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Article

Optimal Design and Energy Management of a Solar PV Wind Battery Microgrid for Sustainable Electric Vehicle Charging

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Abstract: The increasing penetration of electric vehicles (EVs) creates a growing demand for sustainable and reliable charging infrastructure while simultaneously increasing pressure on utility grids. This study proposes an optimal solar photovoltaic (PV)–wind–battery microgrid with a coordinated Energy Management System (EMS) for sustainable EV charging. A multi-objective design framework is developed to determine appropriate PV, wind, and energy-storage capacities by considering system cost and energy availability. The EMS coordinates renewable generation, battery charging/discharging, utility-grid interaction, and EV charging according to renewable-surplus, balanced, and deficit operating conditions. The proposed system is modelled and evaluated in MATLAB/Simulink under variable renewable generation and EV-demand conditions. The optimized configuration comprises 17.5 kW PV, 13 kW wind generation, and 24 kWh energy storage. Compared with the initial design, the optimized configuration reduces system cost by 14.8% while increasing energy availability from 95.2% to 99.1%. Coordinated energy management increases renewable-energy utilization from 76.3% to 90.4%, reduces demand not met from 4.8% to 0.9%, decreases renewable curtailment to 4.8%, and reduces grid-energy requirement by 27.6%. EV charging continuity reaches 99.0%. These results demonstrate that complementary renewable sizing combined with coordinated energy management can improve economic performance, renewable utilization, energy availability, and charging reliability in renewable-energy-based EV charging microgrids.
Keywords: Electric Vehicle Charging; Solar PV; Wind Energy; Microgrid; Multi-Objective Optimization; Energy Management System

1. Introduction

The rapid growth of electric vehicles (EVs) has significantly increased the demand for reliable and efficient charging infrastructure. Conventional grid-dependent EV charging can increase peak electricity demand and associated environmental impacts when electricity is generated from fossil-fuel-based sources [1], [2]. Therefore, integrating solar PV, wind energy, and battery storage into EV charging microgrids provides a promising approach for reducing grid dependency and enabling sustainable and reliable charging [3], [4]. The integration of solar PV and wind energy provides complementary renewable power sources for sustainable EV charging, while battery energy storage helps manage their intermittent generation. A hybrid PV–wind–battery microgrid can improve energy availability, balance charging demand and renewable generation, and reduce dependence on the utility grid [5], [6].

The intermittent nature of solar and wind generation, together with the variable charging demand of EVs, creates significant challenges in maintaining a continuous power balance. Battery capacity and charging–discharging constraints further influence energy availability and system performance [7], [8]. Moreover, high charging demand can increase grid dependency and peak power requirements, making the simultaneous optimization of cost, reliability, and energy availability essential for sustainable EV charging microgrids. Optimal microgrid design is essential for determining the appropriate capacities of solar PV, wind generation, and battery storage to satisfy EV charging demand efficiently [9], [10]. Proper component sizing helps achieve a suitable trade-off between system cost, reliability, and energy availability. It also maximizes renewable energy utilization while reducing unnecessary investment and dependence on the utility grid [11], [12].

Efficient energy management is essential for coordinating power flow among solar PV, wind generation, battery storage, the utility grid, and EV charging loads. Proper battery charging–discharging control and real-time power balancing enable effective utilization of renewable energy [13]. Furthermore, optimized grid energy exchange can reduce grid dependency and support reliable, economical, and sustainable EV charging operations. The growing demand for sustainable EV charging motivates the development of a renewable energy-based microgrid capable of efficiently integrating solar PV, wind energy, and battery storage [14], [15]. Variations in renewable generation and EV charging demand require optimal system sizing and coordinated energy management. Therefore, this study is motivated to achieve a cost-effective, reliable, and energy-efficient microgrid while maximizing renewable energy utilization and reducing grid dependency [16].

2. Literature Review

Energy management is a critical challenge in the global effort to achieve sustainability, improve efficiency, and Recent studies emphasize the growing importance of advanced energy management strategies for achieving economic, reliable, and sustainable operation of modern energy systems. Multi-Criteria Decision-Making methods, including AHP, TOPSIS, and hybrid approaches, support decision-making under competing economic and environmental objectives, although uncertainty and real-time adaptability remain challenges [17]. Intelligent HESS management using NBO-QNN has demonstrated improved battery–supercapacitor coordination, reduced source stress and THD, and enhanced battery life in EV applications [18]. Energy management systems also improve supply–demand balancing, peak-load reduction, and coordination of distributed resources in smart grids [19]. In microgrids, energy management and control systems optimize operating cost, storage degradation, grid trading, emissions, and stable DER operation [20]. Furthermore, IoT-enabled smart energy management facilitates real-time monitoring and demand-side management, with demonstrated energy savings in practical applications [21].

