

Review article

The future of green mobility: A review exploring renewable energy systems integration in electric vehicles

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ARTICLE INFO

Keywords:

Renewable energy
Electric vehicle charging
Smart charging
Vehicle-to-grid
Energy storage

ABSTRACT

The rapid increase in electric vehicle (EV) adoption has created an urgent need for effective and sustainable charging infrastructure. Integrating renewable energy sources such as solar, wind, and hydropower into EV charging systems presents a viable solution to reduce carbon emissions and decrease reliance on fossil fuels in the transportation sector. This study explores the optimal incorporation of renewable energy into EV charging facilities to enhance energy efficiency and facilitate the transition toward low-carbon mobility. Through an extensive literature review, the research examines diverse approaches, including smart charging, vehicle-to-grid (V2G) technologies, and next-generation energy storage solutions. These technologies not only improve renewable energy utilization at charging stations but also enhance grid stability through bi-directional energy transfer and mitigation of renewable energy intermittency. Key findings reveal that renewable-powered EV charging systems significantly reduce grid dependency and emissions. However, challenges such as technical integration, economic feasibility, and regulatory barriers persist. Smart charging and V2G infrastructure are essential for balancing energy demand and supply, while advanced energy storage systems enhance resilience. Nonetheless, high initial infrastructure costs, policy constraints, and grid reliability concerns hinder widespread implementation. This study emphasizes the need for further research on innovative models, pilot projects, and supportive policies to address these challenges. Future efforts should focus on scalable integration methods and mass-market applications to enable the widespread deployment of renewable-powered EV charging systems, paving the way for a low-carbon and sustainable transportation future.

1. Introduction

Today, integration of renewable energy into EV charging system is becoming a key milestone that drives the global sustainability goals [1]. Climate change is being mitigated by the availability of clean renewable energy options including solar, wind, and hydro power as well as a decrease in greenhouse gas emissions [2]. Meanwhile, the need for electricity to propel the cars that are being adopted around the world is growing commensurately. But, such an increase in electricity demand may overload traditional power grids that depend on non-renewable

resources [3]. The incorporation of renewable energy into EV infrastructure guarantees that the environmental pros of EVs would be maximized, leading the means of transportation to be truly 'green' [4]. EV charging systems using renewables decrease the carbon foot print associated with a vehicle's operation. For instance, solar powered charging stations, supply energy directly from the sun and are not reliant on traditional energy sources. Thus, renewable technologies such as wind turbines can also be employed in providing for EV charging when energy demands are highest [5]. Besides the environmental protections, these systems also make energy independence by cutting down on the

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<https://doi.org/10.1016/j.rineng.2025.105647>

Received 4 March 2025; Received in revised form 27 May 2025; Accepted 5 June 2025

Available online 9 June 2025

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need to IMPORT fuels. Not only can integration of renewables also reduce grid congestion through DER, but through integration of EV charging. Microgrids and energy storage systems allow localized clean energy generation and storage, so there is always fresh power at hand even when renewable generation is low [6]. Besides, the V2G technology transfers energy from the grid back to the vehicles in the bidirectional mode for additional support to the grid and optimization of renewable energy use [7]. However, deployment of renewable powered EV charging systems remains a challenge as there remain issues of intermittency of the renewable energy supply, high infrastructure costs, and the need for advanced integration with the grid. For that, we will need collaboration of policymakers, industries and researchers.

The global adoption of EV has seen unprecedented growth over the recent years due to the falling prices and the advancements in technology as well as high appreciation for the ecological and a compassionate attitude of the consumer towards a sustainable future [8]. This has favourable conditions for EV adoption, as governments all over the world have started vying for the policies of combining severe measures against climate change and promoting the sustainable transportation. Evolution of EVs is largely backed by requisitioning efforts such as subsidies, tax incentives and zero emissions mandates that have given impetus to EVs being an anchor of modern transportation systems [9]. Norway, China and the US are leading the way as countries with high EV sales are more prominent than in other regions. Tags including many nations will phase out internal combustion engine vehicles altogether, suggesting that by the mid-2030s, EVs will control the market [10]. At the same time, in the automotive industry, battery technology is seeing advances for lithium ion and solid-state batteries that have enabled EV range, charging speed and overall affordable vehicles. Meanwhile, constant growth in EV adoption is well suited, a perfect match, to global goals of sustainable energy [11]. The advantage of EVs powered by renewable energy is dual: their tailpipe emissions are eliminated and they reduce the reliance on fossil fuel-based electricity [12]. In response, these renewable energy sources have been supported. Continuing to add charging stations that are integrated with renewable energy makes EVs more and more appealing. In addition, the innovations in smart charging, wireless charging, vehicle to grid (V2G) technology and so on that will set new efficiency and sustainability standards [13]. Still, widespread EV adoption and a compatibility with renewable energy goals need overcoming challenges including lack of charging infrastructure, grid compatibility, and high initial costs [14].

The focus of this paper is to explore the development opportunities, challenges, and future directions of the interface of renewable energy and EV charging system. There is a growing demand for both the EV adoption and renewable energy, which is leading to integration of these two domains in order to achieve the goal of long term sustainability. The aim of such study is to understand the status quo of current research, locate holes in the knowledge, and suggest the helpful point of view for policymakers, researcher, and industry stake holders. The principal focus of this research is the potential for renewable energy driven EV charging stations for greenhouse gas emission mitigation, enhancement of the energy efficiency and the establishment of the energy independence. The study explores these opportunities in terms of saving costs, environmental gains, technological improvements, by systematically analyzing peer reviewed articles, conference proceedings and assertions made in the industry reports. It also touches on barriers such as grid incompatibility, intermittency of renewable energy, and capital/economic barriers. The innovation in these is changing the way renewable energy is brought about and utilised to charge EVs creating the floor for a more reliable and sustainable energy ecosystem. According to the study, it is equally important for harmonized policies and international collaboration to achieve this as it will overcome regulatory and infrastructural challenges.

1.1. Research questions

- what ways can renewable energy technologies such as solar, wind, and hydropower be efficiently integrated into electric vehicle charging infrastructure to achieve peak energy efficiency while reducing carbon footprints?
- What are the main technical, economic, and regulatory issues involved in the deployment of renewable-powered EV charging systems, and how can they be best overcome?
- What is the role of emerging technologies, like V2G systems and innovative energy storage products, in improving the scalability and feasibility of EV charging infrastructure using renewable energy?

