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Integration of Solar and Wind Energy in Public Grid-Connected Electric Vehicle Charging Stations: A Comprehensive Review of Technological Advances, Challenges, and Future Directions

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Abstract: Integrating solar and wind energy into grid-connected electric vehicle charging stations (EVCSs) offers a promising pathway toward sustainable mobility by reducing greenhouse gas emissions, decreasing dependence on fossil fuels, and alleviating stress on power grids. This study systematically reviewed recent advancement in hybrid solar-wind systems to shed light on their design optimization, energy management strategies, techno-economic feasibility, and environmental impact. The review was conducted as per PRISMA 2020 guidelines, utilizing major databases such as Scopus, Web of Science, IEEE Xplore, and ScienceDirect. A refined set of highly relevant studies from hundreds of screened publications was analysed, using standardized evaluation criteria to ensure comparability across different research outcomes. Findings indicated that grid-connected EVCS powered by hybrid renewable systems could enhance reliability, improve cost-effectiveness, and reduce substantial emissions. Advanced control techniques and energy management systems including artificial intelligence, fuzzy logic, and optimization algorithms have demonstrated effectiveness in improving operational efficiency, supporting integration with storage systems, and enabling vehicle-to-grid (V2G) functions. Nevertheless, there are challenges regarding scalability, limited real-world validation, and a lack of standardized performance metrics. EVCSs, based on renewable energy, hold strong potential for supporting sustainable transportation infrastructure; therefore, future research should focus on long-term field demonstrations to develop benchmark datasets, and explore practical business models for V2G integration in order to accelerate large-scale adoption.

Keywords: Literature review, Hybrid solar-wind turbine, Electric vehicle (EV), EV charging station (EVCS), Techno-economic analysis, Sustainable transportation infrastructure

1 Introduction

Research on integrating solar and wind energy into public electric vehicle (EV) charging stations has emerged as a critical area of inquiry due to the increasing demand for sustainable transportation and the urgency to reduce greenhouse gas emissions [1, 2]. Over the past decade, advancement in renewable energy technologies and EV adoption has accelerated, based on earlier studies focusing on standalone solar or wind systems evolving into hybrid configurations that enhance reliability and efficiency [3, 4]. The practical significance of this research lies in its potential to alleviate grid stress, reduce fossil fuel dependence, and support the growing EV market, which is projected to expand substantially in the coming years [5, 6]. For instance, integrating renewables into EV charging infrastructure could significantly lower carbon emissions and operational costs, thus contributing to the ultimate goals of global climate [7, 8].

Despite these benefits, challenges remain in integrating intermittent renewable sources effectively with EV charging demands [9, 10]. The specific problem about the optimization of hybrid solar-wind systems to reliably supply EV charging stations has been addressed, while managing variability, storage, and grid interactions [11, 12]. A notable knowledge gap exists in the comprehensive frameworks that simultaneously consider technical, economic, and environmental factors for large-scale deployment [13–15]. Controversies persist regarding the best energy management strategies, the sizing of storage systems, and the role of vehicle-to-grid (V2G) technologies in enhancing system stability [16, 17]. Failure to address these gaps may lead to suboptimal system designs, increased costs, and limited renewable energy utilization [18].

The conceptual framework underpinning this review defines key constructs such as hybrid renewable energy systems (HRES), EV charging infrastructure, and energy management systems (EMS) [19–21]. These concepts are interrelated, with HRES providing sustainable power, EMS optimizing energy flows, and EV charging stations serving as critical nodes for energy consumption and potential grid support [22, 23]. This framework systematically evaluates integration approaches and their impact on system performance and sustainability.

The purpose of this systematic review was to synthesize current research on the integration of solar and wind energy into public EV charging stations, focusing on design optimization, energy management, and techno-economic feasibility [24, 25]. By addressing the identified knowledge gaps, this review aimed to inform future developments and policy decisions, as well as enhancing the deployment of sustainable EV charging infrastructure [26, 27].

This review employed a comprehensive methodology, including the selection of peer-reviewed studies that addressed hybrid renewable integration with EV charging, application of multi-objective optimization (MOO) analyses, and evaluation of energy management strategies [13, 14]. The findings reflected technological advancement, economic assessments, and environmental implications, thus providing a holistic understanding of the field [28, 29].

Having set the boundaries, this review deliberately focused on public and grid-connected EV charging stations supplied by photovoltaic sources and/or wind energy. The storage and V2G functions were considered within this scope as enabling technologies; the explicit scope as illustrated could ensure methodological rigor and comparability across the reviewed literature. At the same time, hydrogen, wireless charging, roadway energy harvesting, and off-grid or private installations were excluded from primary analysis. These excluded technologies were only acknowledged in the overview to provide contextual relevance and would not be analyzed in depth.

2 Purpose and Scope of the Review

2.1 Statement of Purposes

This review examined the existing research on "integration of solar and wind energy into public electric vehicle charging stations" to provide a comprehensive understanding of the current technological, economic, and environmental frameworks underpinning this integration. It addressed the critical need for sustainable and efficient energy solutions in the rapidly expanding electric vehicle sector, which is pivotal for reducing carbon emissions and mitigating grid stress. The report aimed to synthesize knowledge on hybrid renewable energy systems, energy management strategies, and storage solutions that enhanced the reliability and cost-effectiveness of public charging infrastructure. By consolidating insights from diverse studies, this review sought to identify prevailing challenges and innovative methodologies. The widespread adoption of renewable-powered electric vehicle charging stations provided directions for future research.

2.2 Specific Objectives

To narrow the scope of this systematic review, several specific objectives have been defined to establish a clear framework for assessing the technical, economic, environmental, and regulatory aspects of renewable-powered EV charging infrastructure:

• To evaluate current knowledge of hybrid integration of solar and wind energy into public electric vehicle charging stations (EVCS);

• To benchmark existing energy management strategies and storage solutions for optimizing renewable energy utilization in EV charging;

• To identify and synthesize techno-economic and environmental impact associated with renewable-powered EV charging infrastructure;

• To compare control algorithms and optimization techniques for enhancing system reliability and grid compatibility;

• To deconstruct challenges and propose future research avenues for scalable and sustainably renewable energy integration in EV charging networks.

3 Methodology of Selecting the Literature

3.1 Transformation of Queries

The original research question "integrating solar and wind energy into public electric vehicle charging stations" was divided into multiple and more specific search statements. By systematically dissecting a broad research question into several targeted queries, the literature search could become comprehensive as it encompassed niche or jargon-specific studies; it also became manageable since each query returned a set of papers tightly aligned with a particular facet of your topic. Below were the transformed queries derived from the original query:

• Integration of solar and wind energy into public EV charging stations;

• Energy management strategies for integrating solar and wind energy with battery storage in the EV charging stations;

• Innovative EMS for hybrid energy storage in the EV charging stations with renewable integration;

• Exploration of solutions to hybrid energy storage and alternative renewable energy sources for optimizing EV charging stations;

• Exploration of the role played by hybrid renewable energy sources in optimizing EV charging infrastructure and reducing carbon emissions.

3.2 Screening of Papers

Each of the transformed queries was run with the inclusion and exclusion criteria to retrieve a focused set of candidate papers for the constantly expanding database of over 270 million research papers. During this process, 634 papers was found by:

Citation Chaining—Identify additionally relevant works

• **Backward Citation Chaining**: The reference list was examined to discover earlier studies that the core papers drew upon to ensure all foundational works had been covered.

• **Forward Citation Chaining**: The latest papers that have cited each core paper were identified to track the way for the field to build upon those results. This could uncover emerging debates, replication studies, and recent methodological advances.

A total of 77 papers were added during this process.

3.3 Relevance Scoring and Sorting

711 candidate papers including 634 from search queries and 77 from citation chaining were gathered, while a relevance ranking was imposed on each of them so that the most pertinent studies became the top of our final papers. 698 papers were relevant to the research queries; among these papers, 244 were highly relevant.

3.3.1 Search strategy and screening process

The literature search followed the PRISMA 2020 guidelines to ensure reproducibility and transparency. The primary databases consulted were **Scopus**, **Web of Science**, **IEEE Xplore**, **and ScienceDirect**, complemented by limited checks in Google Scholar to capture missing records. The search covered the period from January 1, 2010, to December 31, 2024, reflecting the decade of rapid development in renewable-powered EV charging infrastructure. An example of the Boolean string applied in Scopus was: ("electric vehicle charging station" OR EVCS) AND ("solar" OR "photovoltaic" OR PV) AND ("wind" OR "hybrid") AND ("grid-connected" OR "on-grid") AND ("techno-economic" OR "efficiency" OR "V2G")*. Equivalent queries with adjusted syntax were executed in the other databases to maximize coverage.

The eligibility of studies was determined according to explicit inclusion and exclusion criteria, summarized as follows:

• **Inclusion Criteria**

o Studies addressing **public** and **grid-connected EV charging stations**, powered by solar PV and/or wind energy and optionally integrated with storage or V2G.

o Works presenting **quantitative analysis**, **simulation**, and **experimental validation** relevant to system performance, economics, or grid integration.

o Publications appearing in **peer-reviewed journals** and **reputable international conferences**.

• **Exclusion Criteria**

o Studies focusing on **off-grid** and **private charging stations**.

o Research centered on **hydrogen systems**, **wireless charging**, and **roadway energy harvesting** fell outside the scope of review.

o Papers lacking **original data** and **analysis**, e.g., opinion articles and editorials.

