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A MULTILAYERED SUPERVISORY ENERGY ORCHESTRATION AND CONTROL PARADIGM FOR GRID-INTERFACED ELECTRIC VEHICLE ENERGY REFUELING SYSTEMS COUPLED WITH SOLAR-DRIVEN PHOTONIC POWER CONVERSION

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Abstract

The rapid expansion of electric vehicle deployment demands charging infrastructures that are resilient, energy efficient, and capable of coordinated interaction with existing power grids. This work proposes a multilayered supervisory energy orchestration and control framework for a grid-interfaced electric vehicle energy refueling system integrated with solar-driven photonic power conversion and battery energy storage. The control architecture employs a hierarchical energy management system to dynamically allocate power among renewable generation, grid supply, and storage resources, while component-level controllers regulate power electronic interfaces. The complete system is modeled and evaluated using time-domain simulations in MATLAB/Simulink under diverse operating conditions, including fluctuating solar irradiance, stochastic EV charging demand, battery state-of-charge variations, and grid disturbance scenarios. Simulation results demonstrate improved renewable energy utilization exceeding 30%, reduced grid energy import by approximately 25%, and stable charging operation without interruption. Voltage and frequency deviations remain within prescribed operational limits, while total harmonic distortion is maintained below 5%, satisfying power quality requirements. Comparative performance analysis with conventional control approaches indicates enhanced energy coordination, reduced operational stress on grid and storage components, and improved overall system efficiency. The obtained results confirm that the proposed supervisory control paradigm provides a scalable, robust, and grid-compatible solution for next-generation electric vehicle charging infrastructure with high renewable penetration.

Keywords: Energy Management Systems, Grid-Connected Electric Vehicle Charging, Photovoltaic Energy Conversion, Hierarchical Control Architecture, Battery Energy Storage Systems, Power Quality Control, Supervisory Control.

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Introduction

The rapid growth of electric vehicles (EVs) has increased demand for efficient and reliable charging infrastructure that integrates renewable energy while maintaining consistent power supply [1], [2]. Solar photovoltaic (PV) systems are widely adopted for EV charging due to their scalability, low operational costs, and compatibility with distributed energy frameworks [3]. However, the intermittent nature of solar energy can cause fluctuations in power output, affecting charging reliability [4].

Integrating PV systems with battery energy storage (BESS) helps mitigate variability, provides peak load support, and improves renewable utilization [5]. Effective operation requires a hierarchical control system that coordinates energy management, component-level controllers, and grid interactions to ensure voltage stability, power quality, and optimal energy allocation [6]. Intelligent control strategies enable adaptive power dispatch and smooth transitions between PV, battery, and grid supply [7].

Existing approaches often lack comprehensive hierarchical coordination and are insufficiently tested under dynamic scenarios such as variable solar irradiance, fluctuating EV loads, and grid disturbances [8], [9]. This work proposes a multilayered supervisory energy orchestration and control framework for a grid-connected EV charging system coupled with solar-driven photonic power conversion. The system is modeled and simulated in MATLAB/Simulink to evaluate energy flow, power quality, and operational stability, providing a scalable and intelligent solution for next-generation EV charging infrastructure [2].

I. Guiding Intentions

This research aims to develop a robust and energy-efficient EV charging infrastructure integrating grid connectivity, battery storage, and solar-driven photonic power conversion. The framework prioritizes renewable energy utilization, reduces reliance on grid electricity, and ensures uninterrupted charging under variable environmental and load conditions. Battery management strategies are implemented to regulate charge/discharge cycles and enhance lifespan, while power electronic controls maintain voltage and frequency stability and minimize harmonics. The system employs adaptive supervisory control algorithms, including fuzzy logic–based decision-making, to handle uncertainties in renewable generation and dynamic EV load demand. MATLAB/Simulink-based modeling and simulation are used to evaluate energy flow, operational stability, and performance under diverse scenarios. Collectively, these design intentions guide the development of a scalable, intelligent, and sustainable EV charging system aligned with modern mobility and energy objectives.