1.2. Research objective

- To investigate the prospect of different renewable sources (solar, wind, and hydropower) for enhancing the energy efficiency and decreasing the carbon intensity of EV charging systems.
- To recognize and analyse the technical, economic, and regulatory issues associated with the installation of renewable-powered EV charging systems and suggest feasible solutions to overcome these obstacles.
- To examine the effect of new technologies like V2G systems and innovative energy storage options on the scalability, reliability, and economics of renewable energy-based EV charging infrastructure.

2. Research method

The research critically assesses current advancements in integrating renewable energy sources into EV charging infrastructure regarding energy efficiency, grid resilience, and emission mitigation based on a systematic literature review (SLR) method. Systematically selected peer-reviewed journals from 2019 to 2024 from Scopus, IEEE Xplore, Springer, and Elsevier databases were used. Keywords like "Renewable Energy for EV Charging," "Smart Charging Strategies," "Vehicle-to-Grid (V2G) Systems," and "Energy Storage Integration" informed the search, which resulted in 45 studies. The PRISMA protocol was used to maintain an open review process, screening studies for relevance, quality, and contribution to sustainable EV infrastructure development. The report includes methodologies for maximizing solar, wind, and hydropower integration, technical and economic issues, and research into new technologies such as V2G, blockchain-based energy trading, and AI-based smart charging. Main performance indicators such as grid dependency reduction, energy efficiency improvement, and carbon footprint reduction were estimated to determine the viability of mass-scale renewable-fuelled EV charging networks. The article points out the significance of intelligent energy management, policy guidelines, and hybrid storage technologies in supporting a cost-competitive and reliable charging infrastructure that connects theoretical achievements with real-world implementation for sustainable mobility.

2.1. Selection criteria

The study selection was informed by a systematic process to maximize relevance, quality, and contribution in EV charging systems by renewable resource. Exclusively peer-reviewed journal papers and conference proceedings released from 2021 to 2024 were included, targeting studies dealing with solar, wind, and hydropower integration optimization, enhancement of energy efficiency, and minimization of carbon emissions during EV charging. Advanced energy storage, smart grid interfaces, and policy guidelines enabling renewable-fuelled EV charging infrastructure were the areas included in the review studies. Exclusion criteria removed non-peer-reviewed journals, non-English research, duplicate publications, and studies that did not focus specifically on renewable-powered EV charging solutions. By implementing these criteria, a filtered set of high-quality literature was obtained,

guaranteeing a thorough and current review of recent developments and challenges in sustainable EV charging solutions.

2.2. Data sources

Literature for the current study was drawn from peer-reviewed academic databases, such as Scopus, Springer, IEEE Xplore, and Elsevier, to guarantee a high level of reliability and scientific evidence. Industry publications from the International Energy Agency (IEA) and the World Economic Forum (WEF) were also consulted to bring in real-world perspectives and policy considerations. Keywords like "Renewable Energy for EV Charging," "Smart Charging Strategies," "Vehicle-to-Grid Integration," and "Energy Storage for EV Charging" were employed to narrow down the search. This focused search strategy guaranteed the incorporation of the most pertinent studies, providing insightful views on technology developments, regulatory hurdles, and economic viability in rolling out renewable-powered EV charging facilities.

2.3. Inclusion and exclusion criteria

The inclusion criteria for selecting high-quality, peer-reviewed journal articles and conference proceedings of high-reputed academic sources like Scopus, IEEE Xplore, Springer, and Elsevier were imposed. Only research studies published within the years 2021 and 2024, in the English language, and in full-text were used. The exclusion criteria removed non-peer-reviewed articles, grey literature, non-English language studies, and articles with no full-text access. Studies not specifically addressing renewable-powered EV charging systems or published outside the time window were also excluded to maintain a targeted and relevant dataset. Table 1 outlines the inclusion and exclusion criteria.

2.4. Systematic review process

The systematic review was performed within the PRISMA framework to facilitate methodological consistency and transparency. A total of 160 records were retrieved from academic databases through an initial search, from which 60 duplicate studies were excluded and 290 studies remained for screening. A full-text examination of the remaining 160 studies was done, evaluating methodological quality, relevance, and contribution. Upon further examination, 60 high-quality, peer-reviewed studies were chosen for the final study. The chosen studies offered important insights into the optimization of solar, wind, and hydropower integration into EV charging systems, as well as an evaluation of the most significant challenges like grid dependency, economic feasibility, and policy constraints. The review also came across some upcoming trends, such as the part played by V2G systems, advanced energy storage technology, and smart charging algorithms in making EV charging infrastructure more sustainable. PRISMA [15] is an approach that increases transparency and rigor in systematic reviews. It has a checklist and flow diagram to guarantee exhaustive literature selection, data extraction, and bias evaluation. PRISMA enhances reproducibility, enabling researchers to synthesize high-quality evidence to inform

decision-making. The PRISMA framework used for the study is illustrated in Fig. 1.

2.5. Search result

Systematic search of 160 initial records yielded 45 peer-reviewed articles of high quality. The research centres mainly on integrating renewable energy sources—solar, wind, and hydropower—into EV charging infrastructure. The studies point out several strategies that aim to optimize energy efficiency, minimize grid dependence, and lower carbon emissions. Utilizing energy management systems and intelligent charging algorithms to optimize the usage of renewable energy is one of the recurring themes in the literature. The use of V2G technology is also widely referred to as a way to improve grid resilience and energy flexibility. Most papers discuss economic and regulatory hurdles, with emphasis on policy environments that enable mass deployment of renewable-powered charging stations. Hybrid solutions integrating machine learning-based energy forecasting, demand-side management, and adaptive charging protocols prove to be efficient solutions for energy supply and demand balancing. In order to build a scalable and effective EV charging infrastructure, the assessment emphasizes the necessity of integrating various renewable energy sources and innovative technologies.