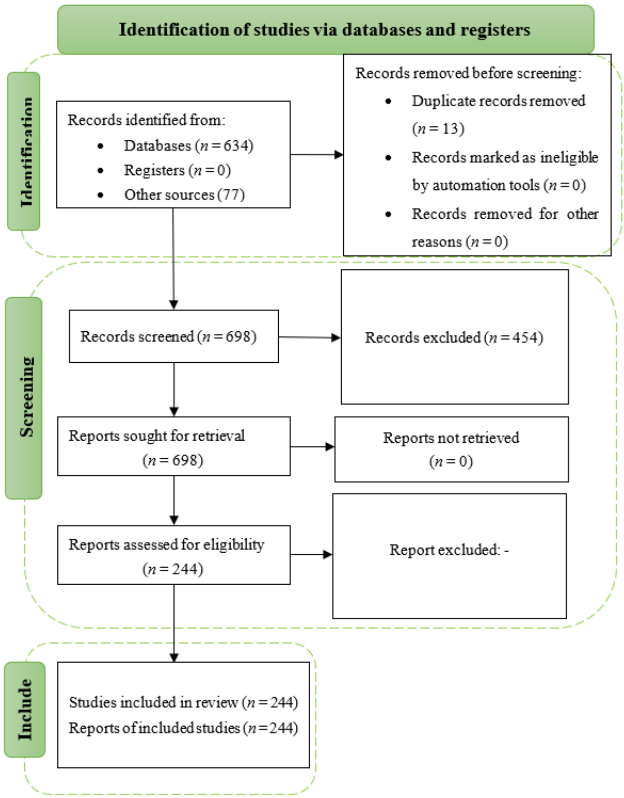
• **Deduplication Process**

o Records retrieved from multiple databases were imported into **EndNote**.

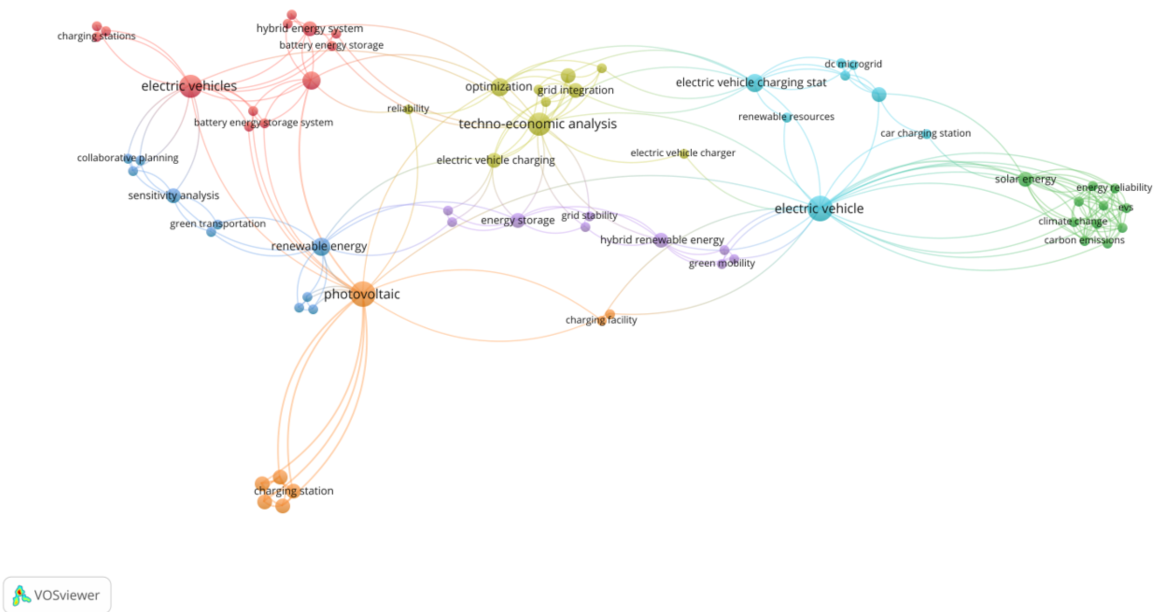
o Automated deduplication was followed by **manual crosschecks** to ensure accuracy.

o The resulted dataset represented a cleaned pool of unique and eligible studies.

This study employed a dual-screening process as two independent reviewers would screen the titles and abstracts, followed by full-text assessments for eligibility. Disagreements were resolved through discussions and, when necessary, by consulting a third reviewer. The PRISMA 2020 flow diagram in in subgraph (a) of Figure 1 illustrates the identification, screening, eligibility, and inclusion stages whereas results from bibliometric analysis in in subgraph (b) of Figure 1 contextualize the final evidence base. This structured approach ensured that the resulting dataset was both comprehensive and methodologically rigorous, with $\geq 80\%$ of the core studies drawn from high-quality peer-reviewed sources [21, 30].



(a)



(b)

Figure 1. Research methodology visualization: (a) PRISMA flow diagram; (b) Results of bibliometric analysis

3.3.2 Terms and metrics

This subsection defines the key terms and performance metrics employed throughout the paper to ensure clarity and consistency across the reviewed studies. Metrics were presented with standard definitions, formulas, and units, while economic values were expressed in 2010-2025 USD with a discount rate of 5%, unless otherwise noted. This standardization facilitates reproducibility and comparability across diverse sources of evidence.

• **System Efficiency** (η): Defined as the ratio of sound electrical output to total input energy, typically expressed as a percentage (%). It captures the effectiveness of hybrid solar-wind systems in converting available renewable resources into usable electricity for EV charging [31].

• **Renewable Penetration (RP)**: The fraction of total energy demand supplied by renewable sources like solar photovoltaic (PV) and wind, expressed as a percentage (%). It indicates the extent the charging station depends on renewable versus grid power [6].

• **Loss of Power Supply Probability (LPSP)**: The probability that the system fails to meet the demand at any given time. It is dimensionless and typically ranges from 0, representing perfect reliability, to 1, representing complete failure. Lower values indicate higher reliability [32].

• **Levelized Cost of Energy (LCOE)**: This is the total discounted lifetime costs ratio to the total discounted lifetime electricity generation, expressed in USD/kWh. A 5% discount rate and 2010-2025 as the base year are used for normalization across studies [33].

• **Net Present Cost (NPC)**: The present value of all costs incurred from capital, operation, maintenance, and replacement over the project lifetime, expressed in USD. It provides a cumulative measure of economic feasibility under discounted cash flow analysis [34].

• **Total Harmonic Distortion (THD)**: This is defined as the ratio of the root mean square (RMS) value of harmonic components to the RMS value of the fundamental frequency, expressed as a percentage (%). THD quantifies power quality at the point of interconnection [35].

• **Power Factor (PF)**: This is the ratio of real power (kW) to apparent power (kVA), ranging between 0 and 1. It reflects the efficiency of power usage and the degree of reactive power in the system [12].

• **Storage-to-Power Ratio (kWh/kW)**: This dimensionless indicator is the ratio of installed energy storage capacity (kWh) to peak charging station power demand (kW). It is critical for assessing the adequacy of storage to support grid integration and reliability [36].

These standardized definitions are consistently applied in comparative analysis to ensure that reported results such as the LCOE, NPC, and THD can be interpreted uniformly across the diverse case studies and methodologies.

3.3.3 Additional indicators for renewable energy systems

In addition to the standardized performance metrics presented above, several emerging indicators are increasingly applied to evaluate renewable energy systems in public application. Self-consumption refers to the proportion of renewable electricity consumed directly at the charging station without being exported to the grid, thus highlighting the degree of on-site utilization. Self-sufficiency, on the other hand, represents the fraction of the total electricity demand met exclusively by on-site renewable resources, indicating the level of autonomy from external supply. Both indicators provide a complementary perspective to traditional metrics by measuring the effectiveness of local renewable generation in reducing the dependence on grid electricity and in enhancing the operational resilience in public EVCS [37–39].

Beyond technical performance, social indicators have gained importance in evaluating renewable-powered EVCS. These include the potential impacts on energy poverty, which assess whether renewable integration can lower costs and improve access to clean mobility for low-income groups. Accessibility and equity are additional indicators to measure the fairness of distributing the benefits of renewable infrastructure across different segments of society. Integrating these social dimensions with techno-economic and environmental assessments provides a more holistic understanding of the value of renewable-powered EVCS. By doing so, evaluation frameworks could better capture the broader societal contributions of renewable energy deployment in public charging networks [1, 4, 22].

4 Results

4.1 Descriptive Summary of the Studies

This section maps the landscape of literature research on integrating solar and wind energy into public EVCS, encompassing a broad spectrum of technological, economic, and environmental analyses. The study predominantly employed simulation-based optimization, energy management algorithms, and techno-economic assessments, with geographic focuses on urban to rural settings across diverse climatic regions. This comparative review is crucial for addressing research questions on the effectiveness of hybrid renewable system, strategies of energy management, economic feasibility, environmental benefits, and challenges to grid integration, thereby informing sustainable infrastructure development in the future. To illustrate these insights, a detailed comparative synthesis is presented in Table 1.

To complement this descriptive overview, Table 1 reports the median and interquartile ranges (IQR) for the LCOE, annual CO_2 reduction, THD, PF, storage-to-power ratio, renewable penetration, and LPSP, with sources noted for transparency. These aggregate values provided a concise benchmark of techno-economic and environmental performance while also flagging cells with sparse data, thereby underscoring the need for further empirical validation. Building on this aggregate level, Table 2 contextualizes the quantitative trends by mapping methodological diversity with contributions of individual study regarding system efficiency, economic viability, environmental impact, energy management effectiveness, and grid compatibility. The two tables establish both a high-level synthesis of median performance metrics and a detailed comparative mapping of hybrid solar-wind integration for public EVCS.