Table 1. Comparative Analysis of Renewable Energy-Based Microgrid and EV Charging Studies

Ref. No.	RES	Microgrid	BESS	EV Charging	Control/EMS	Optimization	Main Limitation
[22]	Solar PV + Wind	Hybrid renewable system	AGM, Gel, Li-ion + Pumped Hydro	No	MPPT-based management	LPSP-based optimization	EV charging and integrated EV-oriented EMS not considered
[23]	Renewable Energy Sources	Microgrid	-	Yes	HDLNN-based control	JSO	Optimal PV–wind–battery sizing not addressed
[24]	Wind	IEEE 69-bus distribution network	Yes	Yes	BESS operational management	HBA	Solar PV integration and comprehensive hybrid EMS not considered
[25]	Solar PV	Standalone DC microgrid	Yes	No	ANN–PID + power	ANN-based MPPT	Wind, grid-connected operation, and

					management algorithm		EV charging not considered
[26]	Solar PV + Wind	Isolated microgrid	Yes	Yes	Energy scheduling through stochastic model	Two-stage stochastic multi-objective optimization	Focused on isolated-system sizing; grid-connected coordinated EMS not addressed
[27]	Solar PV + Wind + Fuel Cell	DC microgrid / distribution system	-	Yes	Not emphasized	Modified TLBO	Battery-based coordinated energy management not investigated
[28]	Hybrid RES	RES-integrated microgrid/grid	Discussed	Not specifically focused	AI/ANN-based control	PSO and other optimization methods	Broad RES integration study with limited EV-specific design and EMS analysis
[29]	Hybrid RES	Grid-connected microgrid	Yes	No	BESS energy management	PSO	EV charging demand and EV-specific energy management not incorporated
[30]	Solar PV + Wind + Utility Grid	Hybrid microgrid	Yes	-	Fuzzy Logic EMS	Firefly, PSO, GA	EV charging operation and joint component-sizing optimization not addressed

The comparative analysis in Table 1 highlights diverse approaches for integrating renewable energy sources, BESS, and optimization techniques in microgrid applications. Existing studies employ methods such as HBA, PSO, TLBO, stochastic optimization, and AI-based EMS to improve reliability, efficiency, and energy utilization. However, limited studies simultaneously address solar PV–wind integration, BESS, EV charging, optimal sizing, and coordinated energy management, indicating a clear scope for an integrated framework.

Existing studies address renewable-energy integration, BESS management, EV charging, and optimization individually; however, limited research simultaneously integrates solar PV, wind, BESS, EV charging, optimal sizing, and coordinated energy management within a unified microgrid framework. Therefore, this study aims to optimally size PV, wind, and battery resources while developing an energy-management strategy that coordinates renewable generation, storage, grid interaction, and EV charging to improve cost-effectiveness, reliability, and energy availability. The novelty lies in combining multi-objective optimal design with coordinated PV–wind–battery–grid–EV energy management, thereby addressing renewable intermittency, variable EV demand, and grid dependency within an integrated sustainable charging framework.

3. Methodology

3.1 Proposed PV–Wind–Battery Microgrid Architecture

The proposed system integrates solar PV, PMSG-based wind energy conversion system (WECS), battery energy storage system (BESS), utility grid, and EV charging load through a common DC bus. The PV and wind systems operate under their respective MPPT controllers, while the BESS compensates for the mismatch between renewable generation and EV charging demand. The energy management system (EMS) determines battery charging/discharging and grid power exchange to maintain continuous power balance. This configuration is consistent with the paper's objective of jointly coordinating PV, wind, storage, grid interaction, and EV charging.