II. Hierarchical Intelligent Energy Management System (HI-EMS)

A. Supervisory Energy Management Strategy

An The Hierarchical Intelligent Energy Management System (HI-EMS) constitutes the principal control architecture governing the coordinated operation of the grid-interfaced electric vehicle charging infrastructure. The HI-EMS adopts a multi-tier supervisory control paradigm in which energy coordination and dynamic regulation are decoupled across distinct temporal layers. This architectural stratification enables the system to simultaneously address long-horizon energy optimization objectives and short-horizon electrical stability requirements.

At the upper supervisory echelon, the HI-EMS executes global energy orchestration by continuously assimilating heterogeneous system state variables, including photovoltaic power availability, battery state-of-charge, grid exchange status, diesel generator operational readiness, and stochastic electric vehicle charging demand. The supervisory controller employs intelligent inference mechanisms to synthesize these multidimensional inputs into optimal power dispatch commands, ensuring prioritized utilization of renewable energy while preserving system resilience and operational constraints.

In contrast to deterministic or threshold-based energy dispatch strategies, the proposed HI-EMS exhibits adaptive decision-making capability under conditions of renewable intermittency and load uncertainty. Photovoltaic generation is preferentially exploited to supply instantaneous charging demand and replenish battery reserves. When renewable resources are insufficient, the system transitions into storage-assisted or hybrid supply modes, wherein battery discharge and auxiliary generation are dynamically coordinated to maintain uninterrupted charging service. Activation of the diesel generator is constrained to conditions characterized by concurrent renewable scarcity and low battery energy reserves, thereby mitigating excessive fuel consumption and mechanical stress.

Energy coordination within the HI-EMS framework is governed by the instantaneous power equilibrium relationship

$$P(PV)(t) + P(DG)(t) + P(bat,dis)(t) + P(grid)(t) = (EV)(t) + P(bat,ch)(t) + P(loss)(t) \quad (1)$$

ensuring real-time conservation of energy across the hybrid system.

B. Battery State-of-Charge (SoC) Dynamics

Battery dynamics are regulated through state-of-charge evolution modeling, which enforces electrochemical operating limits and prolongs storage lifespan.

$$So(t+1) = SoC(t) + (\eta ch \bullet Pb\ at, ch(t) \bullet \Delta t)/ Ebat, max - (Pb\ at, di(t) \bullet \Delta t)/(\eta d\ is \bullet Ebat, max) \quad (2)$$

Diesel generator engagement is further optimized using load-dependent fuel consumption characteristics, enabling efficiency-aware dispatch scheduling.

The hierarchical structure of the HI-EMS facilitates seamless coordination with fast-acting local controllers responsible for power electronic interfaces, voltage–frequency regulation, and harmonic suppression. This layered control topology suppresses undesirable interactions between subsystems, enhances transient response, and ensures compliance with grid power quality standards. Collectively, the HI-EMS enables a scalable, resilient, and intelligence-driven control solution that significantly improves renewable energy penetration and operational efficiency in modern electric vehicle charging infrastructures.

III. Fuzzy Logic–Based Supervisory Control

The proposed supervisory control employs a fuzzy logic–based intelligent algorithm to dynamically orchestrate energy flow among photovoltaic generation, battery storage, diesel backup, and grid supply under stochastic load and renewable intermittency. Unlike conventional deterministic controllers, this method leverages linguistic abstraction, membership functions, and rule-based inference to handle system uncertainties and nonlinearities without requiring exact predictive models.

power availability, battery state-of-charge, grid exchange status, diesel generator operational readiness, and stochastic

$$U(t) = \frac{\sum_{i=1}^{N} \mu_i \cdot y_i}{\sum_{i=1}^{N} \mu_i} \quad (3)$$

where yidenotes the output action corresponding to the i-th rule and N is the total number of active rules. This control signal dynamically determines the participation levels of the battery, diesel generator, photovoltaic array, and grid, ensuring smooth transitions, minimal generator cycling, and adherence to operational constraints.