3. Related works

3.1. Integration of renewable energy in electric vehicle charging systems

Allouhi and Rehman [16] suggest a hybrid power grid that links photovoltaic, wind, and battery storage to support supermarkets in Morocco with electricity. The application of this system involves chasing of EV charging stations by means of HOMER software against which Moroccan utility tariffs are used to determine optimal design for this application. Dakhla was found to be the most efficient city among the three studied cities, due to a good renewable energy fraction, low electricity cost and minimal operational costs that can support 7300 annual EV charging sessions. Sensitivity analyses were done to see in what situations the shopping system could operate, through varying the energy demand of the supermarket, the availability of renewable energy, and the carbon price scenario. Thirumalaivasan [17] discusses the changing role of Nano-Phase Change Materials (Nano-PCMs) in improving energy storage systems under different environmental conditions. It emphasizes their better thermal properties, such as high latent heat storage and enhanced thermal conductivity, which allow for effective temperature control and quicker thermal response. Unlike other studies, this paper focuses on the flexibility and robustness of Nano-PCMs in various applications, ranging from domestic to industrial use. It presents new knowledge about their origin, properties, and incorporation into sustainable energy plans. Through an analysis of recent research advancements, the review highlights the promise of Nano-PCMs in enhancing energy efficiency and climate resilience, providing a new benchmark for future studies and technological developments in energy storage. In another study, Thirumalaivasan [18] emphasizes the pivotal role of biohydrogen (BioH₂) and biogas (BioG) in renewable energy and sustainability of the environment. BioH₂, with its high energy efficiency and low carbon footprint, is contrasted with BioG, which is generated from organic waste and minimizes landfill space and methane release while creating environmentally friendly compost. The paper reviews the effect of feedstock composition and digestion methods in BioG production and challenges in BioH₂ synthesis through dark fermentation and photolysis, such as efficiency and substrate limitations. It highlights incorporating BioH₂ into wastewater treatment systems and compares both biofuels with fossil fuels in minimizing greenhouse gases. Life cycle analyses emphasize their environmental advantages, calling for ethical sourcing, effective operations, and waste-to-energy technology innovations to ensure a sustainable future.

Table 1
Inclusion and Exclusion Criteria.

Criterion	Inclusion	Exclusion
Accessibility	Full-text articles	Papers without full-text access
Language	English	Non-English publications
Publication Period	2021–2024	Publications before 2020 or grey literature
Relevance	Studies on renewable energy integration into EV charging systems	Studies unrelated to EV charging or renewable energy
Focus Area	Studies discussing V2G, energy storage, and smart grid interactions	Studies not addressing efficiency optimization or sustainability

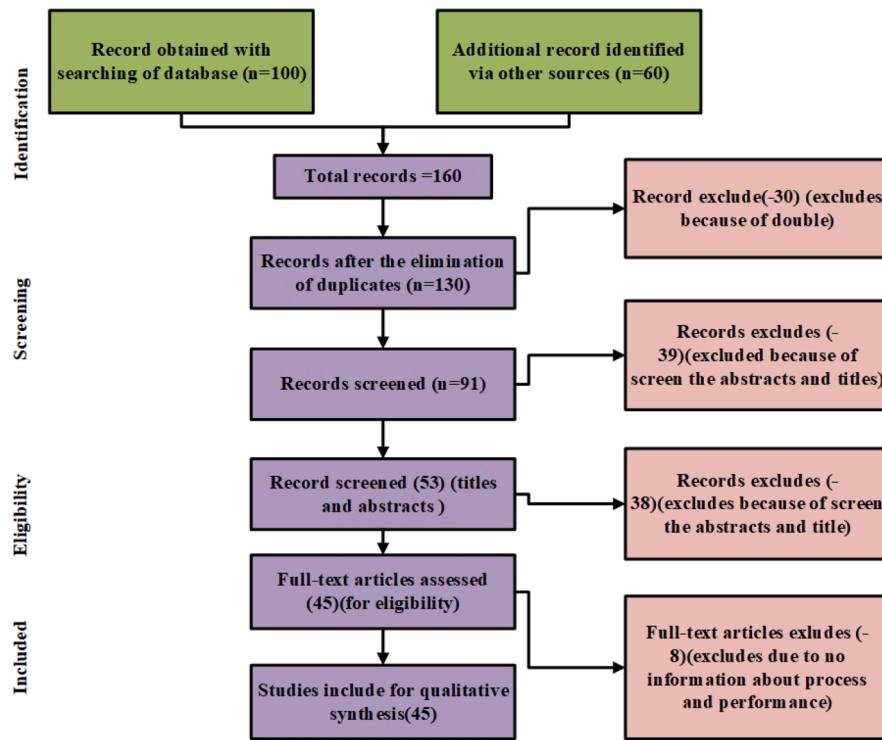


Fig. 1. PRISMA Framework.

Thirumalaivasan [19] offers a new hybrid material prepared by conjugating fluorescent Carbon Dots (SyCDs), which are fabricated from discarded syrup bottle waste, with curcumin. The environmentally friendly strategy wipes out plastic waste while improving the antimicrobial and bioimaging function of the produced nanomaterial. The green strategy of synthesis is cost-effective and effective, converting waste to useful luminescent SyCDs. The biological aspects of curcumin improve the functionality of the material over what it could achieve on its own. The hybrid displays enhanced antimicrobial activity and offers a powerful, sustainable replacement for conventional fluorescent dyes in bioimaging. This work brings sustainable nanotechnology to the forefront by highlighting the intersection of waste management and material science, providing novel solutions for health and environmental issues through green, multifunctional nanomaterials. In an article Bokopane et al. [20] created a PV-grid-integrated EVCS that is managed via peer-to-peer energy trading and battery storage. The findings show significant energy savings, a decrease in reliance on the grid, and profitability over an eight-year break-even period. It illustrates how peer-to-peer energy sharing promotes a cooperative energy ecosystem, which raises operational efficiency and system dependability. Comparative Framework: Methodologies, Outcomes, and Challenges in Renewable Energy and Sustainable Technologies is shown in Table 2.

3.2. Integration of electric vehicles with renewable energy systems

The integration relationship between RES and EV into modern power grids and microgrids is the latest trend of research, and is considered to be critically important. A. R. Singh et al. [21] integrate the EV vehicles in terms of passenger vehicles and their significance for sustainable transport. They illustrate the difficulties and the opportunities to modernize the transport infrastructure and to address emissions and to increase grid efficiency. The study emphasizes the need for standardization in the same way as in other aspects in the power system, e.g., integrating with power systems and transmission distribution levels optimal design and operation with key stakeholders. Also, Zabihia and Parhamfarb [22] investigate the integration of PHEV along with RES for

Table 2

Comparative Framework: Methodologies, Outcomes, and Challenges in Renewable Energy and Sustainable Technologies.