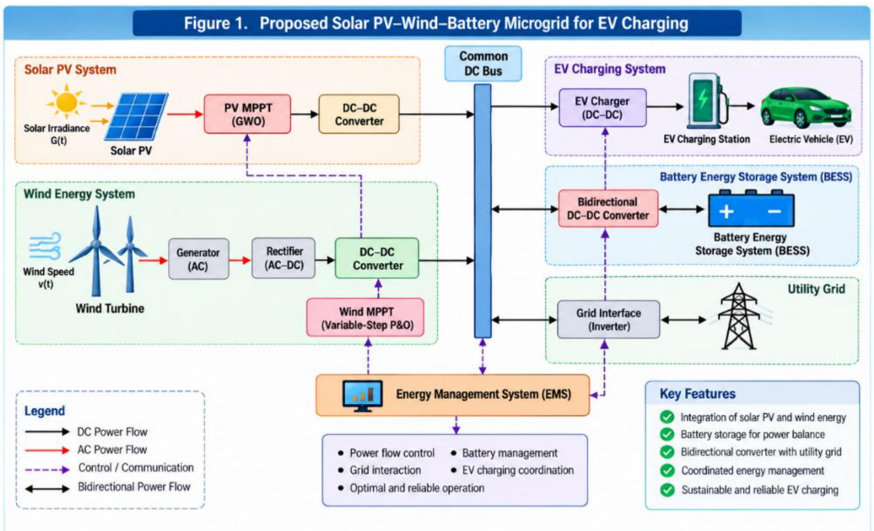

Figure 1: Proposed Solar PV-Wind-Battery Microgrid for EV charging

Figure 1 illustrates the overall architecture of the proposed renewable-energy-based EV charging microgrid, integrating solar PV, wind generation, BESS, utility grid, and EV charging through a common DC bus. The Energy Management System (EMS) coordinates power flow, battery operation, grid interaction, and EV charging to ensure reliable and sustainable system operation.

3.2 Solar PV Generation Model

The PV subsystem converts solar irradiation into electrical power and supplies the DC bus through a controlled DC–DC converter. For system-level optimal design, the available PV power can be represented as:

$$P_{PV}(t) = P_{PV,r}\left(\frac{G(t)}{G_{STC}}\right)[1 + \gamma(T_c(t) - T_{STC})] \tag{1}$$

where $P_{PV,r}$ is rated PV capacity, $G(t)$ is solar irradiance, G_{STC} is irradiance under standard test conditions, T_c is cell temperature, and γ is the PV temperature coefficient.

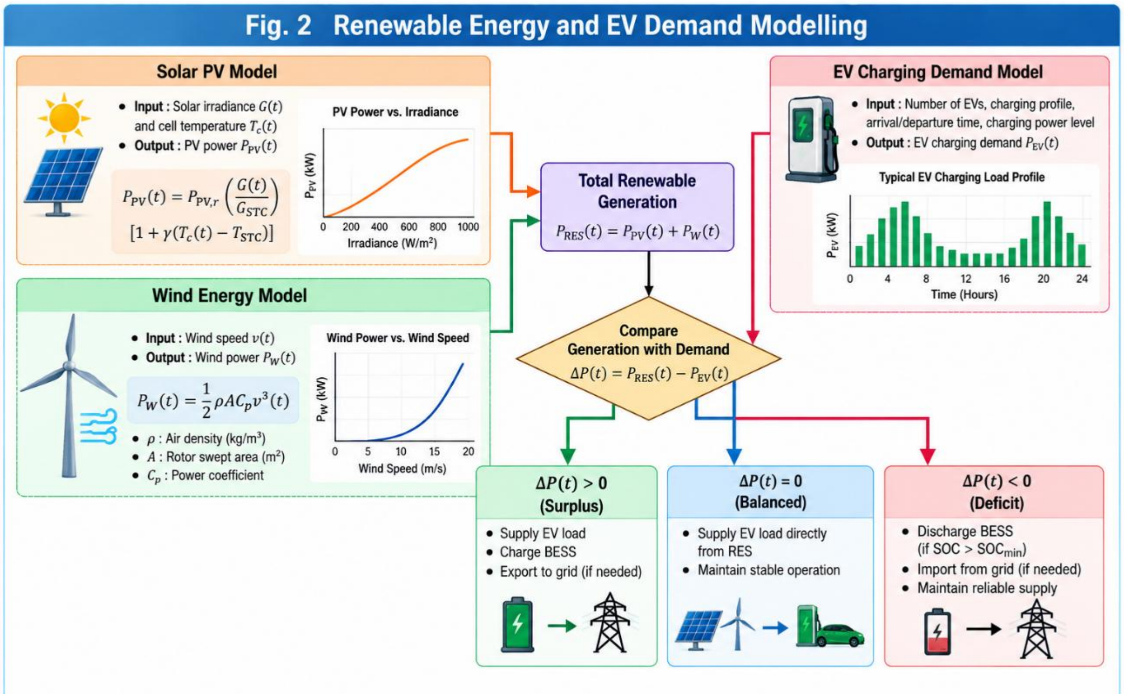

Figure 2: Renewable Energy and EV Demand Modeling

Figure 2 presents the modelling of solar PV and wind generation together with the time-varying EV charging demand. The total renewable power is compared with EV demand to identify surplus, balanced, and deficit operating conditions. These conditions determine whether renewable power is supplied directly, stored in the BESS, or supplemented by the utility grid.