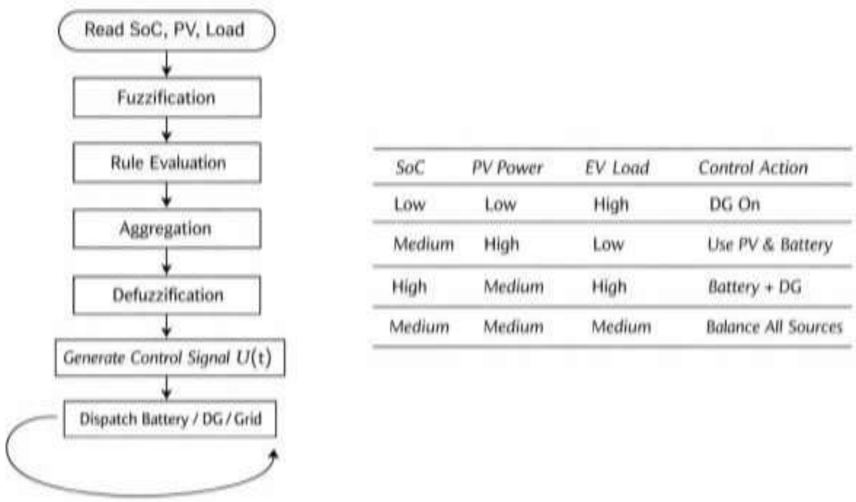
while the battery SoC evolution is governed by the discrete-time state,

$$So(t+1) = SoC(t) + \frac{\eta_{ch}P_{bat,ch}(t) - P_{bat,dis}(t)/\eta_{dis}}{E_{bat,max}} \Delta t \quad (4)$$

and the diesel generator is conditionally activated based on the rule,

$$UD(t) = 1 \; if$$
$$So(t) < SoCmin \text{ and } PPV\,(t) < PEV\,(t) \quad (5)$$

fuzzy supervisory control logic follows a continuous algorithmic loop.



SoC	PV Power	EV Load	Control Action
Low	Low	High	DG On
Medium	High	Low	Use PV & Battery
High	Medium	High	Battery + DG
Medium	Medium	Medium	Balance All Sources

Fig. 1. Hierarchical fuzzy inference–driven supervisory control flow and linguistic rule mapping for hybrid energy source dispatch.

system states are read, fuzzified, evaluated against the rule base, aggregated, defuzzified to produce U(t), and dispatched to component-level controllers, after which SoC and power flow are updated and the next control interval is processed.

This hierarchical structure ensures that the fuzzy logic decisions integrate seamlessly with DC–DC and DC–AC conversion controls, voltage and frequency regulation, and harmonic suppression, resulting in a resilient, adaptive, and energy-efficient coordination of renewable, storage, and auxiliary generation in grid-connected electric vehicle charging infrastructures.

IV. Adaptive Hybrid Energy Orchestration

Hybrid renewable–conventional coordination in the proposed framework is realized through an adaptive supervisory dispatch mechanism that orchestrates photovoltaic generation, battery energy storage, grid interaction, and auxiliary diesel support under continuously evolving system states. Unlike static merit-order scheduling, source participation is governed by dynamic prioritization coefficients derived from real-time assessment of renewable intermittency, electrochemical storage availability, and demand intensity.