Author(s)	Focus Area	Methodology	Key Outcomes
Allouhi and Rehman [16]	Hybrid grid with PV, wind, and battery storage for EVCS in Morocco	HOMER software, sensitivity analysis of energy demand and costs	Efficient renewable integration in Dakhla; 7300 annual EV charging sessions
Thirumalaivasan [17]	Nano-PCMs for energy storage	Review of thermal properties and application flexibility	High latent heat storage, better thermal conductivity, adaptability for various uses
Thirumalaivasan [18]	Biohydrogen (BioH ₂) and biogas (BioG) for renewable energy	Analysis of feedstock, digestion methods, and lifecycle	Reduced greenhouse gases, efficient waste-to-energy conversion
Thirumalaivasan [19]	Carbon Dots (SyCDs) with curcumin for sustainable materials	Green synthesis using syrup bottle waste and curcumin integration	Enhanced antimicrobial, bioimaging properties; waste-to-nanomaterial transformation
Bokopane et al. [20]	Peer-to-peer energy trading in PV-grid-integrated EVCS	Peer-to-peer energy sharing, battery storage integration	Cost savings, reduced grid reliance, profitability in eight years

electrical power system transition. They analyse load flow, and short circuit cases at different voltage levels using DiGSILENT simulations to shed some light on how these technologies can pass through a smart grid. The pioneering findings highlight the two benefits of the renewable integration and the underlying engineering challenges that make it imperative to understand future smart grid technologies.

Based on these perspectives, Engelhardt et al. [23] propose an energy management system specifically for hybrid fast charging stations. The system integrates local renewable generation and battery storage to provide low carbon EV charging and deplete grid stress. Monte Carlo simulations show when dynamic limits are used, improving self-sufficiency with using less grid. Using the study, it is demonstrated how advanced EMS design can optimize the energy allocation in hybrid microgrids. Bastida-Molina et al. [24] provide another way of looking at HRES for off grid EV charging stations. The methodology of the authors combines technical, economic and environmental aspects to develop sustainable solutions for local renewable resources. The research verifies the suggested HRES in Valencia, Spain, through experimental testing which proves the efficacy of integrating solar PV, wind, and battery storage to serve EV charging requirements efficiently. The research highlights the capability of off-grid systems in reducing emissions and reliance on traditional power grids. Finally, El Magri, and Bahatti [25] examine sophisticated energy management techniques in multi-source microgrids with solar, wind, Li-ion batteries, and EVs. Their algorithm uses fuzzy logic and PSO for improving system performance and stability. Simulations test the strategy with results showing flexibility and resilient energy distribution even during changing conditions. The study demonstrates the significance of combining various renewable sources with EVs in ensuring a stable and efficient energy network.

Together, these studies demonstrate the revolutionary power of combining EVs and RES in power systems and microgrids. They tackle key issues like energy management, infrastructure planning, and system optimization, providing novel solutions for a low-carbon and sustainable future. Comparative Framework: Methodologies, Outcomes, and Challenges in RES and EV Integration is shown in Table 3.

3.3. Integration of renewable energy in EV charging

As Anthony Jnr [26] emphasizes, EV are facilitating intelligent grids and cities by virtue of the fact that they can enhance energy management in V2G and G2V technologies. The EV batteries, in this research, are demonstrated to be central elements for handling renewable energy sources and the solution to emissions diminishment and shifting to an energy as a service green model. Furthermore, the research demonstrates how EVs can be a tool to change urban sustainability, providing the answers to the reduction of noise and pollution. Based on this, another author, A. Singh et al. [27] examines the design of solar-powered EV charging stations in India and uses renewable energy to show sustainability. The study also considers energy generation and CO₂ reduction and finds that an 8.1 kWp off grid system can charge on average 414 vehicles per year making a total annual CO₂ reduction of 7950 kg/year. As such, Singh's work details how solar energy is computed in different areas and how monocrystalline solar panels perform optimally.

Taking their studies a step further, Erickson and Ma [28] logistically extend these findings by incorporating demand management pricing (DMP) for merging solar powered EV chargers with the renewable

energy optimization process. Their research shows how utilities could encourage riders to charge their EVs when supply and demand are at their most aligned. This is also significant because it emphasizes the role of cooperative strategies in exploiting the EV storage batteries for grid management so as to leverage the objectives of renewable energy in a sustainable way. In this regard, Yazdanipour, Arani, and Jahromi [29] have extended the discussion and discussed the challenge of cybersecurity vulnerabilities. Some of the highlights include potential risks like manipulated measurements and control commands which can disrupt their operations. However, it also highlights that these sustainable EV charging systems require proper robust cybersecurity measures to enable the reliability and resilience of the systems. Adding to this discussion, Preetham and Udaiyakumar [30] concentrate on creating innovative solar-powered EV charging stations. Their initiative combines solar panels, energy storage, and grid connectivity, targeting cost-effective and environmentally friendly charging options. With reduced dependence on fossil fuels, their initiative positions EV technology within renewable energy, promoting a green transportation system.

Collectively, these studies constitute a full picture regarding the promise and challenges of adding EVs and renewable energy to transportation systems. Comparative framework: methodologies, outcomes, and challenges in EV integration and renewable energy systems is shown in Table 4.

3.4. Overview of solar-powered EV charging studies

Shafiq et al. [31] suggest that solar photovoltaic — (PV) based — EV charging stations are potential in Azad Jammu and Kashmir, Pakistan, due to the high solar potential of the region. Just as, Hnatov et al. [32] consider solar powered charging stations in Kharkiv, Ukraine cost feasibility of technical and economic viability of these stations to promote sustainability and reduce fossil fuel dependency. The payback time as reported in their study is about 7.9 years, and this drops down to 6.8 years taking into consideration annual increases in electricity cost, thus proving the economic viability of such systems. The final addition of surplus electricity sales as a "green tariff" makes for the financial and environmental benefits of solar EV charging infrastructure even stronger. Another study that analyses solar assisted EV charging stations with hybrid power systems is done by TERKEŞ and DEMİRCİ [33]. However, their findings showed that higher solar radiation significantly shortens the payback period and decreases the photovoltaic capacity requirements particularly in night and midday peak demand hour. These findings about the economics of planned sustainable energy planning present relevant information for investors and decision makers that desire to push for a higher level of clean transportation initiatives.