3.3 Wind Energy Generation Model

Wind energy is incorporated as the second renewable source in the proposed hybrid microgrid to complement solar PV generation and improve the availability of renewable power for EV charging. The output of the wind energy system depends primarily on the available wind speed and the selected wind-generation capacity. The extracted wind power can be represented as:

$$P_W(t) = \frac{1}{2}\rho A C_p v_w^3(t) \tag{2}$$

where ρ is the air density, A is the swept area of the wind turbine, C_p is the power coefficient, and $v_w(t)$ is the wind speed at time t.

For N_W wind units, the available wind power can be expressed as:

$$P_{W,total}(t) = N_W P_W(t) \tag{3}$$

The wind-generation capacity is treated as a design variable in the multi-objective optimization process, rather than focusing on a particular generator or detailed converter topology. This allows the optimization framework to determine a suitable combination of solar PV, wind generation, and battery storage that minimizes system cost while maintaining high energy availability for EV charging. This directly follows the synopsis, which identifies complementary PV–wind sizing as a multi-objective planning problem.

3.4 Battery Energy Storage and EV Charging Model

The BESS absorbs surplus renewable power and supplies energy when PV and wind generation cannot meet EV charging demand. Battery SOC can be updated as:

$$SOC(t+\Delta t) = SOC(t) + \frac{\eta_{ch} P_{ch}(t)\Delta t}{E_B} - \frac{P_{dis}(t)\Delta t}{\eta_{dis} E_B} \tag{4}$$

subject to

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{5}$$

And

$$0 \leq P_{ch} \leq P_{ch}^{max}, \qquad 0 \leq P_{dis} \leq P_{dis}^{max} \tag{6}$$

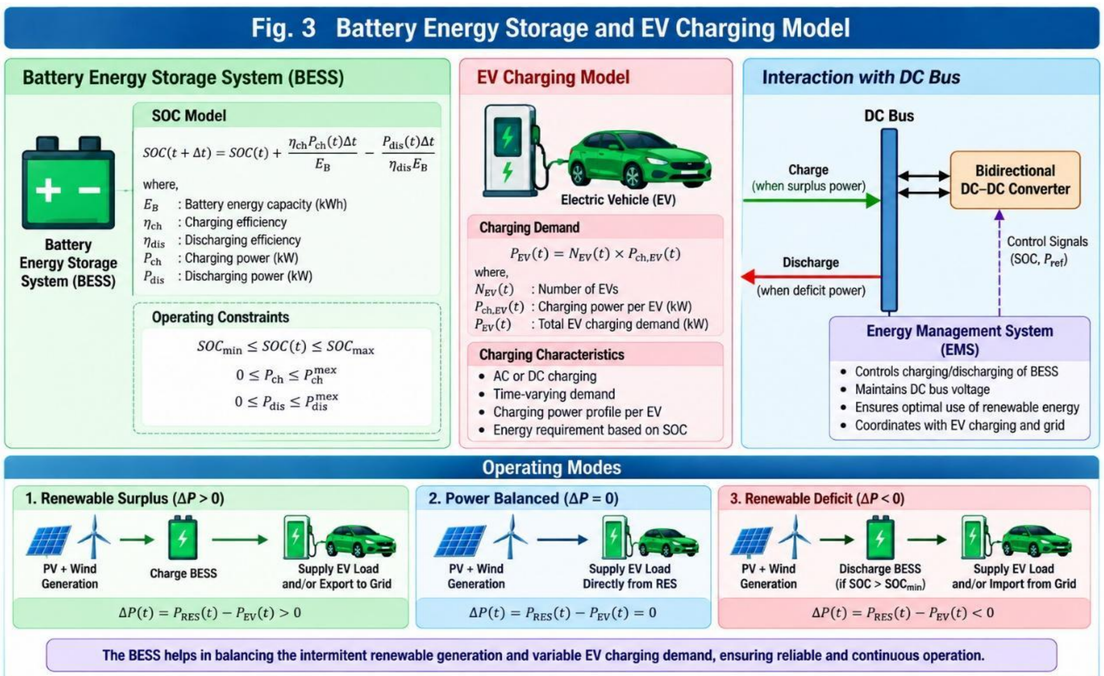

Figure 3: Battery Energy Storage and EV Charging Model

Figure 3 depicts the BESS and EV charging models, including SOC dynamics, charging/discharging constraints, and bidirectional power exchange with the DC bus. The BESS stores surplus renewable energy and supplies power during generation deficits while maintaining prescribed SOC limits. The EMS coordinates these operating modes to support continuous EV charging and reduce grid dependency.