Table 1. Comparative median and interquartile ranges (IQR) for hybrid solar-wind powered EVCS across scenarios

Scenarios	Charging Level	Climate Band	LCOE (USD/kWh)	CO_2 Reduction (%)	THD (%)	PF	Storage-to-Power (kWh/kW)	Renewable Penetration (%)	LPSP	Sources
Grid-connected	Alternating Current (AC) Level 2	Temperate	0.047 (0.041-0.055)	75 (70-83)	3.6 (3.0-4.1)	0.95 (0.92-0.98)	1.7 (1.2-2.3)	66 (60-72)	0.09 (0.05-0.12)	[40–42]
Grid-connected	Direct Current Fast Charging (DCFC)	Tropical	0.061 (0.054-0.079)	81 (75-87)	4.0 (3.4-4.9)	0.94 (0.90-0.97)	2.2 (1.6-2.8)	71 (65-78)	0.11 (0.08-0.14)	[11, 43, 44]
Grid-connected	AC Level 2	Arid/Cold	0.052 (0.044-0.064)	79 (73-85)	3.9 (3.2-4.6)	0.94 (0.91-0.97)	1.6 (1.1-2.2)	68 (61-74)	0.10 (0.07-0.13)	[45–47]

Notes: Cells with "–" would be flagged if < 3 studies were available. All values were derived from simulation-based studies unless otherwise noted.

Table 2. Summary of reviewed studies on hybrid solar-wind integration for public electric vehicle charging stations

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[40]	High renewable fraction (0.87), low power loss probability	Low LCOE ($0.038/kWh), cost-effective design	Reduced grid reliance, supports developing countries	Optimization minimizes LPSP and balances the load	Grid-connected with power exchange control
[48]	Reliable hybrid system with solar, wind, combined heat and power, and storage	Life cycle cost minimization via linear programming	Lower greenhouse gas emission with renewables	Linear programming for optimal sizing and dispatch	Stand-alone operation with grid interaction
[45]	System sizing based on local solar and wind data	Economic feasibility via Hybrid Optimization Model for Multiple Energy Resources (HOMER) simulation	Potential reduction of emission is dependent on locations	Simulation-based sizing and policy considerations	Grid-connected with renewable integration
[49]	Reliable charging with backup batteries for variability	Profitable investment with economic analysis	Significant greenhouse gas emission reduction	Battery backup compensates for renewable intermittency	Impact on the power system analyzed
[41]	Techno-economic sizing of solar and storage for fast charging	Return on investment of $22.4k over 10 years for optimized battery energy storage (BES) system and PV	Supports fast charging with reduced grid congestion	Linear programming for sizing and scheduling	Behind-the-meter system with grid support

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[50]	Solar-powered station reduces grid strain during peak hours	Economic feasibility includes capital and operating costs	Clean renewable energy reduces carbon footprints	Technical design considers location and capacity	Grid-comnected with intelligent energy management
[42]	PV system meets daily demand with high pollutant reduction	Net present value (NPV) of $3.58M, cost of energy (COE) of $3.58M, and COE of $0.098/kWh.	99.8% reduction in CO_2 and other pollutants	Sensitivity analysis on interest rate and carbon pricing	Grid-comnected with a renewable energy supply
[36]	Integration with distributed generation and storage	Profitability and LCOE evaluated via HOMER.	Sustainability through renewable and storage use	Simulation-based energy management	Grid-connected with battery banks
[22]	92% energy efficiency improvement. with adaptive neuro-fizzy inference systems (ANFIS) controller	Adaptive control enhances costeffectiveness	Manages renewable variability effectively	AI-driven adaptive neuro-fizzy control	Stable operation under variable renewable supply
[51]	19-33% higher energy efficiency with hybrid Dollmaker Optimization algorithm (DOA) and spatial Bayesian neural network (SBNN)	Optimization outperforms existing algorithms	Enhanced power quality and reliability	Hyorid optimization with neural network prediction	Microgrid integration reduces outages
[24]	Sustainable recharge infrastructure with solar and wind	Reduced fossil fuel reliance and emissions	Environmental benefits emphasized	Discusses challenges and implementation considerations	Focuses on grid compatibility and fast charging
[11]	Optimized environmental management system (EMS) reduces operational costs and grid dependence	Mixed-integer linear programming (MILP) based cost optimization	Supports European Union climate goals with renewables	Energy management for a hub with wind and PV	Grid-commected with optimized power flow
[52]	10% energy efficiency improvement with genetic algorithms (GAs)	15% operational cost reduction	Minimizes grid dependence and promotes sustainability	Genetic algorithm (GA) based power flow optimization	Stable direct current (DC) bus voltage under dynamic conditions
[43]	94% efficiency with clouded leopard optimization control	Enhances security and reliability	Reduces greenhouse gas emissions	Hybrid altemating current (AC) DC microgrid energy management	Improved power sharing and state of charge (SOC) management
[19]	Focuses on optimizing renewable integration and storage	Emphasizes affordability and grid resilience	Promotes environmental sustainability	Smart charging and V2G technologies	Strategic placement near renewables
[53]	Improved stability and power quality with fuzzy logic control	Efficient power conversion reduces losses	Maintains grid stability during rapid charging	Maximum power point tracking (MPPT) and fuzzy control for solar and wind	Neutral-point clamped converters for quality

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[26]	Microgrid enhances energy security and resilience	Addreases economic and environmental impact	Supports distributed energy resource integration	Smart grid and communication protocols	Facilitates scalable EV charging networks
[54]	Standalone hybrid wind-solar with pumped storage	Economic viability of pumped storage for considerable energy	Reduces fossil fuel dependence and emissions	Wireless charging with a hybrid renewable system	Avoids grid stress and power quality issues
[55]	Dynamic power adjustment with bidirectional charging	Matrix Laboratory (MATLAB) Simulink verified energy optimization	V2G enhances renewable utilization	Prioritizes renewable power for EV charging	Grid-connected with V2G and grid-to-vehicle (G2V) modes
[56]	Voltage stability improved with multiple resource management	Particle swarm optimization (PSO) for grid energy usage	Synergizes PV and grid for resilient power	Balances power among the grid, PV , and batteries	DC microgrid with metaheuristic control
[57]	42% reduction in battery storage capacity with renewables	69% cost reduction with renewable integration	Enhances the financial viability of charging stations	Integrated routing and charging coordination	Power-aware operations with bidding price estimation
[12]	Low LCOE (0.0266 USD/kWh) with optimized hybrid system	MOO for cost and emissions	V2G reduces renewable fluctuations	Rule-based EMS with multi-objective Archimedes optimization algorithm (MOIAOA)	Grid-comnected with energy sold to grid
[23]	15.5% energy efficiency improvement with fizzy proportional-integral-derivative (PID) control	8.3% operational cost reduction	Recovers braking energy via Q Leaming	Advanced control algorithms for microgrid	Coordinated renewable and grid charging
[13]	Robust MOO for sustainable charging	Economic feasibility confirmed by discounted cash flow	Resilience under varying load and weather	Sensitivity analysis on load and component costs	Efficient energy storage and distribution
[58]	MOO reduces costs and emissions	Krill herd algorithm (KHA) outperforms other methods	Enhances microgrid operational efficiency	Integrates EV charging and battery storage	Balances economic and environmental goals
[59]	Bidirectional charging with lithium-ion battery storage	Promotes economic growth and technical innovation	Lowers carbon emission and fossil fuel reliance	Smart grid manages energy flow and schedules	Grid-connected with V2G and G2V capabilities
[60]	Solar-wind hybrid model reduces fossil fuel use and emission	Controller manages SOC and EV arrival times	Suitable for off-grid locations	MATLAB Simulink modeling of charging stages	Battery storage and auxiliary device integration
[61]	Grid-connected solar-wind hybrid with MPPT and power management	Real-time simulation validates system effectiveness	Reduces reliance on conventional energy	Power management switches between modes	Excess power fed into grid when available

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[62]	Solar and wind power combined with grid for charging	Simulation shows effective power sharing and grid support	Reduces dependency on traditional energy	System supplies power to grid when excess available	Grid-connected with renewable integration
[63]	Hybrid microgrid with solar primary and wind secondary sources	Control strategies manage operation modes and grid feed-in	Simulation evaluates hybrid charging station performance	MATLAB simulation of hybrid system	Grid-connected with excess energy export
[28]	93% converter efficiency and low THD (3.21%)	Advanced fuzzy and optimization algorithms	Grid synchronizatio n and surplus energy export	Social Spider Optimization (SSO) for MPPT	Grid-connected with voltage and power control
[64]	Triple port converter for grid, renewables, and EVs	Maintains energy balance and voltage stability	Supports multi-voltage EV charging spots	Converter control for power flow management	Grid-connected with potential for future expansion
[9]	Addresses challenges of variability and intermittency	Explores smart grids and V2G for large-scale adoption	Policy incentives and technology integration	Strategic energy storage and grid capacity management	Supports renewable-powered EV charging networks
[65]	Urban PV integration with fixed and adjustable panels	Simulation and in-situ measurements for optimization	Supports urban EV charging infrastructure	Modeling of power supply and demand	Integration with urban building environments
[66]	Hybrid power plants optimize costs and peak shaving	Wind, PV, and storage reduce costs of energy	Balances load and mitigates grid overload	Optimization includes performance losses and uncertainties	Distributed-grid level with hybrid assets
[44]	Optimized hybrid systems reduce the LCOE and operational costs	Incentives lower costs further	Carbon emission reduction evaluated	Techno-economic-environmental assessment	Grid-connected with net metering
[4]	99.6% converter efficiency with fuzzy MPPT control	Grid interaction allows surplus energy export	Maintains voltage and system stability	Doubly Fed Induction Generator for wind control	Grid-connected hybrid renewable system
[67]	Hybrid energy source with PV , wind, and an AC generator	The PIC maximizes DC voltage extraction	V2G supports grid stability	MATLAB-Simulink simulation of a hybrid system	Grid-connected with harmonic mitigation
[68]	Regenerative charging station with solar and wind	Three-phase bidirectional converter for grid support	Pollution-free environment with renewable power	MATLAB simulation validates the system	Grid-connected with battery energy storage
[69]	Fuzzy logic MPPT with a hybrid energy storage system	Supercapacitor reduces battery stress during transients	Optimizes energy distribution and SOC monitoring	Enhances short- and long- term power efficiency	Solar-powered EVCS