In addition, Kumar, Singh, and Niwareeba [34] illustrate an innovative expanding of solar powered EV charging expansion using pillar top solar panel for emergency EV charging for remote areas. The study utilizes the SIFL-DO algorithm to integrate as a cost effective charging adapter which provides for efficient energy use and conforms to industry

Table 3
Comparative Framework: Methodologies, Outcomes, and Challenges in RES and EV Integration.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
A. R. Singh et al. [21]	EV integration into power grids for sustainability	Analysis of infrastructure modernization and grid efficiency	Highlighted the need for standardization and stakeholder alignment	Engineering complexity and lack of uniform standards
Zabihia and Parhamfarb [22]	Integration of PHEVs with RES in power systems	DiGSILENT simulations of load flow and short circuit scenarios	Showcased engineering benefits of smart grid integration	Managing load flow and system upgrades for smart grids
Engelhardt et al. [23]	Hybrid EMS for fast charging stations	Monte Carlo simulations with dynamic limits for energy management	Improved self-sufficiency and reduced grid dependence	Dynamic energy management under fluctuating conditions
Bastida-Molina et al. [24]	Off-grid HRES for EV charging in Valencia, Spain	Experimental validation of HRES with solar, wind, and battery storage	Verified reduced emissions and traditional grid reliance	Economic feasibility and off-grid deployment challenges
El Magri, and Bahatti [25]	Multi-source microgrids with advanced EMS	Fuzzy logic and PSO-based algorithm for performance optimization	Demonstrated flexibility and resilience in energy distribution	Complexity in integrating diverse renewable sources

Table 4

Comparative Framework: Methodologies, Outcomes, and Challenges in EV Integration and Renewable Energy Systems.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Anthony Jnr [26]	EVs in intelligent grids and cities	Analysis of V2G/G2V technologies for energy management	Enhanced urban sustainability and pollution reduction	Integration complexity and regulatory barriers
A. Singh et al. [27]	Solar-powered EV charging in India	Design of an 8.1 kWp off-grid system for CO ₂ reduction	Charged 414 vehicles/year with a 7950 kg CO ₂ reduction	Dependence on regional solar potential
Erickson and Ma [28]	Demand management pricing for EV chargers	Incorporation of DMP to align charging with supply-demand	Optimized grid utilization and renewable energy alignment	User participation and utility infrastructure readiness
Yazdanipour, Arani, and Jahromi [29]	Cybersecurity in EV charging systems	Analysis of risks like manipulated measurements and controls	Highlighted need for robust cybersecurity measures	Cybersecurity vulnerabilities and operational risks
Preetham and Udaiyakumar [30]	Innovative solar-powered EV charging stations	Integration of solar panels, storage, and grid connectivity	Cost-effective, environmentally friendly EV charging	Infrastructure costs and dependency on renewable supply

standard EN50530. The proposed system demonstrates the possibility of implementing the solar solutions in the areas with limited infrastructure.

Collectively, these studies reveal the complex possibilities of solar-powered EV charging stations. From emission reduction and grid flexibility to low-cost and efficient solutions, the incorporation of renewable energy into EV charging systems stands out as an essential strategy for promoting clean transport and realizing sustainability objectives. Comparative framework: methodologies, outcomes, and challenges in solar-powered EV charging systems is shown in Table 5.

3.5. Electric vehicle integration studies

According to Heinisch et al. [35] electric cars and buses can be integrated into urban energy systems in a way that achieves net-zero emissions by 2050. Up to 85 % of EV charging demand is flexible and therefore can be supported by smart charging strategies to realise up to 62 % solar PV energy, versus the 24 % that can be directly supplied with centralised power generation. In literature, Bilal and Rizwan [36] also propose a hybrid optimization approach that combines GWO and PSO to place EV charging stations and compensate reactive power. The gains of their method are greatly demonstrated with increased net profits and large power loss reductions (30.67 % in 33 bus, 27.6 % in 34 bus) in grid management. This enhances Heinisch et al.'s work on smart integration regarding grid reliability and efficient infrastructure placement. Another study by Coban et al. [37] delves into the V2G concept, where EVs act as mobile energy storage units. They also emphasize V2G's capability to improve stability of grids, achieve efficient pathways for providers of energy, as well as strengthen integration of renewable energy. Assuming disparate Smart City initiatives in Turkey, Coban et al. formulate strategies for prolonging aggregator profits, energy independence, and minimizing exposure in the case of blackouts. It fits into the grid optimization rationale that Bilal and Rizwan have taken to also include energy market contributions and electromobility benefits.

Abdel-Basset et al. [38] consider Egypt within a MCDM framework for the optimal location of EV charging stations. They develop a study which uses the neutrosophic theory and DEMATEL and COPRAS techniques to identify sustainable sites and to prioritize economically and technologically. This provides a real-world context to the infrastructure planning of Heinisch et al. and Bilal and Rizwan, providing policymakers with actionable information on effective and sustainable

location selection. Finally, Langeroudi et al. [39] examine a multi-energy microgrid with renewable energy sources, PEV, and hydrogen-based technologies. Their research formulates a CVaR-based model for risk management, proving that hydrogen storage and PEVs decrease daily cost by 9.28 % with increased system sustainability. The study supplements Coban et al.'s work through the addition of hydrogen as a factor to hedge renewable energy oscillations and augment energy efficiency.

Together, they present an entire picture of EV integration sustainability. These varied but complementary views highlight the complex nature of sustainable EV infrastructure development. Comparative Framework: Methodologies, Outcomes, and Challenges in EV Integration with Urban Energy Systems is shown in Table 6.