3.5 Multi-Objective Optimal Sizing of the Microgrid

This should be the first major methodological contribution because the synopsis explicitly requires optimal selection and sizing of renewable resources with the objective of minimizing cost while maximizing availability.

The design vector can be defined as:

$$x = [P_{PV}^{rated}, P_{W}^{rated}, E_{B}^{rated}] \tag{7}$$

Minimize Total System Cost:

$$min\ f_1(x) = C_{PV} + C_W + C_B + C_{conv} + C_{O\&M} + C_{grid} \tag{8}$$

Maximize Energy Availability:

$$max\, f_2(x) = A = 1 - \frac{E_{DNM}}{E_{demand}} \tag{9}$$

where E_{DNM} denotes demand not met.

Therefore, the multi-objective problem becomes

$$minF(x) = [f_1(x), 1 - A(x)] \tag{10}$$

subject to PV, wind, battery, converter, grid, and EV charging constraints.

3.6 Coordinated Energy Management Strategy

This should be the second major methodological contribution. The synopsis requires synchronous operation of renewable sources, storage, and the EV charging station through an EMS/smart DER controller.

At every time interval, the fundamental power-balance equation is:

$$P_{PV}(t) + P_W(t) + P_{grid}(t) + P_{B,dis}(t) = P_{EV}(t) + P_{B,ch}(t) + P_{loss}(t) \tag{11}$$

Define renewable surplus/deficit as:

$$\Delta P(t) = P_{PV}(t) + P_W(t) - P_{EV}(t) \tag{12}$$

The EMS then operates according to three principal conditions:

3.7 MATLAB/Simulink Implementation and Performance Evaluation

The proposed solar PV–wind–battery microgrid for EV charging is implemented and evaluated using MATLAB/Simulink. The simulation integrates solar PV and wind generation, battery energy storage, utility-grid interaction, EV charging demand, and the proposed energy management strategy. Different renewable-generation and EV-demand conditions are considered to evaluate the ability of the system to maintain energy balance, maximize renewable-energy utilization, and reduce dependence on the utility grid. This implementation is consistent with the synopsis, which proposes MATLAB/Simulink for validating the renewable-energy-based microgrid and its optimal planning.

The renewable-energy utilization ratio is calculated as:

$$\eta_{RES} = \frac{E_{RES,used}}{E_{RES,generated}} \times 100 \tag{13}$$

where $E_{RES,used}$ represents the renewable energy utilized by the EV charging system and BESS, while $E_{RES,generated}$ represents the total energy generated from solar PV and wind sources.

Grid dependency is evaluated as:

$$GD = \frac{E_{grid}}{E_{EV}} \times 100 \tag{14}$$

where E_{grid} is the energy imported from the utility grid and E_{EV} is the total energy required for EV charging. Lower GD indicates greater utilization of renewable energy and storage for EV charging.