Photovoltaic generation is accorded primary dispatch precedence due to its non-dispatchable yet cost-optimal nature, while battery storage functions as a temporal energy moderator, compensating short-duration supply–demand discrepancies. This coordinated behavior is mathematically enforced through a normalized dispatch formulation,

$$P(t) = \lambda i(t)\ Prated, \quad \sum_{i} \lambda(t) = 1 \qquad (6)$$

where the adaptive weighting factors λi (t) encode supervisory prioritization. Diesel generation is deliberately constrained via a conditional activation criterion,

$$P\_D(t) = \{\ 0\ ,\ if\ SoC(t) > SoC\_thr \wedge P\_PV(t) \geq P\_Load(t) \quad \{\ \_DG\hat{\ }rated\ ,\ otherwise \qquad (7)$$

thereby curtailing fossil fuel reliance and associated emissions. Grid interaction is modulated as a residual balancing variable to alleviate network stress, expressed as,

$$Pgrid\ (t) = PLoad\ (t) - \sum_{i \neq grid} Pi\ (t) \qquad (8)$$

The supervisory prioritization logic enables smooth reconfiguration between grid-connected and islanded modes without inducing voltage or frequency discontinuities. This hierarchically coordinated dispatch paradigm enhances renewable absorption, mitigates operational transients, and substantially improves system resilience under stochastic electric vehicle charging behaviour, distinguishing the proposed approach from conventional rule-based energy scheduling schemes.

V. Adaptive Hybrid Energy Orchestration

A. MPPT algorithms for renewable extraction

Maximum power point tracking (MPPT) constitutes a critical control function for maximizing renewable energy extraction under stochastic environmental conditions. In the proposed system, MPPT is implemented at the converter interface to dynamically regulate the operating point of the photovoltaic array, ensuring optimal energy harvesting despite irradiance and temperature fluctuations.

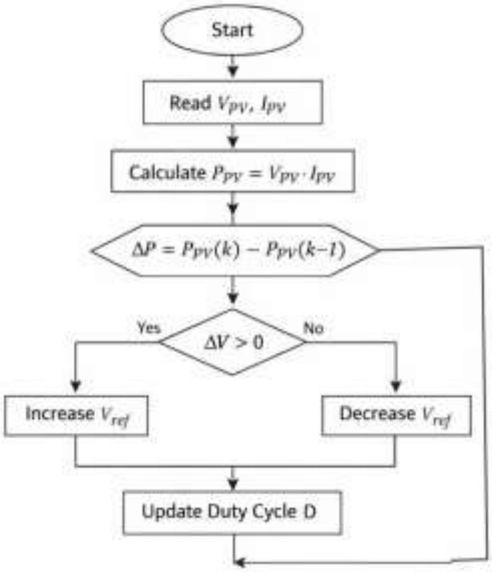


Fig. 2. Flowchart for MPPT Control Algorithm.

The control objective of MPPT is achieved by enforcing the stationarity condition of the power–voltage characteristic of the photovoltaic generator, expressed as,

$$\mathrm{d}P\_PV/\mathrm{d}V\_PV = 0 \qquad (9)$$

where PPV=VPV·IPV. Among the various tracking methodologies, perturb-and-observe (P&O) logic is adopted due to its computational efficiency and compatibility with real-time embedded implementation. The algorithm introduces small voltage perturbations and evaluates the resulting power variation to iteratively converge toward the global maximum operating point.

To enhance tracking robustness under rapidly changing irradiance, incremental conductance principles are embedded by comparing instantaneous and incremental conductance values, governed by the relation,

$$dI\_PV \;/\; dV\_PV = -\, I\_PV \;/\; V\_PV \qquad (10)$$

which enables accurate discrimination between left and right operating regions of the maximum power point. The MPPT controller generates a reference duty ratio for the DC–DC converter, thereby modulating the effective load impedance seen by the photovoltaic array.

This adaptive extraction mechanism minimizes steady-state oscillations, improves convergence speed, and ensures sustained renewable utilization across diverse operating regimes. The integration of MPPT at the converter level significantly enhances overall system efficiency and reduces reliance on auxiliary energy sources.

B. PR/PI-Based Inverter Control

Power quality regulation in the proposed system is enforced through a dual-loop inverter control architecture employing Proportional–Integral (PI) and Proportional–Resonant (PR) controllers. The control strategy is designed to maintain voltage magnitude, frequency stability, and harmonic suppression under both grid-connected and islanded operating modes.