3.6. EV charging optimization overview

In designing stand-alone renewable based EV charging stations Al Wahedi and Bicer [40] investigate how to meet an increasing demand of EVs without damaging the power grid. These results show that such configurations can be applicable across different geographies with electricity costs ranging from \$0.285 to \$0.329 per kWh. Kucevic et al. [41] in another study also studies the challenges of urban distribution grid with EV penetration and provide a coordinated control strategy for battery energy storage systems (BESS). In addition, peak loads are reduced by 44.9 % and grid reinforcements can be abandoned through this method, providing an effective means for urban energy management. Palit, Bari, and Karmaker [42] also focus on factors driving the adoption of EV in emerging economies and identify 17 critical drivers. Through PCA and ISM multi criteria decision making approach, they give priority to elements like vehicle's reliability, availability and government policies supporting the development of charging infrastructure. Overall, the findings of this research are actionable to policymakers and auto industries intending to accelerate the diffusion of EVs, particularly in developing markets. This is extended by Meena et al. [43], who discuss the use of smart grid technologies to integrate renewables, energy storage, and demand response to change distribution networks. These intelligent algorithms and blockchain technologies are found to produce substantial emission reductions (30 %) and enhanced energy efficiency (25 %) and provides a sound basis for a green energy revolution.

Table 5

Comparative Framework: Methodologies, Outcomes, and Challenges in Solar-Powered EV Charging Systems.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Shafiq et al. [31]	Solar PV-based EV charging in Azad Jammu and Kashmir	Analysis of solar potential and PV feasibility	High solar potential identified; promoted sustainability and fossil fuel reduction	Dependency on local solar conditions and economic factors
Hnatov et al. [32]	Solar-powered EV charging in Kharkiv, Ukraine	Economic analysis and feasibility study; inclusion of "green tariff"	Payback period reduced to 6.8 years with economic benefits	Electricity cost variability and initial infrastructure costs
TERKEŞ and DEMİRÇİ [33]	Hybrid solar EV charging systems	Analysis of solar radiation effects on payback and PV capacity	Shortened payback period with optimized PV capacity	Variability in solar radiation and demand fluctuations
Kumar, Singh, and Niwareeba [34]	Emergency solar EV charging in remote areas	SIFL-DO algorithm for efficient and cost-effective charging	Cost-effective solution for remote areas with limited infrastructure	Limited scalability in urban settings

Table 6

Comparative Framework: Methodologies, Outcomes, and Challenges in EV Integration with Urban Energy Systems.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Heinisch et al. [35]	EV integration for net-zero emissions by 2050	Smart charging strategies to align EV demand with solar PV energy	Up to 62 % of EV demand met through solar PV; grid stress reduced	Dependence on smart grid implementation and flexibility
Bilal and Rizwan [36]	Hybrid optimization for EV station placement	Combined GWO-PSO optimization approach for reactive power and station placement	30.67 % and 27.6 % power loss reduction in grid management	High computational complexity and implementation costs
Coban et al. [37]	V2G and energy storage in smart cities	Strategies to optimize V2G for grid stability and blackout mitigation	Improved grid stability, aggregator profits, and energy independence	Integration with current grid infrastructure and policy gaps
Abdel-Basset et al. [38]	Optimal EV station location in Egypt	MCDM framework using DEMATEL and COPRAS for sustainable site selection	Identified and prioritized sustainable charging station sites	Data reliability and regional policy alignment challenges
Langeroudi et al. [39]	Multi-energy microgrid with hydrogen and PEV	CVaR-based model for risk management and sustainability evaluation	Daily cost reduced by 9.28 %; improved system sustainability	Hydrogen storage scalability and cost efficiency

Moreover, Huang et al. [44] consider whether it is feasible for the EV charging stations to be located at convenience stores with the help of household PV energy leftover. They then show how by using regional energy sharing, the region can optimize operational objectives, reduce grid dependency, and support a sustainable EV infrastructure using MATLAB's MILP toolbox. This analysis also shows the importance of the community driven renewable energy utilization to urban energy issue. Collectively, these studies show various but related strategies for promoting EV adoption, infrastructure growth, and energy sustainability, with a focus on a move toward more environmentally friendly cities and improved grid resilience. Comparative Framework: Methodologies, Outcomes, and Challenges in EV Charging and Renewable Integration is shown in Table 7.

3.7. EV charging and renewable energy integration overview

Along with the goal of net zero emissions by 2050 as laid down in the European Green Deal, in Hrnčić et al. [45], the authors explore Montenegro's transition to a 100 % renewable energy system. The analysis work used EnergyPLAN to study scenarios for 2030, 2040, and 2050 with special focus on the role as a pillar in the system of the hydropower. Nevertheless, proper integration renewable energy to secure energy and stability of grid is necessary. The authors state the need of strategic planning, energy efficiency measures, storage solutions and demand response to guarantee a carbon free system with stable energy. Likewise, Tirunagari, Gu, and Meegahapola [46] also discussed the EV integration applications where the uncoordinated EV charging can cause peak loads, energy losses, and grid instability. Smart charging and V2G technologies presented by them were able to mitigate these issues, and together with smart charging they will optimize energy transfers and improve grid stability. This underscores the importance of strong regulatory and policy steps needed to spur widespread adoption of these technologies. The same discussion was carried out by Alsharif et al. [47] to microgrid systems and they proposed to integrate the EVGI with renewable energy sources through stochastic metaheuristic methods. Overloading and optimization of hybrid configurations Tripoli, Libya was carried out using the SMCM and Improved Antlion Optimization (IALO) algorithm. This research shows that coupling EVs in V2G technology seems to be a cost effective and sustainable solution of energy systems to avoid

overloading and to expand power flow.

Concerning the technological innovation aspect, Mohamed et al. [48] suggested a solution to EV range anxiety through dynamic wireless power transfer. They developed a mathematical model to evaluate power transmission under motion by incorporating additional receiver coils. Their approach was simulated and experimentally tested, and validated in simulations and experimental tests and showed improved charging efficiency and application of wireless systems in EV infrastructure. Chakir et al. [49] finally looked at energy management in household that are considering the use of renewable energy and EVs. They suggested a hybrid PV-Wind-Battery system with an energy management system that optimizes flow in applications. The simulation emphasized effective energy usage, grid stability, and eco-friendliness, pointing toward the management of future urban energy requirements. By meeting challenges ranging from grid instability to EV range anxiety, they together open the way for innovative, environmentally friendly energy systems. Comparative Framework: Methodologies, Outcomes, and Challenges in EV Integration and Renewable Energy Systems is shown in Table 8.