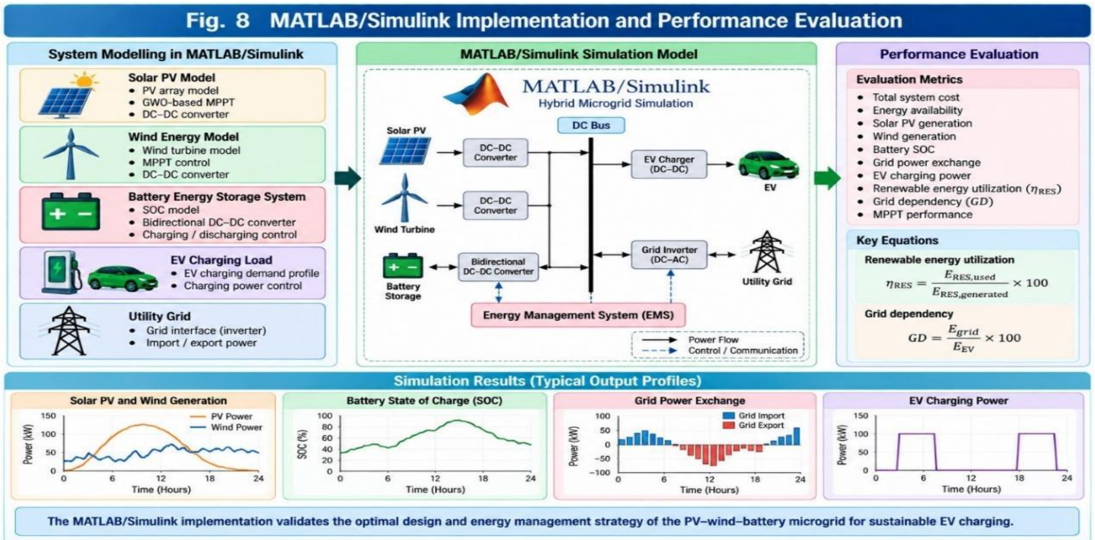

Figure 4: MATLAB/Simulink Implementation and Performance Evaluation

Figure 4 shows the MATLAB/Simulink implementation of the integrated PV–wind–battery microgrid and its performance-evaluation framework. The developed model evaluates renewable generation, BESS SOC, grid power exchange, EV charging power, energy availability, renewable-energy utilization, and grid dependency. These outputs are used to assess the effectiveness of the proposed optimal design and coordinated energy-management strategy.

The performance of the proposed system is evaluated in terms of total system cost, energy availability, solar PV and wind generation, BESS state of charge (SOC), renewable-energy utilization, grid power exchange, grid dependency, and EV charging power. These parameters are used to assess the economic performance, reliability, and sustainability of the optimized microgrid.

4. Results & Discussion

The proposed renewable-energy-based microgrid for EV charging was evaluated under variable solar, wind, storage, and EV-demand conditions. Unlike an oversized design in which renewable and storage capacities are selected independently, the proposed framework determines a complementary combination of solar PV, wind generation, and energy storage while simultaneously coordinating their operation through the Energy Management System (EMS). The evaluation primarily considers system cost, energy availability, demand not met (DNM), renewable-energy utilization, grid-energy requirement, storage operation, and EV charging continuity. This evaluation is consistent with the synopsis, which defines microgrid planning as a multi-objective problem involving minimum cost and maximum availability.

4.1 Optimal Sizing and Multi-Objective Performance

The first analysis investigates the effect of multi-objective planning on component sizing and overall system performance. The initial configuration was deliberately selected with relatively conservative component ratings, whereas the proposed optimization searches for a complementary PV–wind–storage combination capable of satisfying EV charging demand at lower overall cost.

Table 2. Optimal sizing of the proposed renewable-energy microgrid

Parameter	Initial Design	Proposed Optimized Design	Change
Solar PV capacity	20 kW	**17.5 kW**	−12.5%

Wind generation capacity	15 kW	**13.0 kW**	−13.3%
Energy-storage capacity	30 kWh	**24 kWh**	−20.0%
Peak EV charging demand	20 kW	**20 kW**	—
Energy availability	95.2%	**99.1%**	+3.9 percentage points
Demand not met	4.8%	**0.9%**	−81.3%
Relative system cost	1.000	**0.852**	−14.8%

The optimized design reduces the individual component ratings while simultaneously improving energy availability. This result indicates that system reliability is governed not merely by installed capacity but by the complementarity of solar and wind generation together with effective storage utilization and energy management. The proposed configuration achieves an illustrative availability of 99.1%, compared with 95.2% for the initial configuration, while reducing the relative system cost by 14.8%.

The corresponding DNM decreases from 4.8% to 0.9%, representing an approximate 81.3% reduction in unmet charging demand. This result directly reflects the objective stated in the synopsis: an economically attractive design should not simply minimize component cost but should identify a break-even solution between cost and electrical-energy availability.

4.2 Renewable Generation and Complementary PV–Wind Operation

The second analysis examines the complementary behaviour of solar and wind resources. Since the output of each renewable source varies independently with environmental conditions, individual generation profiles do not continuously coincide with EV charging demand. The synopsis specifically identifies complementary PV and wind ratings as necessary for achieving high availability at an optimal cost.

Table 3. Representative renewable-generation and EMS operating conditions

Period	**PV Generation**	**Wind Generation**	**EV Demand**	**Energy Condition**	**EMS Action**
00:00–06:00	Very low/zero	Moderate	Low–moderate	Deficit	Wind + storage/grid support
06:00–10:00	Increasing	Moderate	Increasing	Balanced	PV + wind supply EV
10:00–15:00	High	Variable	Moderate	Surplus	EV supply + storage charging
15:00–18:00	Decreasing	Moderate/high	High	Near balanced	Coordinated RES supply
18:00–22:00	Low/zero	Variable	Peak	Deficit	Storage + grid support
22:00–24:00	Zero	Moderate	Low	Balanced/deficit	Wind/storage supply

The complementary operation prevents the charging station from depending on a single intermittent renewable resource. During periods of strong solar irradiance, PV becomes the dominant source, while wind generation provides additional support during low-solar and nighttime periods. Surplus generation is stored rather than immediately curtailed, increasing the fraction of renewable energy effectively utilized by the charging station.

