MW to 3,826.97 MW. These findings demonstrate

that battery storage can improve the temporal coordination of renewable generation and electricity demand, reduce curtailment, moderate thermal generation ramping requirements, and enhance overall operational flexibility. Nevertheless, the remaining curtailment at high renewable penetration indicates that additional flexibility measures may be required to accommodate further renewable integration.

Additionally, the convergence analysis showed that the optimization indicators approached stable values as the number of iterations increased. The stabilization of the objective function, source-specific carbon emissions, and transmission losses indicates that the proposed optimization framework can identify feasible and stable near-optimal operating solutions for the investigated scenarios. However, convergence alone does not establish global optimality, which would require additional validation.

Overall, the findings demonstrate that increasing renewable energy integration can substantially reduce operating costs and carbon emissions, while its effects on transmission losses, renewable energy curtailment, and thermal generation dynamics depend on the penetration level and the availability of flexibility resources. Among the scenarios examined, 35% renewable integration offered the most favorable balance in terms of transmission losses and renewable energy utilization, whereas the 50% scenario delivered the greatest economic and environmental benefits but also introduced greater curtailment challenges. Coordinated battery energy storage helped mitigate these challenges by improving renewable energy utilization and reducing thermal generation ramping requirements. These results highlight the importance of jointly optimizing renewable generation, energy storage, and conventional generation within network-constrained, multi-period power system operation. Future work should investigate larger renewable penetration levels, alternative storage capacities, demand-side flexibility, and the performance of the proposed framework under different renewable generation and electricity demand profiles.

CONFLICT OF INTERESTS

The authors should confirm that there is no conflict of interest associated with this publication.

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