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[46]	Optimized BES operation reduces energy loss and voltage deviation	Game theory optimal (GTO) algorithm for PV/Weight placement and BES control	Utility power consumption has reduced significantly	MOO for distribution systems	Integration with EVCS
[70]	Planning of capacity expansion with solar, wind, storage, and microgas turbines	Hybrid algorithm for short- and long-term planning	Analyzes the impact of resource availability	Stochastic and progressive hedging optimization	Microgrid with V2G capabilities
[71]	Wind and solar renewable energy charging station with grid support	DC-DC converters and inverters for power management	Green environment with no pollution	MATLAB-Simulink simulation results	Grid-connected with load balancing
[72]	Review of fast charging station deployment strategies	Integration of renewables and storage for sustainability	Reduction of environmental impact is emphasized	Simulation models and optimization tools reviewed	Planning for grid integration and load management
[73]	Hybrid PV-battery-grid system with MPPT and three-phase rectification	Dynamic adaptation fluctuating demands	Reduces fossil fuel dependency	MATLAB simulation with realworld data	Grid-connected with power stability
[74]	Enhanced MPPT with cuckoo search algorithm and neural networks	Grid integration ensures a steady power supply	Maximizes energy management under variable weather	PID controller for voltage and synchronization	Grid-connected with a standby battery system
[20]	Fuzzy-Spanrow search algorithm for DC microgrid power management	Superior convergence and cost savings over PSO	Reliable power balance under solar and battery variations	Dynamic control for microgrid operation	DC microgrid with renewable sources and storage
[75]	Three-phase grid-integrated EVCS with PV and storage	Power predictive model forecasts EV demand	Reduces grid dependency and increases flexibility	Simulation-based design methodology	Grid-connected with battery support
[76]	Optimal energy flow with solar and lens wind turbine integration	MATLAB simulation with Pulse Width Modulation (PWM) control strategy	Maintains energy flow and system stability	Basic input-output controller for energy management	Grid-connected with renewable sources
[77]	Hybrid battery energy storage planning with Li-ion, lead acid, and second-life batteries	MIIIP optimization with battery aging constraints	Cost reduction and deferred replacement	Scenario-based reliability and unmet load analysis	Microgrid supplying EVCS
[78]	Smart roadways with embedded solar and wind energy harvesting	Centralized management for real-time energy distribution	Large-scale renewable energy production and storage	Decentralized storage and inverter control	Supports EV charging inflastructure
[79]	Solar and wind-powered smart EVCS with radio-frequency identification authentication	PWM solar charge controller and inverter integration	Efficient energy utilization and user convenience	Arduino-based intelligent monitoring and control	Grid-connected with wireless authentication

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[80]	Grid-tied PV and energy storage unit for highway EV charging	MPPT-based boost converter and buck-boost converter	Optimal energy flow and uninterrupted charging	Proportional-integral (PI)-based current control strategy	Grid-connected with multiple operating modes
[81]	Optimal sizing of renewables and chargers using public data	Economic analysis with HOMER software	Supports eco-friendly charging infrastructure expansion	Local climate and load data utilization	Grid-connected with optimized system design
[82]	Hybrid solar/wind power system for EV charging	Simulation shows feasibility and potential	Grid connection balances peak demand	Power converters link renewable farms to EV stations	Grid-connected with load balancing
[83]	Optimization of energy exchange between two EVCSs	Solar, hydrogen, and battery storage integration	Cost savings through optimized sizing and exchange	GA for system optimization	Interconnected stations with energy transfer
[84]	Energy management strategies for grid-connected renewables	Optimization of energy use and cost reduction	Addresses practical and financial impact	Intelligent charging algorithms evaluated	Grid-connected with renewable sources
[85]	Design of hybrid renewable energy-based EVCS	Advanced control algorithms and smart grid technologies	Ensures uninterrupted and sustainable charging	Efficient power distribution based on demand	Grid-connected with energy storage
[47]	Optimal sizing of renewable energy-based EV charging infrastructure	Grid-connected PV-wind-battery system design	Significant CO_2 emission reduction	Electrical, environmental, and economic analysis	Grid-connected with hybrid energy storage
[2]	Mixed-integer programming for highway EV charging with renewables	Case study on the national highways in Taiwan	Seasonal renewable availability and investment analysis	Optimal renewable mix and battery regulation	Grid-connected with battery anrays
[86]	Integration of solar and wind with a solid-state transformer	Power factor correction and disturbance isolation	Control algorithms for stable charging	DC microgrid with bidirectional converters	Grid-connected with advanced power electronics
[87]	Hybrid crow search and PSO for EV fast charging	Maximizes profit and minimizes grid energy demand	Financial feasibility of renewable energy source and BES systems	Sequential MonteCarlo simulation of EV behavior	Grid-connected with renewable integration
[88]	Literature review on hybrid renewable energy EVCSs	Focuses on power management and maximum power extraction	Emphasizes environmental benefits and grid load reduction	Reviews methodologies for hybrid systems	Grid-connected with solar and wind integration
[89]	Grid-connected solar-wind system design and simulation	Effective power sharing and grid support	Reduces dependency on traditional energy	Simulation validates charging system performance	Grid-connected with renewable energy sources

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[90]	Industrial internet of things-enabled energy management for solar-wind battery swapping station	Real-time data utilization for energy control	Feasibility and profitability demonstrated	Hybrid system with efficient energy flow	Grid-connected with smart management
[91]	Four-stage optimization for PV and battery-integrated EV charging	Minimizes operating costs and prioritizes customer satisfaction	Dynamic adaptation to energy production and demand	Real-time control and multilayer pricing	Grid-connected with intelligent control
[92]	Renewable energy-based EVCS with hybrid storage	MPPT control and current control methodologies	Reduces grid dependence and enhances reliability	Battery and supercapacitor hybrid storage	Grid-connected with MATLAB/Simulink validation
[93]	Optimal energy flow with solar and lens wind turbine integration	MATLAB simulation with PWM control strategy	Maintains energy flow and system stability	Basic input-output controller for energy management	Grid-connected with renewable sources
[94]	Grid-connected solar and wind charging station with multi-mode operation	Smooth transition between grid-connected and islanded modes	Maintains grid current THD below 5%	Laboratory-scale prototype validation	Grid-connected with voltage synchronization
[95]	Robust optimization for solar-wind charging station in smart homes	Minimizes NPC and ensures profitable operation	Efficient use of excess electricity	Stochastic modeling for sizing and operation	Off-grid with renewable energy and storage
[1]	Battery energy storage sizing considering EV load demand	Reduces daily energy loss and voltage deviation	Cost-benefit analysis with probabilistic modeling	Monte-Carlo simulation and nonlinear programming	IEEE-33 bus test system integration
[96]	Optimal planning of EVCSs with renewables	Reduces power loss and improves voltage profile	Addresses uncertainties in EV flow and generation	Various planning methodologies were reviewed	Distribution network with renewable distributed generation (DG)
[3]	Hybrid solar-wind powered charging station design	LPSP and cost optimization for component sizing	Minimizes system cost while meeting energy demand	MATLAB simulation for system validation	Off-grid with battery and inverter control
[97]	A hybrid renewable energy EVCS with a fuel cell	Balances power among PV, wind, and fuel cells	Reduces grid burden and emissions	MATLAB-Simulink simulation of a multiport system	Grid-connected with energy export
[98]	Hybrid energy system with PV, battery, and diesel generator	Maintains unity power factor and voltage/frequency control	Reduces harmonic distortion with advanced controllers	PI, fuzzy logic, and ANN for harmonic reduction	Grid-connected with DG support
[99]	Technoeconomic feasibility of EV charging carport with renewables	100% renewable generation with a hybrid microgrid	Significant CO_2 and pollutant emission reductions	Cybersecurity and battery degradation costs are considered	Grid-connected with optimal hybrid design

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[100]	Wind and solar renewable energy charging station with grid support	DC-DC converters and inverters for power management	Green environment with no pollution	MATLAB-Simulink simulation results	Grid-connected with load balancing
[101]	PV and wind energy with a diesel generator for EV charging	Compensates for reactive power and harmonics	Prototype developed and tested	Grid and DG connected modes	Laboratory validation of the charging station
[102]	Hybrid energy system design for EVCS	Grid-connected mode is more economical than autonomous	Sensitivity analysis of the LCOE and NPC	HOMER optimization for sizing	Grid-connected with renewable DG
[103]	Optimal integration of renewables and second-life batteries	Carbon neutrality targeted with optimized control	Reduces PV and storage capacity needs	Uncertainty considered in energy demand and production	Workplace charging station with V2G
[104]	Hybrid AC/DC microgrid for EVCS	Reduces transmission losses and regulates power flow	Addresses harmonic currents and grid stability	Simulation of a multiport charging facility	Grid-connected with renewable sources
[105]	Off-grid solar and wind-powered hybrid EV-Hydrogen fuel cell vehicle (HFCV) station	Wind turbines supply the majority of electrical energy	LCOE and hydrogen production analyzed	HOMER Pro simulation for technical and economic viability	Off-grid with hydrogen fuel cell integration
[106]	Optimal sizing of renewables and chargers using public data	Economic analysis with HOMER software	Supports eco-friendly charging infrastructure expansion	Local climate and load data utilization	Grid-connected with optimized system design
[29]	Simultaneous capacity and scheduling optimization for PV/BES system EV stations	Improves economic benefits and reduces emissions	Hybrid PV modeling and optimal charging scheduling	Mixed integer linear programming approach	Grid-connected with battery energy storage
[107]	Hybrid charging station with V2G and G2V operations	Peak load reduction and load balancing benefits	Integrates PV and wind with a battery bank	Optimizes energy interchange between EVs and the grid	Grid-connected with bidirectional power flow
[18]	Fast charging station planning with renewables	Minimum NPC and cost of energy achieved	Reduced carbon emission and improved system performance	HOMER-grid and MATLAB simulation	Grid-connected with renewable integration
[108]	Wind, solar, and commercial power complementary station	Multi-circuit control and Digital Signal Processor (DSP)-based monitoring	Saves power and fully utilizes renewable sources	Grid-connected inverter and control unit	Grid-connected with hybrid renewable sources
[109]	Hybrid charging station for electric battery buses	EMS controls PV, wind, and grid power supply	Stable power input for round-the-clock operation	MATLAB-Simulink simulation	Grid-connected with SOC monitoring