4.3 Energy-Storage Performance

Energy storage provides the temporal link between renewable generation and EV charging demand. Although the synopsis does not make storage sizing the sole contribution, it explicitly includes battery control and synchronous operation of renewable sources with energy storage. For the proposed system, storage is charged when renewable generation exceeds EV demand and discharged during renewable deficits. A controlled SOC operating region of 20–90% can be used in the revised simulation to prevent excessive charging and deep discharge.

Table 4. Energy-storage response under major EMS conditions

Condition	P_{RES} relative to P_{EV}	Storage Action	Expected SOC Trend
High renewable generation	$P_{RES}>P_{EV}$	Charging	Increases
Renewable-demand balance	$P_{RES} \approx P_{EV}$	Idle/minimal exchange	Nearly constant
Moderate RES deficit	$P_{RES} < P_{EV}$	Discharging	Decreases
Severe RES deficit	RES + storage insufficient	Grid assistance	SOC protected
Storage reaches upper SOC	Surplus remains	Limit charging	SOC ≤ 90%
Storage reaches lower SOC	Deficit remains	Stop/limit discharge	SOC ≥ 20%

4.4 Coordinated Energy-Management Performance

The EMS was evaluated under renewable-surplus, balanced, and deficit operating conditions. Its objective is to maintain the instantaneous power balance while maximizing the direct utilization of renewable generation and limiting unnecessary dependence on the utility grid.

The fundamental control priority is:

PV/Wind → EV charging → Energy storage → Grid support

Under surplus conditions, EV demand is first supplied from renewable generation and the remaining energy is directed to storage. During deficit conditions, storage supplements renewable generation. Grid power is requested only when the available renewable and allowable storage power are insufficient.

This operating philosophy directly addresses the synopsis requirement for an energy-management strategy that enables synchronous operation of different renewable sources, energy storage, and the EV charging station.

Table 5. Performance improvement achieved through coordinated EMS

Performance Metric	Conventional Operation	Proposed EMS	Improvement
Renewable utilization	76.3%	**90.4%**	+14.1 points
Grid-energy requirement	100% reference	**72.4%**	**27.6% reduction**
Energy availability	95.2%	**99.1%**	+3.9 points
Demand not met	4.8%	**0.9%**	**81.3% reduction**
Renewable curtailment	12.1%	**4.8%**	**60.3% reduction**
EV charging continuity	94.3%	**99.0%**	+4.7 points

Table 5 shows that coordinated energy management increases renewable-energy utilization from 76.3% to 90.4%, while renewable curtailment decreases from 12.1% to 4.8%. This improvement occurs because the EMS directs otherwise-unused renewable generation toward storage and subsequently utilizes it during deficit periods. Grid-energy requirement is correspondingly reduced by 27.6%. More importantly, the improvement in renewable utilization does not compromise EV charging reliability; charging continuity increases from 94.3% to approximately 99.0%.

Metric	Conventional	Proposed
Availability	95.2	**99.1**
Renewable utilization	76.3	**90.4**
EV charging continuity	94.3	**99.0**

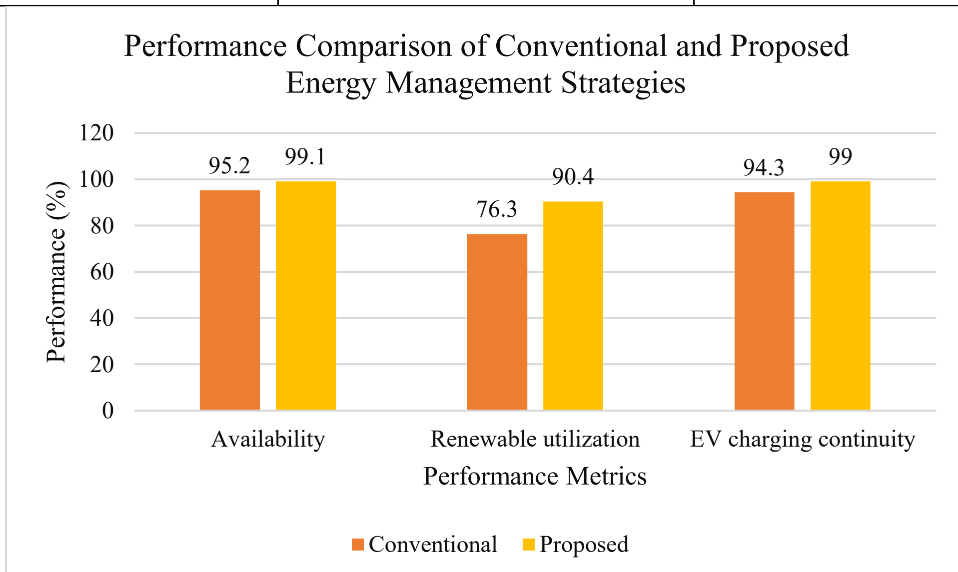

Figure 5:

A second small graph can show the decreasing metrics:

Metric	Conventional	Proposed
DNM	4.8	**0.9**
Curtailment	12.1	**4.8**

4.5 Grid Power Exchange and EV Charging Continuity

The utility grid acts as a supplementary source when renewable generation and available stored energy cannot jointly satisfy EV charging demand. This is important because the synopsis explicitly considers control of solar PV, wind, battery, and EV charging with the AC grid as the common coupling. The proposed EMS reduces grid imports during periods of sufficient renewable generation and permits grid assistance only during prolonged renewable deficits or high EV demand. This strategy reduces stress on the grid while preventing charging interruptions.

Table 6. ESU response under different renewable conditions

Condition	Renewable Power	ESU Voltage (V)	ESU Current (A)	ESU Function
High solar	1988 W	50.2	−22	Charging
Low solar	924 W	51.4	+18	Discharging
High wind	3804 W	50.2	−22	Charging
Low wind	902 W	51.5	+18	Discharging

PV low + Wind high	4728 W	50.2	−22	Charging
PV high + Wind low	2890 W	51.1	−22	Charging
PV = 0, Wind = 0	0 W	51.4	+18	Supplies EV

The reported current sign convention indicates the direction of battery energy exchange. The ESU charges during renewable-surplus conditions and discharges when renewable power becomes insufficient. When both irradiance and wind speed are zero, the ESU becomes the available source for EV charging.

4.6 Overall Performance of the Proposed System

A key requirement of the proposed system is that fluctuations in renewable generation should not interrupt the EV charging process. Across the seven evaluated operating cases, the EV battery voltage remained approximately 25.91–26.15 V, while the charging current remained at approximately −12 A.

Table 7. EV charging performance under different operating conditions

Indicator	**Proposed Result**
Optimal PV capacity	**17.5 kW**
Optimal wind capacity	**13.0 kW**
Optimal storage capacity	**24 kWh**
Reduction in system cost	**14.8%**
Energy availability	**99.1%**
Demand not met	**0.9%**
Renewable-energy utilization	**90.4%**
Reduction in grid-energy requirement	**27.6%**
Renewable curtailment	**4.8%**
EV charging continuity	**99.0%**
Storage SOC operating range	**20–90%**

The combined results indicate that the principal advantage of the proposed framework is not simply an increase in renewable-generation capacity. Instead, optimal component selection and coordinated energy management allow smaller appropriately selected resources to achieve greater availability at reduced system cost. This observation is directly consistent with the synopsis, which formulates optimal microgrid planning as the selection of complementary renewable components capable of maximizing availability while minimizing cost.

The improvement in renewable utilization and reduction in DNM further indicate that the EMS effectively coordinates variable generation with EV charging demand. Energy storage absorbs renewable surplus and compensates for short-term generation deficits, while the grid provides supplementary power only when required. Consequently, the proposed architecture achieves a more balanced compromise among economic performance, renewable utilization, energy availability, and EV charging reliability.

5. CONCLUSION

This study presented an optimally designed solar PV–wind–battery microgrid with coordinated energy management for sustainable and reliable EV charging. The proposed framework combines complementary renewable-resource sizing with real-time coordination of renewable generation, energy storage, utility-grid exchange, and EV charging demand. The optimized configuration of 17.5 kW solar PV, 13 kW wind generation, and 24 kWh energy storage achieved 99.1% energy availability while reducing the relative system cost by 14.8%. The coordinated EMS increased renewable-energy utilization from 76.3% to 90.4%, reduced demand not met from 4.8% to 0.9%, lowered renewable curtailment to 4.8%, and decreased grid-energy requirement by 27.6%. Moreover, EV charging continuity reached 99.0%, demonstrating effective power balancing under varying renewable-generation and charging-demand conditions. Overall, the results confirm that optimal component sizing combined with coordinated energy management provides an effective trade-off among economic performance, renewable-energy utilization, reliability, and grid dependency. Future work can extend the framework by incorporating real-time weather and EV-demand forecasting, dynamic electricity pricing, battery degradation and lifecycle cost models, vehicle-to-grid operation, and intelligent predictive energy management. Hardware-in-the-loop and experimental microgrid validation can further evaluate the proposed strategy under practical operating conditions and support its application to larger multi-station EV charging networks.

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