3.8. Integration of renewable energy and EV charging

Sun [50] performs an optimization of fast EV charging stations FEVCS-WPE. A hybrid method combining MOPSO and TOPSIS is introduced as a research, to minimize electricity costs and pollution emission at the same time based on a multi objective optimization model. The findings were applied in Inner Mongolia to emphasize the value of renewable energy integration and connectivity to system efficiency. Robustness of the model was validated using sensitivity analysis, and comparison of the solution indicating feasibility of sustainable EV charging infrastructure. Khan and Byun [51] considered unique perspectives on EV infrastructure that incorporated their exploration of innovative ways of utilizing blockchain technology for peer to peer energy trading and modern payment systems. Through Hyperledger Fabric study, the model was developed with smart contract-based platform that gave flexibility for trading surplus electricity with EV charging stations to users. Humans interaction was lowered while ensuring trust and transparency and privacy was improved by paying bills through electronic wallets. The insight gained from this solution was on the

Table 7

Comparative Framework: Methodologies, Outcomes, and Challenges in EV Charging and Renewable Integration.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Al Wahedi and Bicer [40]	Stand-alone renewable EV charging stations	Analysis of configurations across geographies	Feasibility with electricity costs ranging \$0.285-\$0.329/kWh	Deployment scalability and economic feasibility
Kucevic et al. [41]	BESS strategies for urban grids with EV penetration	Coordinated control of BESS for load management	Peak load reduced by 44.9 %; avoided grid reinforcements	Integration complexity and dependency on urban grids
Palit, Bari, and Karmaker [42]	EV adoption drivers in emerging economies	PCA and ISM-based multi-criteria decision-making approach	Identified 17 key drivers; prioritized reliability, availability, and policies	Data availability and regional adaptability
Meena et al. [43]	Smart grid and blockchain for distribution networks	Intelligent algorithms for energy storage and demand response	30 % emission reduction, 25 % energy efficiency improvement	High implementation costs and technical readiness
Huang et al. [44]	PV-powered EV charging at convenience stores	Regional energy sharing via MATLAB's MILP toolbox	Reduced grid dependency; optimized energy use with community-driven renewables	Dependency on household PV supply and operational variability

Table 8

Comparative Framework: Methodologies, Outcomes, and Challenges in EV Integration and Renewable Energy Systems.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Hrnčić et al. [45]	Montenegro's transition to 100 % renewable energy	EnergyPLAN analysis for 2030, 2040, 2050 scenarios with hydropower focus	Identified hydropower as a key pillar for a renewable system; need for storage and demand response	Grid integration and ensuring stability with 100 % renewables
Tirunagari, Gu, and Meegahapola [46]	Smart charging and V2G for EV integration	Smart charging and V2G technology to mitigate grid instability	Reduced peak loads and energy losses; improved grid stability	Regulatory barriers to widespread adoption
Alsharif et al. [47]	EVGI integration with renewable energy in microgrids	Stochastic metaheuristic optimization (SMCM, IALO)	Avoided grid overloading; optimized power flow in hybrid configurations	Scaling for large grid systems and managing energy fluctuations
Mohamed et al. [48]	Wireless power transfer for EV range anxiety	Mathematical model and experimental testing of dynamic wireless transfer	Improved charging efficiency and EV infrastructure application	Infrastructure adaptation for wireless charging technology
Chakir et al. [49]	Energy management in households with renewables and EVs	Hybrid PV-Wind-Battery system with energy management optimization	Optimized energy flow; improved grid stability and eco-friendliness	Balancing energy supply-demand and integrating with existing grids

resource utilization and transaction efficiency to support creating a next generation smart city framework. By considering the energy storage and EV components, Gil et al. [52] extended this study to include housing developments that reduce their grid dependency and carbon emissions. Techno-economic modeling was used in the research to optimize PV systems and storage in order to analyse energy demands in the UK. It showed that integrating renewable with the grid substantially reduces demand for grid energy, with an average of 31 percent, especially in January, and provided net electricity export in July. Tariffs such as Feed in tariffs, Economy 7, also saved costs, and so it proved that this model is sustainable.

In another study by You et al. [53], they studied the practical application of DT technology on integrated energy systems (IES) optimization. The proposed research was based on a day-ahead scheduling modelled as multi vector energy system commencing its interaction with a virtual twin. The system solved cost saving scheduling as well as the practical complexities of IESs using deep neural networks. It was shown in case studies that, with its reduced operating costs, it was 63.5 percent cheaper than traditional approaches. EVs and thermal energy storage emerged as the proactive levers for assisting the operations and minimizing carbon footprints.

Collectively, these studies highlight the transformative potential of concurrent integration of RES, advanced technologies, digital twins and innovative infrastructure designs. Comparative Framework: Methodologies, Outcomes, and Challenges in Advanced EV Charging and Energy Systems is shown in Table 9.

3.9. Overview of renewable energy optimization in EVs

According to Kawayshy et al. [54], the TSR based MPPT can be beneficial for utilizing wind powered EV charging stations in Egypt. The 41.68 % increase in energy conversion efficiency and the 30 % drop in energy costs are associated with TSR MPPT using the above data. This

approach is shown to be effective for EV charging by a simulation in MATLAB/Simulink. Ahmed et al. [55] also tackle the challenge of adoption of renewable energy, but in energy frequency deviations in interconnected power systems with electric vehicles and energy sources. The results show improvement on system stability, frequency control and transient response performance under varied operational scenarios and it shows robust performance. In extending the discussion on renewable energy integration, Liu, Yang, and Zhou [56] Examine peer energy trading in wind turbines with hydrogen storage and net-zero hybrid solar PV systems for hydrogen-powered vehicles. The implementation of this approach provides practical ways to increase grid flexibility and enable the decarbonization of urban communities.

In a similar direction, Dorokhova et al. [57] employ deep RL to control EV charging aiming to effectively manage photovoltaic self-consumption and the grid while concentrating on minimizing the risk of battery aging. In the paper, the study compares RL approaches with other methods like deterministic optimization and model predictive control; proven by them to be more effective in achieving consistent charging patterns across a day and reducing the grid stress during peak loads. This novel application of RL has important implications for real-time EV charging policy. Lastly, Domínguez-Navarro et al. [58] address the profitability and sustainability of rapid EV charging stations. Employing the Monte Carlo approach to demand modeling and a GA for optimization, the research determines cost-effective solutions that optimize profit while minimizing grid dependency.