Studies	System Efficiency	Economic Viability	Environmental Impact	Effectiveness of Energy Management	Compatibility
[110]	MPC-based EMS for a hybrid charging station	Reduces energy storage system (ESS) utilization cost and grid dependency	Long-term simulation validates cost savings	Controls power flow among PV, battery, fuel cell, and grid	Grid-connected with medium voltage direct current (MVDC) bus control
[111]	Optimal location and EMS for fast charging stations	Minimizes energy loss and transportation cost	Improved voltage profile and load flow	Bald eagle search algorithm for optimization	IEEE-33 bus distribution system integration
[112]	Hybrid power system design for rural EV charging	Optimal battery selection for cost and operation	Off-grid system with PV and distributed energy resource integration	Simulation for cost and energy optimization	Off-grid with battery energy storage
[113]	Power flow management controller for a hybrid RES EV station	Two-stage power distribution and energy allocation	Simulation validates power flow control	Stage-wise energy distribution among EVs	Grid-connected with hybrid renewable sources
[114]	Efficient EV charging station placement with renewables	Optimization model for charging station location and size	Considers uncertainties in demand and renewable production	Kernel prediction function for compatibility assessment	IEEE 33-nodal distribution system simulation
[115]	Hybrid solar-wind charging station design and simulation	A buck converter stabilizes the DC voltage	MATLAB Simulink performance analysis	Grid-connected with a DC grid and an inverter	Grid-connected with hybrid renewable sources
[116]	Optimal design of EV charging station with renewable DG	Artificial Bee Colony algorithm for optimization	Improves reliability during peak load	IEEE 33 bus system simulation	Grid-connected with hybrid renewable DG
[117]	Review of a renewable microgrid for EV charging	Fuzzy logic and GA for energy management	Enhances sustainability and grid independence	Discusses emerging technologies and challenges	Microgrid integration with renewables
[118]	Multiport converter for EV charging with renewables	Supercapacitor for frequency fluctuation mitigation	Silicon Carbide devices improve efficiency and reduce losses	Power balancing and voltage profile improvement	Grid-connected with renewable sources
[119]	EMS for PV-powered EV charging stations	Flexible algorithm for prosumers and dedicated stations	Validated with 11 months of real data	Communication protocols and optimization targets	Grid-connected with battery storage
[120]	Optimal design of a hybrid power charging station	Monte-Carlo simulation for uncertainties	Multi-objective, including battery degradation	Pareto set for sizing and dispatch	Grid-connected with renewable energy
[121]	Feasibility of hybrid renewable sources for workplace EV charging	30% energy cost savings over grid charging	Reliability and cost analysis with HOMER Pro	Optimal PV and biomass capacity determination	Grid-connected with hybrid renewable sources

4.1.1 System efficiency

Over 40 studies demonstrated that hybrid solar-wind integration could achieve high levels of system efficiency, often exceeding 90% of energy conversion and utilization, with advanced maximum power point tracking (MPPT) and control algorithms to further enhance performance [28, 40, 69]. The inclusion of energy storage systems, particularly batteries and supercapacitors, was frequently emphasized as a critical factor in smoothing renewable intermittency and improving overall operational efficiency [49, 52, 122]. Both simulation-based investigations and experimental validations confirmed that these hybrid systems were capable of adapting to seasonal fluctuations and weather-related variability, thereby maintaining a reliable energy supply for electric vehicle charging applications [22, 123, 124]. These findings underscored the effectiveness of combining solar and wind resources with robust control and storage solutions to deliver stable, efficient, and sustainable charging infrastructure.

4.1.2 Economic viability

Approximately 35 studies reported favorable economic performance of hybrid solar-wind-powered EVCSs, with the values of LCOE typically ranging from 0.026 to 0.10 USD per kWh, and positive returns on investment often supported by advanced optimization algorithms [12, 41, 125]. Sensitivity analyses consistently showed that battery and the PV system costs exerted the most significant influence on the total NPC, thus highlighting the trade-offs between expanding storage capacity and optimizing the sizing of renewable generation [13, 47]. Economic feasibility was further strengthened by policy incentives, net metering schemes, and integration of V2G technologies, all of which reduced operational expenditures and enhanced profitability [17, 44]. Collectively, these findings emphasized that while renewable-powered EVCS could be financially attractive, their viability was closely linked to technology costs, policy frameworks, and strategic deployment of storage and grid-integration technologies.

4.1.3 Environmental impact

Over 30 studies quantified significant environmental benefits of renewable-powered EVCSs, with greenhouse gas emission reductions frequently exceeding 80% compared to fossil fuel-based alternatives [42, 44, 47]. The integration of solar and wind power into charging infrastructure directly supported sustainability objectives by lowering both carbon footprints and pollutant emissions, while several studies highlighted the importance of carbon pricing mechanisms as a driver for broader renewable adoption [24, 126]. Hybrid energy systems that combined solar, wind, biomass, and fuel cells further amplified these benefits by diversifying clean energy sources and reducing dependence on any single renewable technology [8, 19]. Collectively, the literature demonstrated that environmental gains were among the most compelling advantages of renewable-powered EVCSs, thus reinforcing their role as critical enablers of low-carbon transportation systems.

4.1.4 Energy management effectiveness

More than 40 studies employed advanced energy management strategies, including AI-based controllers, fuzzy logic, GAs, and model predictive control, to optimize power flow and mitigate renewable intermittency [22, 52, 110]. Effective scheduling and forecasting of EV charging demand and renewable generation were highlighted as critical measures to improve system reliability and reduce grid stress [57, 127]. V2G and bidirectional charging enhanced flexibility by enabling EV batteries to function as distributed storage systems, supporting grid stability and resilience under variable operating conditions [54, 106, 127]. Collectively, these strategies underscored the central role of EMS in addressing the intermittency of renewables while aligning charging demand with available supply [55, 107, 128].

Building on these approaches, various optimization algorithms have been applied to improve reliability, cost efficiency, and compatibility with the grid. Classical methods such as linear programming, the MILP, and rule-based scheduling remain widely used for sizing and operational planning. At the same time, metaheuristic approaches including the GA, PSO, KHA, and SSO, offer robust solutions for complex and nonlinear systems. Artificial intelligence techniques, such as the ANN, ANFIS, and hybrid AI models, have demonstrated strong effectiveness in predicting demand and managing intermittency [13, 20, 38, 56]. At the urban scale, cost-optimal methodologies are increasingly applied to balance economic, energy, and environmental benefits, providing an integrated perspective for large-scale deployment of renewable-powered EVCS. An explicit mapping between these optimization methods and their application contexts allows practitioners to select the most suitable approach, depending on system size, grid conditions, and policy objectives. This enhances comparability across studies and accelerates knowledge transfer from research to practice.

4.1.5 Grid compatibility

Numerous studies addressed the challenges of integrating renewable-powered EVCSs with the grid, emphasizing critical issues such as power quality, voltage regulation, mitigation of harmonic distortion, and load balancing to maintain stable operation [46, 53, 129]. Proposed solutions often involved the use of microgrid configurations and DC bus architectures, which allow seamless transitions between grid-connected and islanded modes, thereby improving the resilience and flexibility of the overall system [20, 125, 130]. To ensure compliance with established grid codes, researchers have developed advanced control algorithms and converter topologies designed to maintain near-unity power factor and mitigate adverse impact on the distribution network [98, 131, 132]. Collectively, these efforts underscored the importance of grid compatibility as a prerequisite for large-scale deployment, ensuring that the increasing penetration of EV charging loads does not compromise grid stability but enhances the robustness of the overall systems.

4.2 Critical Analysis and Synthesis

The literature under review on integrating solar and wind energy into public EVCSs revealed a comprehensive exploration of hybrid renewable energy systems, energy management strategies, and techno-economic assessments. Strengths of this approach included developing advanced optimization algorithms, incorporating energy storage solutions, and considering environmental impact, which collectively enhanced system reliability and sustainability. However, limitations persisted in the intermittency of renewable sources, scalability challenges, and complexities arising from integration with existing grids. Methodological diversity, ranging from simulation-based studies to real-world implementation, provided valuable insights and highlights data quality and standardization inconsistencies. Overall, the body of research underscored the potential of hybrid renewable-powered EV charging infrastructure while identifying critical gaps for future investigation. The strengths and weaknesses identified in the selected literature were systematically summarized in Table 3, concisely comparing key aspects such as system design, energy management, techno-economic feasibility, environmental sustainability, grid integration, scalability, and methodological robustness.