In the synchronous reference frame, PI controllers regulate the DC-link voltage and active–reactive power exchange by eliminating steady-state error in constant reference signals. The PI control law is defined as,

$$GP(s) = Kp + Ki/s \qquad (11)$$

where Kp and Ki represent proportional and integral gains, respectively. This formulation ensures stable DC-link regulation and controlled power flow between the inverter and the grid.

For AC-side voltage and current regulation, PR controllers are implemented in the stationary reference frame to achieve zero steady-state error for sinusoidal signals without coordinate transformation. The PR control law is expressed as,

$$GP(s) = Kp + Kr \bullet s/(s2 + \omega 2) \qquad (12)$$

where $\omega 0$ denotes the fundamental grid angular frequency and
Kr defines resonant gain. This structure provides high selectivity at the fundamental frequency, enabling effective harmonic attenuation.

Power quality compliance is ensured by constraining total harmonic distortion (THD) and frequency deviation according to,

$$THD = sqr(\Sigma V2)/V1 \leq THDmax \qquad (13)$$

The coordinated PI–PR control framework guarantees rapid dynamic response, improved waveform fidelity, and compliance with grid and EV charging standards.

C. THD-Limited Inverter Regulation Strategy

Voltage and frequency regulation within the proposed charging infrastructure is explicitly enforced through harmonic-constrained inverter control, ensuring compliance with grid codes and EV charger power quality requirements. Unlike conventional regulation schemes that focus solely on RMS voltage and nominal frequency tracking, the proposed approach embeds total harmonic distortion (THD) as an active supervisory constraint within the control loop.

The inverter output voltage is regulated to remain within permissible bounds while maintaining harmonic distortion below prescribed thresholds, expressed as,

$$|(t) - V\_nom| \leq \Delta V\_max \qquad (14)\ \text{And}$$

$$|(t) - f\_nom| \leq \Delta f\_max \qquad (15)$$

where $Vnom$ and $fnom$ denote nominal voltage and frequency, respectively. Harmonic content is continuously evaluated using the distortion index,

$$THD = sqr(\Sigma V^2)/V_1 \qquad (16)$$

and constrained such that,

$$THD \leq THDmax$$

where Vh represents higher-order harmonic components and $V1$ is the fundamental voltage magnitude. The control architecture dynamically adjusts inverter reference signals and resonant gains whenever the harmonic index approaches the allowable limit, thereby preventing waveform degradation under nonlinear EV charging loads.

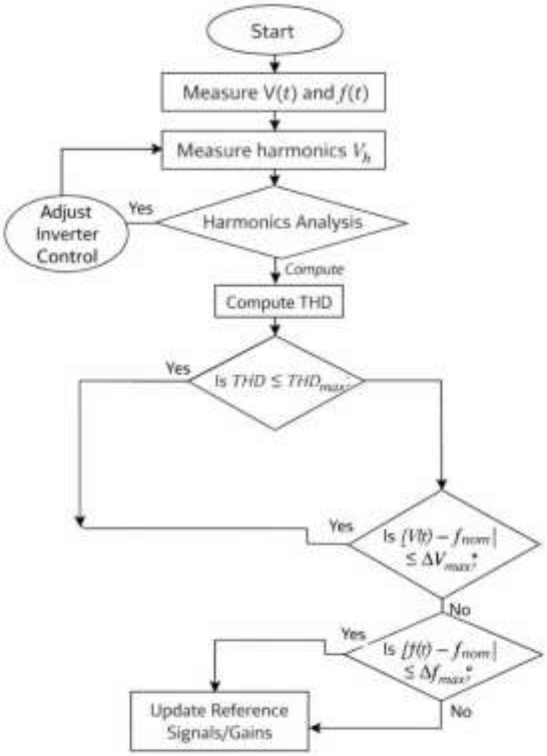


Fig. 3. Flowchart of THD-constrained voltage and frequency supervisory control.

During islanded operation, frequency regulation is achieved through inverter-dominant control with adaptive reference adjustment, while voltage regulation is preserved through inner-loop

feedback. In grid-connected mode, synchronization mechanisms ensure seamless compliance with grid voltage and frequency profiles without inducing harmonic amplification.
This THD-aware regulation strategy enhances waveform fidelity, mitigates resonance effects, and ensures robust power delivery across diverse operating conditions, elevating the system beyond conventional voltage-frequency control schemes.

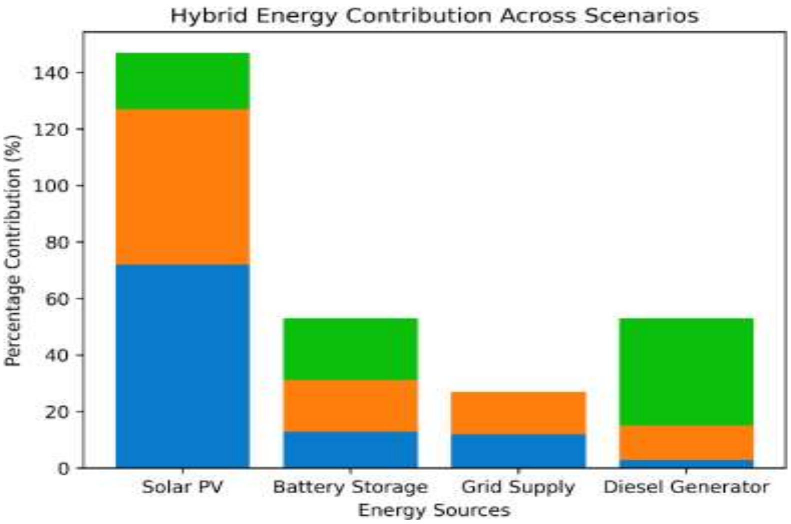


Figure4. Hybrid energy contribution of Solar PV, Battery Storage, Grid Supply, and Diesel Generator across scenarios S1, S2, and S3 based on percentage utilization.

The hybrid stacked representation in Figure 1 is based on the numerical representation of Table 4 which shows how the contribution of both energy sources changes in the conditions of various renewable and grid availability. The tendency of the proposed energy management system to adapt to the new conditions is proved by the fact that the percentage of renewable in S1 is decreased and the percentage of diesel in S3 is increased, which Figure 1 visually highlights

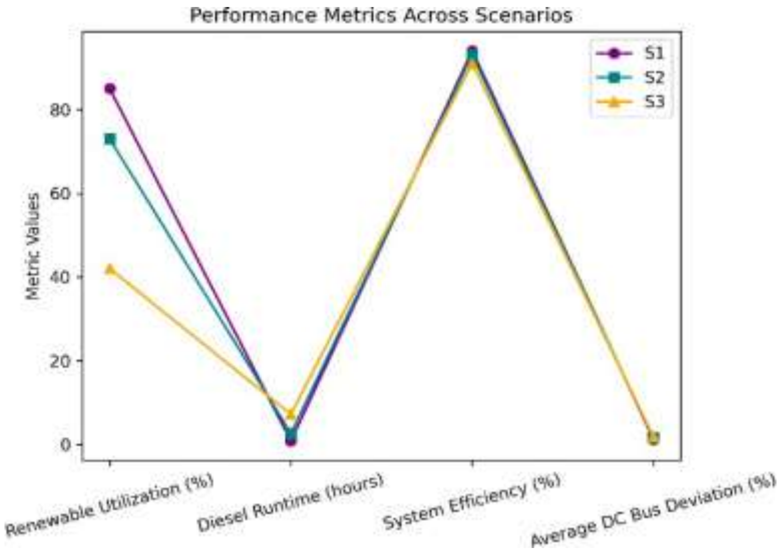


Figure 5. Comparative visualization of renewable utilization, diesel runtime, system efficiency, and DC bus deviation across scenarios S1, S2, and S3

Fuel savings are estimated by comparing continuous diesel operation versus controlled hybrid operation

Problems and Future Research Proposals.