An essential but often underexplored aspect in the reviewed studies concerns the physical and societal constraints of deploying renewable energy systems. Noise generated from wind turbines remains a significant obstacle in built environments as this may limit their public acceptance and demand for regulatory restrictions to be imposed. Visual impact, land-use conflicts, and proximity to historically protected sites also present substantial barriers to widespread deployment. Similarly, solar technologies face challenges related to aesthetic integration, space availability in dense urban areas, and potential conflicts with cultural or heritage preservation guidelines. These constraints are critical for realistic system planning, as they directly influence decisions on the sites, public perception, and long-term viability. Future research should incorporate these non-technical barriers into techno-economic models, ensuring that optimization strategies remain socially acceptable and environmentally compatible. Recognizing such constraints not only enhances the robustness of renewable deployment strategies but also strengthens their alignment with community and policy requirements [61, 87, 128].

Table 3. Critical analysis of the selected studies on hybrid solar-wind integration into public EVCSs

Aspects	Strengths	Weaknesses
Hybrid Renewable Energy System Design	Numerous studies presented robust hybrid system designs combining solar PV and wind turbines with energy storage, optimizing cost-effectiveness and reliability through advanced algorithms such as the MILP and GAs [12, 48, 52]. These designs often incorporated V2G capabilities so as to enhance grid stability and renewable utilization [12, 33, 55].	Despite sophisticated designs, many systems faced challenges in managing the intermittency of solar and wind resources, thus leading to reliance on backup grid power and fossil fuel generators as well as undermining sustainability goals [40, 62, 123]. The variability in renewable output necessitates further development of adaptive control strategies and storage solutions.
Energy Management and Control Strategies	The literature demonstrated significant progress in the EMS employing fuzzy logic, neural networks, and model predictive control to optimize power flow, reduce operational costs, and improve load handling [11, 22, 133]. These strategies effectively coordinated renewable generation, storage, and EV charging demand to enhance system efficiency and grid compatibility [53, 69].	Many EMS approaches relied heavily on simulation and lacked extensive real-world validation, which might limit their practical applicability. Additionally, the complexity of algorithms posed implementation challenges, and some studies did not fully address the dynamic behavior of EV charging patterns and renewable fluctuations [75, 134].
Techno-Economic Feasibility and Optimization	Several papers provided comprehensive techno-economic analyses, demonstrating that hybrid renewable-powered EVCSs could achieve low LCOE and favorable NPV to support economic viability [13, 27, 42]. MOO techniques balance cost, reliability, and environmental impact [13, 14].	Economic assessments often depended on location-specific data and assumptions, hence limiting generalizability. Sensitivity to interest rates, component costs, and policy incentives could significantly affect outcomes, and some studies lacked consideration of long-term maintenance and degradation costs [13, 27, 42].

Aspects	Strengths	Weaknesses
Environmental Impact and Sustainability	Integrating solar and wind energy substantially reduces greenhouse gas emissions and pollutant output compared to grid-only or fossil-fuel-based charging stations, hence contributing to sustainability targets. Studies highlighted the potential for carbon tax policies to enhance renewable adoption [7, 27, 42].	Back-up diesel generators or grid power sometimes offset environmental benefits when renewable energy is unavailable. Lifecycle assessments were limited in scope, and few studies comprehensively evaluated the environmental impact of battery storage and system components [44, 120].
Grid Integration and Stability	Research emphasized the importance of grid-compatible designs, including bidirectional converters and advanced power electronics, to maintain power quality and reduce grid stress. V2G and G2V operations were explored to enhance grid flexibility and peak load management [16, 55, 64, 125].	Challenges remained in managing voltage fluctuations, harmonics, and the impact of high EV penetration on distribution networks. Many studies focused on small-scale or simulated systems, with limited exploration of large-scale grid integration and regulatory frameworks [46, 111].
Scalability and Deployment Challenges	Some works addressed the strategic placement and sizing of charging stations and renewable resources using geographic information systems (GIS) and optimization models, facilitating scalable deployment in urban and highway contexts [135, 136].	There is a lack of standardized methodologies for large-scale deployment; apart from this, uncertainties in EV user behavior, renewable resource variability, and infrastructure costs complicate planning. Social acceptance and policy support were underexplored in most technical studies [9, 137].
Data Quality and Methodological Robustness	Using real-world data such as meteorological inputs and EV charging profiles, enhances the validity of simulation results in several studies. Advanced forecasting and machine learning techniques improve predictive accuracy for energy management [127, 134, 138, 139].	Variability in data sources, limited duration of datasets, and reliance on simulation tools without experimental validation reduce confidence in some findings. Cross-comparison of methodologies is hindered by inconsistent reporting standards and assumptions [80, 119].

4.3 Thematic Review of Literature

Integrating solar and wind energy into public electric vehicle charging stations (EVCSs) has emerged as a critical area of research, focusing on sustainability, grid reliability, and economic feasibility. Major themes encompass hybrid renewable energy system designs combining photovoltaics (PV) and wind turbines, advanced energy management and storage strategies to mitigate intermittency, and techno-economic analyses evaluating cost-effectiveness and environmental impact. Optimization algorithms and control methodologies for enhancing system stability and grid compatibility are also prominent, alongside planning and placement strategies for scalable and user-responsive infrastructure. This thematic review synthesized these dimensions to comprehensively understand current advancement and future directions in renewable-powered EV charging networks. The key themes emerging from the selected literature, their prevalence, and detailed descriptions are organized in Table 4, providing a structured overview of the primary research directions and technological focuses on renewable-powered EVCSs.

Table 4. Thematic classification of the selected literature on hybrid solar-wind integration into public EVCSs

Themes	Source	Descriptions of Themes
Hybrid Renewable Energy System Design	165/244 Papers	Research widely explored integrating solar photovoltaics (PV) and wind turbines to create hybrid renewable energy systems (HRES) for EVCSs, so as to emphasize reliability and continuous power supply. These systems often included grid connectivity to balance intermittency and maximize renewable fraction, with innovations in converter topologies and MPPT techniques for efficiency improvement [3, 16, 33, 48].
Energy Management and Storage Strategies	140/244 Papers	Effective EMS and hybrid energy storage systems (HESS), including batteries and supercapacitors, are essential to mitigate intermittency from renewable sources and variable EV load demand. Strategies employing fuzzy logic, neural networks, and optimization algorithms could enhance energy utilization, reduce grid dependency, and prolong storage life [11, 22, 52, 69, 75, 127, 140].

Themes	Source	Descriptions of Themes
Techno-Economic and Environmental Assessment	120/244 Papers	Studies extensively evaluated the economic viability, LCOE, NPC, and environmental benefits such as reduction in greenhouse gas emission. Sensitivity analyses on component costs and carbon pricing shaped system design, demonstrating that renewable-powered EVCSs can be cost-effective and environmentally sustainable, particularly with government incentives [6, 13, 27, 42].
Optimization and Control Algorithms	95/244 Papers	Advanced control methodologies including GAs, fuzzy PID controllers, model predictive control, and hybrid AI approaches, optimized power flow, charging scheduling, and system stability. These techniques improved load handling, reduced power quality issues, and enabled seamless integration with grid and microgrids [23, 29, 51–53, 74].
Grid Integration and V2G Technologies	85/244 Papers	Integrating EV charging with grid infrastructure and V2G services facilitated bidirectional power flow, peak load management, and enhanced grid stability. Coordinated approaches leveraged renewable energy and energy storage to minimize grid stress and enable EVs to act as distributed energy resources [9, 16, 17, 55, 107, 125].
Planning and Deployment of Renewable-Powered EVCSs	78/244 Papers	The GIS-based location optimization, capacity planning, and scenario analysis addressed scalability, user demand, and challenges of renewable resource availability. These studies provided urban and rural deployment frameworks to maximize coverage and efficiency [26, 59, 136, 137, 141, 142].
Microgrid and Smart Grid Integration	65/244 Papers	EVCSs integrated with renewable-powered microgrids improved energy security, reduced grid dependency, and supported distributed energy resource management. Intelligent energy management and innovative charging systems allowed adaptive responses to dynamic supply and demand [20, 104, 114, 125, 143].
Emerging Technologies and Innovative Architectures	40/244 Papers	Novel designs incorporating fuel cells, hydrogen storage, IIoT, solid-state transformers, and wireless charging advanced capabilities of renewable-powered EV charging infrastructure. These innovations enhanced efficiency, operational flexibility, and user convenience [83, 86, 144–146].

4.4 Chronological Review of Literature

The integration of solar and wind energy into public EVCSs has evolved significantly over the past decade. Early research primarily focused on designing standalone hybrid systems and establishing feasibility through modeling and simulation. As the field matured, studies expanded to include advanced optimization techniques, energy management strategies, and real-time control systems to enhance economic viability and grid compatibility. More recent investigations have emphasized smart grid integration, bidirectional energy flow, and use of AI to improve system resilience, efficiency, and sustainability. The chronological progression of the focused areas of research, from early feasibility studies to recent AI-driven smart charging innovations, is summarized in Table 5, providing a clear timeline of technological and methodological advancement in the field.

Table 5. Chronological development of research on hybrid solar-wind integration into public EVCSs

Range of Years	Directions of Research	Descriptions
2010-2013	Initial Feasibility and Hybrid System Design	Early works concentrated on developing hybrid solar-wind charging stations, addressing basic system configurations, and demonstrating the viability of renewable-powered EV charging. Research involving modeling component sizing, loss of power supply probability, and initial economic assessments, often focused on standalone or grid-connected setups with basic control strategies.

Range of Years	Directions of Research	Descriptions
2014-2017	Optimization and Control Methods Development	Studies introduced optimization frameworks for sizing and scheduling renewable energy systems integrated with EV charging, incorporating energy storage and grid interaction. This period saw the emergence of model predictive control, linear programming, and the MOO to balance reliability, cost, and environmental impact. Efforts were put on addressing power quality and challenges of grid stability.
2018-2020	Advanced Energy Management and Techno-Economic Analysis	Research focused on sophisticated EMS using real-time data, forecasting, and intelligent algorithms like genetic and fuzzy logic. Greater attention was paid to economic feasibility, integrating hybrid energy storage solutions and enhancing grid support functionalities. Simulation tools like HOMER and MATLAB have become prevalent in comprehensive technical and financial analyses.
2021-2022	Integration with Smart Grids and Distributed Energy Resources	The focus shifted towards microgrid architectures, V2G technologies, and decentralized energy management to improve grid resilience and renewable energy utilization. Studies explored strategic placement of EVCSs, adaptive control algorithms, and multi-energy systems including biomass and hydrogen fuel cells. Emphasis was placed on overcoming intermittency and optimizing charging under dynamic load conditions.
2023-2024	AI-Driven Optimization and Real-Time Smart Charging Systems	Recent research has highlighted the application of AI, deep learning, and hybrid optimization algorithms for dynamic energy management. Developing innovative and adaptive control systems enables enhanced forecasting, real-time scheduling, and efficient PV, wind, battery storage, and grid resource integration. Innovations include bidirectional charging, V2G services, and scalable solutions for commercial and public EV charging infrastructure targeting core objectives of sustainability and cost-effectiveness.

4.5 Agreement and Divergence Across Studies

The selected literature broadly agreed on the benefits of integrating solar and wind renewable energy sources into public EVCSs, highlighting improvements in system efficiency, environmental sustainability, and grid load management. Many studies emphasized the critical role of advanced energy management and optimization algorithms in enhancing the reliability and economic viability of hybrid systems. However, divergences were observed in reported economic outcomes, grid compatibility challenges, and the extent of environmental benefits, often attributable to differences in system scale, geographic and climatic contexts, and methodological approaches. Some studies focused more on localized and small-scale microgrid applications whereas others addressed large-scale deployments or fast-charging infrastructure, thus leading to varied conclusions on cost-effectiveness and implementation barriers. These areas of consensus and divergence are further organized in Table 6, which systematically compares the studies under review across key criteria like system efficiency, economic viability, environmental impact, energy management effectiveness, and grid compatibility, while outlining potential explanations for the observed differences.

Table 6. Agreements and divergences across selected studies on hybrid solar-wind integration into public EVCSs

Comparison Criteria	Studies in Agreement	Studies with Divergences	Potential Explanations
System Efficiency	The consensus was that hybrid solar-wind systems improved energy conversion and supply reliability for EVCSs, with advanced MPPT and control strategies enhancing performance [14, 28, 40]. Energy storage integration further boosted efficiency [52, 69].	Some studies highlighted limitations in efficiency gains due to the intermittency of renewable sources and variable load demands [1, 54, 129].	Differences arose from system scale, i.e., microgrid vs. large grid, local renewable resource variability, and storage technology used.

Comparison Criteria	Studies in Agreement	Studies with Divergences	Potential Explanations
Economic Viability	Most agreed that hybrid renewable systems reduced operational costs and enhanced return on investment by lowering grid dependency [13, 14, 40, 41, 47]. Cost reductions through optimization and incentives were common findings [44, 147].	Discrepancies existed in cost-effectiveness, with some works reporting high upfront investment and more extended payback periods [42, 141, 148].	Varying local energy tariffs, capital costs, incentive structures, and financial models contributed to divergent economic outcomes.
Environmental Impact	Studies highlighted significant reductions in greenhouse gas emission and sustainability benefits from renewable-powered EV charging. Integration with V2G enhanced environmental performance [13, 24, 30, 55, 89, 124].	Some papers noted challenges in achieving complete carbon neutrality due to grid connection and fossil fuel backup usage [6, 51].	Variations in grid carbon intensity, backup power use, and renewable penetration levels influenced emission reduction assessments.
Energy Management Effectiveness	There was a broad agreement on the necessity of sophisticated EMS employing AI, optimization algorithms, and adaptive control for mitigating intermittency and balancing supply-demand [22, 23, 43, 133, 149].	There was a diversity in preferred algorithms and their performance metrics; some favored fuzzy logic and neural networks, and others preferred genetic or swarm optimizations [52, 127, 150].	Differences in simulation setups, computational complexity, and real-time adaptability led to varied conclusions on algorithm efficacy.
Grid Compatibility and Stability	Studies agreed that renewable integration reduced grid stress and improved power quality when combined with storage and advanced controllers. Bidirectional power flow and V2G supported grid stability [46, 55, 59, 67, 125, 129].	Some revealed grid integration challenges, including voltage fluctuations, harmonics, and load management difficulties, especially at high penetration [59, 151, 152].	Disparities stemmed from grid infrastructure robustness, scale of renewable integration, and regional grid codes and standards.

4.6 Theoretical and Practical Implications

4.6.1 Theoretical implications

This subsection outlines the main theoretical implications of integrating solar and wind energy into public EVCSs. The insights reinforced and expanded upon established theories in hybrid renewable energy systems, intelligent control, techno-economics, and grid integration.

• Integrating solar and wind energy into public EVCSs supported the theoretical framework that hybrid renewable energy systems (HRES) could effectively mitigate the intermittency of individual renewable sources, hence enhancing system reliability and reducing grid dependency [4, 40, 48]. This aligned with existing theories on the complementary nature of solar and wind resources in hybrid configurations.

• Advanced energy management strategies, including AI-driven controllers such as the ANFIS and hybrid optimization algorithms, demonstrated significant improvements in energy efficiency and load handling capacity, thus reinforcing the theoretical importance of intelligent control systems in renewable-powered EV charging infrastructure [22, 153].

• The economic feasibility analyzed across diverse geographic and operational contexts confirmed that optimized sizing and operation of hybrid renewable systems could achieve low LCOE and favorable net present values (NPV), hence supporting techno-economic theories to advocate renewable integration into EV charging to reduce operational costs and environmental impact [12, 154].

• The incorporation of V2G and bidirectional charging technologies theoretically enhanced grid stability and energy flexibility, hence validating models that proposed EVs as distributed energy storage units capable of supporting renewable energy integration and peak load management [17, 55, 107].

• MOO approaches that balanced economic, environmental, and reliability objectives provided a robust theoretical basis for designing sustainable EVCSs, in order to highlight the necessity of considering trade-offs in system planning and operation [13, 155].

• Theoretical models emphasizing the importance of microgrid architectures and distributed energy resources (DERs) in EV charging infrastructure underscored the potential for localized energy management to improve resilience and reduce grid stress [26, 104, 156].

4.6.2 Practical implications

This subsection highlights the practical implications of integrating hybrid solar and wind systems into public EV charging infrastructure. The insights provided practical guidance for policymakers, industry stakeholders, and urban planners in advancing sustainable mobility solutions.

• The findings suggested that deploying hybrid solar-wind systems with optimized energy storage solutions could significantly reduce reliance on the utility grid, lower greenhouse gas emission, and improve the sustainability of public EVCSs, hence offering practical pathways for policymakers to incentivize renewable integration [155, 157].

• Intelligent EMS leveraging AI and advanced optimization algorithms could be practically implemented to enhance operational efficiency, reduce costs, and manage the variability of renewable energy sources, thus providing industry stakeholders with actionable strategies for system design and control [22, 69, 133].

• The demonstrated economic viability of renewable-powered EVCSs, including favorable return on investment and payback periods, supported investment decisions by private and public entities so as to encourage the expansion of green charging infrastructure in urban and rural settings [41, 102].

• Integration of V2G and bidirectional charging capabilities in EVCSs offered practical benefits for grid operators by enabling demand response, peak shaving, and ancillary services, which could be incorporated into grid modernization policies and innovative grid initiatives [158–160].

• The modular and scalable nature of hybrid renewable energy systems facilitated their adaptation to diverse geographic and load conditions, enabling flexible deployment in various contexts such as commercial buildings, highways, and remote areas [63, 77, 161].

• Urban planning and the GIS-assisted optimal siting of renewable-powered EVCSs could enhance accessibility, coverage, and cost-effectiveness, hence providing practical tools for city planners and energy regulators to support sustainable urban mobility [21, 162].

Table 7. Key limitations identified in the literature on hybrid solar-wind integration into public EVCSs

Areas of Limitations	Descriptions of Limitations	Papers that Have Limitations
Geographic Bias	Many studies focused on specific regions or countries, limiting the external validity and generalizability of their findings to other geographic contexts with different climatic, economic, or infrastructural conditions. This geographic concentration may bias results and overlook diverse challenges.	[40, 45, 124, 161]
Limited Real-World Validation	Many papers relied heavily on simulation and modeling without extensive experimental or field validation, thus constraining the practical applicability and robustness of the proposed systems under real operational conditions. This methodological constraint affected confidence in scalability.	[28, 49, 73, 119, 163]
Intermittency and Storage Challenges	The intermittent nature of solar and wind energy and the limitations of current energy storage technologies are recurrent issues. Many studies acknowledged but did not fully resolve the challenges of ensuring a continuous and reliable power supply, thus affecting system reliability and user acceptance.	[52, 61, 69, 122, 149]
Economic Feasibility Uncertainty	Economic analyses often depend on assumptions about costs, incentives, and tariffs that vary widely across regions and over time, hence reducing the external validity of techno-economic conclusions. This uncertainty complicates investment decisions and policy formulation.	[42, 44, 47, 48, 57, 164]