Even though these results are positive, a number of technical and operational issues are noted. The intermittency of renewable energy is also one of the main issues as it requires very responsive control algorithms and sufficient storage capacity in order to prevent the lack of service. Stochastic user behavior makes the prediction of the EV load demand challenging and, therefore, makes real-time energy management decisions not easy. Though this would be good in the aspect of reliability, it would add mechanical delays, fuel logistics, maintenance needs, and acoustic and environmental issues. The degradation of batteries with repeated charge-discharge cycles requires particular SOC control and the sophisticated battery health control. Power electronic converters need fine tuning to avoid harmonics, variation in voltages and to avoid loss of efficiency. Also, the switching of the grid-connected and islanded modes without temporary disturbances requires advanced synchronization systems. Operationally, the complexity of the system is enhanced by the fact that there is coordination of various sources of energy that need intelligent supervisory control and qualified maintenance staff.

VI. Conclusion

The proposed research will offer an effective design and a smart control plan of a hybrid EV charging station that combines renewable energy, battery, and diesel reserve to guarantee sustainable and reliable charging of the station. The study shows that the renewable utilization, decreasing the number of diesel fuel used, system efficiency, and emissions are considerably improved with the help of mathematical modeling, simulation, and performance appraisal. The suggested structure will solve real-world issues of renewable intermittency and grid inability and provide a scalable approach to EV infrastructure in the future, especially in remote and energy-bound areas.

References

1. J. Ravi Kiran, T. Sirisilla, N. Vamshi, S. Ajay Kumar, M. Vardhan, and A. V. Vishal, “Integrated EV charging system with renewable energy sources and grid connectivity,” J. Electr. Syst., vol. 20, no. 11s, Jun. 2025.
2. M. Hadero and B. K. Baseem Khan, “Development of DC microgrid integrated electric vehicle charging station with fuzzy logic controller,” Front. Energy Res., vol. 10, 922384, 2022.
3. Z. Ullah, K. M. Kotb, M. R. Elkadeem, L. Yan, T. Khan, H. S. Qazi, F. Badshah, and M. A. Abido, “Integrating electric vehicles and renewable energy in modern power systems: A review of EV charging station design, control strategies, and emerging trends,” Ain Shams Eng. J., vol. 16, no. 10, pp. 103592, Jul. 2025.
4. M. M. Mousa, A. El-Shahat, and N. D. J. Zidan, “Optimizing grid-tied hybrid renewable systems for EV charging infrastructure: Techno-economic analysis and comparative study,” Energy Reports, 2025.
5. T. Chaudhari, S. Banker, C. Bariya, M. Priyadarshi, M. Parmar, and D. Parmar, “Electric vehicle charging station energy management and grid-connected renewable energy source simulation design,” Int. J. Intell. Syst. Appl. Eng., vol. 10, no. 6249, Mar. 2024.
6. S. Yadnik and S. Tiwari, “Renewable energy based multimode electric vehicle charging station: A review,” Int. J. Res. Advent Technol., 2022.

7. B. Mohan, V. R. Maddukuri, and M. Moturu et al., “Design and implementation of electric vehicle charging station with solar energy, diesel generator, and ANFIS control,” J. Theor. Appl. Inf. Technol., Feb. 2025.
8. Electric vehicle charging by use of renewable energy technologies: A comprehensive and updated review,” Comput. Electr. Eng., vol. 118, Part B, 109401, Sept. 2024.
9. “Electric vehicle charging stations and the employed energy management schemes: A classification based comparative survey,” SN Appl. Sci., Sept. 2024.
10. “Energy management system for hybrid renewable energy-based electric vehicle charging station,” IEEE Access, 2023.