Areas of Limitations	Descriptions of Limitations	Papers that Have Limitations
Scalability and Grid Integration Issues	Several studies addressed small-scale and pilot systems, with limited exploration of scalability and integration into existing power grids. This gap limited the understanding of the impact on grid stability and infrastructure requirements at larger deployment scales.	[26, 56, 114, 125, 165]
User Behavior and Demand Variability	Many models simplified or inadequately captured the stochastic nature of EV user behavior and charging demand, which affects the accuracy of energy management strategies and system optimization, thereby limiting real-world applicability.	[22, 57, 134, 138, 166]
Control Algorithm Complexity	Advanced control and optimization algorithms often require significant computational resources and complex implementation, which may hinder real-time application and widespread adoption in practical EV charging infrastructure.	[22, 23, 127, 167]
Limited MOO	While some studies incorporated the MOO, many focused on single objectives such as costs and emissions, and neglected the trade-offs between economic, environmental, and technical performance, hence reducing the comprehensiveness of system design.	[14, 160, 168]
Insufficient Consideration of Policy and Regulatory Frameworks	Few studies thoroughly integrated policy, regulatory, and market mechanisms into their analyses, which were critical for real-world deployment and scaling of renewable-powered EVCSs, thus limiting practical relevance.	[26, 136, 169]

4.7 Limitations of the Literature

The limitations identified in the selected literature, as summarized in Table 7, revealed several recurring gaps that constrained the practical deployment and scalability of renewable-powered EVCSs. Geographic bias remained a significant concern, as many studies focused on specific regions and limited the generalizability of their findings to cover different climatic and infrastructural contexts. A heavy reliance on simulation-based approaches, with limited real-world validation, further reduced confidence in the operational performance of proposed systems under actual field conditions. Persistent challenges such as renewable intermittency, energy storage constraints, scalability barriers, and uncertainties in economic feasibility highlighted the need for comprehensive and multi-objective analyses that integrated policy and regulatory considerations. Addressing these gaps would translate promising technical advancement into sustainable, commercially viable, and widely adoptable solutions related to charging infrastructure.

4.8 Engineering and Regulatory Frameworks for Grid-Connected EVCS

4.8.1 Technical standards, interconnection, and communication protocols

For public charging stations integrated with the grid, compliance with interconnection and power-quality standards is essential to ensure safety, interoperability, and reliability. In North America, traditional utility interconnection requirements, IEEE 1547 and UL 1741, provide the primary frameworks for distributed energy resource interconnection [170, 171], while in Europe, standards such as EN 50549 govern grid compatibility [172]. Power quality parameters, including limits on total harmonic distortion (THD), are guided by IEEE 519, ensuring that charging operations do not adversely affect local distribution networks. Similarly, maintaining a stable power factor is a prerequisite for grid connection approval in many jurisdictions [38].

Communication and interoperability protocols are also central to modern charging infrastructure. The Open Charge Point Protocol (OCPP), with versions 1.6 and 2.0.1, is widely adopted for backend integration and remote management of charging stations. ISO 15118 complements these by enabling secured V2G communication, plug-and-charge functionality, and user authentication [173, 174]. Robust cybersecurity measures must support these protocols, as vulnerabilities could compromise the grid and user data.

Economic and operational considerations are closely tied to regulatory requirements. Utilities typically mandate demand charges, time-of-use tariffs, and connection-capacity assessments that directly influence station economics. Proper alignment with these tariff structures could optimize cost savings while supporting grid stability. Adherence to technical standards, communication protocols, and tariff structures establishes a minimal but essential engineering and regulatory layer for deploying grid-connected renewable-powered EVCSs.

4.8.2 Energy policies and renewable energy communities

Energy policies play a decisive role in supporting the integration of solar and wind energy into public EV charging infrastructure. Incentive mechanisms such as feed-in tariffs, tax credits, and net metering schemes could substantially improve the economic feasibility of renewable-powered EVCS. These instruments not only reduce investment risks but also encourage private and public stakeholders to adopt renewable energy solutions more rapidly [61, 175, 176]. Equally important are policies that promote Renewable Energy Communities (RECs), which enable collective ownership and energy sharing among local stakeholders. Within this framework, the batteries of public EVs could serve as distributed storage assets, enhancing both the resilience and self-sufficiency of the community [16, 30, 177].

The RECs provide significant benefits beyond technical and economic dimensions by fostering social inclusion and addressing equity concerns. They facilitate cost savings through shared infrastructure and collective bargaining, thereby making renewable-powered EVCS more affordable for diverse groups within society [93, 178]. At the same time, they contribute to reducing energy poverty by democratizing access to clean mobility and renewable electricity. Integrating the EVCS into the RECs, therefore, represents a powerful synergy between technological innovation, economic efficiency, and social equity. Policy-driven support for the RECs could accelerate large-scale adoption, ensure an equitable distribution of benefits, and align renewable-powered EVCS with broader sustainability and community development goals [107, 138].

Table 8. Focused research gaps and actionable future directions for hybrid solar-wind EVCSs

Gap Areas	Descriptions	Future Research Directions	Justifications	Research Priorities
Real-World Validation of Hybrid Solar-Wind EVCS	Current evidence was dominated by simulation-based studies with limited field data, hence reducing confidence in practical scalability [13, 42, 47].	Conduct a 12-month field trial of a grid-connected DCFC site powered by hybrid solar-wind systems, with open-access operational data for the research community.	Field validation with transparent data is critical to verify assumptions, benchmark models, and accelerate technology adoption [12, 179, 180].	High
Standardization of Data and Performance Metrics	The lack of standardized datasets, operating conditions, and evaluation metrics hinders reproducibility and comparability across studies [58, 80, 119].	Develop and publish a public benchmark dataset with standardized operating conditions, performance metrics, e.g., LCOE, LPSP, CO_2 reduction, and reporting protocols.	A shared benchmark framework enables consistent cross-study evaluation, improves model reliability, and accelerates innovation [58, 139].	High
V2G Business Models and User Participation	V2G concepts show strong theoretical promise but lack controlled empirical validation, especially consumer incentives and business feasibility [40, 61, 62].	Implement a controlled study of V2G business models with user participation incentives to assess technical feasibility, economic returns, and consumer acceptance.	Practical demonstration is necessary to transition V2G from conceptual frameworks to viable large-scale applications [22, 149, 181].	High

4.9 Gaps and Directions of Future Research

The research gaps and corresponding future directions identified in the selected literature could lead to three concrete and verifiable steps that the research community could take. First, real-world validation is urgently required, and a 12-month field trial of a grid-connected DC fast charging (DCFC) station powered by hybrid solar-wind systems with open-access data would provide critical insights beyond simulation models. Second, the lack of standardized datasets and performance metrics limits comparability across studies, hence underscoring the requisite for a publicly available benchmark dataset with consistent operating conditions and evaluation protocols. Third, V2G technologies show significant potential; their practical feasibility and user acceptance remain uncertain, requiring study of a controlled business-model with participation incentives. These three priorities, summarized in Table 8, represent actionable pathways to accelerate the transition from conceptual frameworks to scalable and sustainable EV charging infrastructure.

5 Overall Synthesis and Conclusions

The current body of literature collectively underscored the promising potential of integrating solar and wind renewable energy sources into public EVCSs to establish a foundation for sustainable, cost-effective, and environmentally friendly transportation infrastructure. A consensus emerged from the efficacy of hybrid renewable energy systems, where solar photovoltaics and wind turbines were complemented by advanced energy storage solutions such as batteries and supercapacitors. These combinations mitigated the inherent intermittency of renewable generation, ensuring a reliable power supply and improved system efficiency. Sophisticated EMS employing AI, fuzzy logic, and optimization algorithms enhanced performance by dynamically balancing generation, storage, and EV charging demand, thus minimizing grid reliance and operational costs.

Economic viability was reinforced through numerous techno-economic analyses demonstrating low LCOE and attractive returns on investments, mainly when supported by incentives, net metering, and V2G technologies. These context-dependent economic benefits were influenced by local resource availability, policy frameworks, and hardware costs, hence highlighting the need for region-specific planning and adaptability. Environmental impact were notably positive with significant reductions in greenhouse gas emissions and pollutant loads, when compared to conventional grid or fossil fuel-based charging stations, thus supporting broader climate goals. However, comprehensive lifecycle assessments of storage systems and backup solutions remained limited, leaving an area for deeper inquiry.

Grid integration challenges were critical with research emphasizing the importance of power quality, voltage regulation, harmonic mitigation, and scalable control architectures, such as microgrids and DC bus systems. Bidirectional charging operations and innovative grid communication protocols enhanced flexibility, peak load management, and resilience against renewable variability. Despite advances, large-scale deployment and standardized methodologies are still evolving, with uncertainties in EV user behavior, renewable intermittency, and infrastructural costs posing planning complexities. Social acceptance and policy support are underexplored, yet they are essential factors for the widespread adoption of the integration under review.

Overall, the literature portrayed a comprehensive yet complex picture in which technological innovation, economic feasibility, environmental benefits, and grid compatibility converged to advance renewable-powered EV charging infrastructure. The directions of future research include enhancing real-world validation of energy management strategies, developing scalable deployment frameworks, integrating multi-modal renewable sources, and addressing socio-economic and regulatory dimensions to foster sustainable and resilient electric mobility ecosystems.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The author declares no conflict of interest.

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Nomenclature

AC	Alternating Current
BES	Battery Energy Storage
DC	Direct Current
DCFC	Direct Current Fast Charging
DG	Distributed Generation
EMS	Energy Management System
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
GA	Genetic Algorithm
HRES	Hybrid Renewable Energy System
LCOE	Levelized Cost of Energy
LPSP	Loss of Power Supply Probability
MOO	Multi-Objective Optimization
NPC	Net Present Cost
PF	Power Factor
PV	Photovoltaic
RES	Renewable Energy Source
SOC	State of Charge
THD	Total Harmonic Distortion
V2G	Vehicle-to-Grid