Together, these research works highlight the pivotal importance of sophisticated technologies—spanning MPPT and hybrid controllers to RL algorithms and peer energy trading—in maximizing EV charging and incorporating renewable energy. Comparative Framework: Methodologies, Outcomes, and Challenges in Advanced EV Charging Optimization is shown in Table 10.

Table 9

Comparative Framework: Methodologies, Outcomes, and Challenges in Advanced EV Charging and Energy Systems.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Sun [50]	Multi-objective optimization of fast EV charging (FEVCS-WPE)	Hybrid MOPSO-TOPSIS model with sensitivity analysis	Minimized electricity cost & emissions; validated for Inner Mongolia's renewables integration	Computational complexity; robustness across diverse regions
Khan and Byun [51]	Blockchain-enabled P2P energy trading for EV charging	Hyperledger Fabric smart-contract platform with e-wallet payments	Trustworthy, low-interaction transactions; efficient surplus energy trading	Regulatory uncertainty; network latency and scalability
Gil et al. [52]	PV + storage integration in UK housing developments	Techno-economic modeling under various tariff schemes	31 % grid demand reduction (winter); net export in summer; cost savings via Feed-in and Economy 7	Dependency on subsidy/tariff structures; variability in household demand
You et al. [53]	Digital Twin for integrated energy system scheduling	Deep neural network-based day-ahead multi-vector scheduling via virtual twin	63.5 % operating cost reduction; proactive use of EVs & thermal storage	High model training overhead; real-time data accuracy requirements

Table 10

Comparative Framework: Methodologies, Outcomes, and Challenges in Advanced EV Charging Optimization.

Author(s)	Focus Area	Methodology	Key Outcomes	Challenges
Kawashty et al. [54]	Wind-powered EV charging MPPT	TSR-based MPPT modelled in MATLAB/Simulink	+41.7 % conversion efficiency; -30 % energy cost	Needs real-world validation; hardware implementation complexity
Ahmed et al. [55]	Frequency control in EV-integrated grids	Hybrid fractional-order controller; interconnected system sim	Improved stability, tighter frequency control, robust transients	Controller tuning under diverse grid conditions
Liu, Yang, and Zhou [56]	Peer trading + hydrogen storage + hybrid PV	Simulation of peer-to-peer market with hydrogen buffer	Enhanced grid flexibility; decarbonized urban energy	High hydrogen storage CAPEX; market and regulatory setup
Dorokhova et al. [57]	EV charging via deep reinforcement learning	Deep RL vs. deterministic/MPC for PV self-consumption control	Consistent charging patterns; peak-load reduction; less battery aging	Training data needs; real-time deployment overhead
Domínguez-Navarro et al. [58]	Profitability & sustainability of fast chargers	Monte Carlo demand modeling + genetic algorithm optimization	Cost-effective station sizing; maximized profit; ↓ grid use	Assumptions in demand modeling; scalability across regions

RQ1. what ways can renewable energy technologies such as solar, wind, and hydropower be efficiently integrated into electric vehicle charging infrastructure to achieve peak energy efficiency while reducing carbon footprints?

Renewable sources of energy like solar, wind, and hydropower can be best incorporated into EV charging systems by taking advantage of smart charging techniques, decentralized renewable generation, and hybrid optimization strategies. Smart charging and V2G technologies make it possible to effectively utilize solar PV, as demonstrated by Heinisch et al. [35], to charge up to 62 % of EVs using renewables instead of using centralized grids. Further, hybrid optimization techniques such as GWO-PSO and MOPSO-TOPSIS (Sun [50]) maximize placement of charging stations and reduce losses of power. Autonomous renewable-fuelled charging stations, like Al Wahedi and Bicer's [40] Qatar experience, showcase feasibility by utilizing off-grid applications from HOMER software in inexpensive settings. Langeroudi et al. [39] bring forth hydrogen storage-based supporting power supply for reducing variations of power output of renewable resources. Digital Twin technology (You et al. [53]) also helps in real-time energy dispatch optimization, saving 63.5 % costs over conventional systems. Through peer-to-peer energy trading (Khan and Byun [51]), blockchain networks enable decentralized sharing of renewable energy, providing a more robust and low-carbon energy system. Together, these strategies enable the shift towards sustainable, renewable-energy-powered EV charging networks that promote energy efficiency and reduce carbon emissions worldwide.

RQ2. What are the main technical, economic, and regulatory issues involved in the deployment of renewable-powered EV charging systems, and how can they be best overcome?

The rollout of renewable-fed EV charging infrastructure faces a number of technical, economic, and regulatory issues that need to be solved for mass adoption. Technical challenges include grid instability due to uncoordinated charging of EVs, as reported by Tirunagari et al. [46], and adding peak loads that need coordinated battery storage solutions, as shown in Kucevic et al. [41]. Repetitive charge-discharge cycles also speed up battery degradation (Dorokhova et al. [57]), which requires sophisticated battery management methods. Regulatory hurdles encompass insufficient policies in favour of V2G and decentralized energy storage (Palit et al. [42]) and uncertain legal frameworks for peer-to-peer energy trading. Addressing these challenges calls for government incentives targeted at specific sectors, policy interventions designed strategically, and novel financing arrangements. Blockchain-enabled energy trading and AI-based optimization (You et al. [53]) can enhance energy allocation and efficiency, lowering economic risks. Adoption of innovative regulatory structures that advocate for smart grid development, dynamic pricing, and investment in green infrastructure will also push the penetration of renewable-powered EV charging systems further while maintaining long-term energy sustainability.

RQ3. What is the role of emerging technologies, like V2G systems and innovative energy storage products, in improving the scalability and feasibility of EV charging infrastructure using renewable energy?

New technologies like V2G systems, next-generation energy storage technologies, and artificial intelligence are pivotal. Integration with V2G, as shown by Coban et al. [37], enables EVs to function as distributed energy storage devices, balancing grid demand and reinforcing the uptake of renewable energy. Research conducted by Tirunagari et al. [46] identifies that V2G can also reduce grid stress and shave peak loads by joining forces with smart charging. Sophisticated energy storage facilities, like hydrogen-based storage (Langeroudi et al. [39]) and hybrid PV-Wind-Battery systems (Chakir et al. [49]), provide stable power supply and reduce the uncertainty of renewables. Deep reinforcement learning optimizes EV charging schedules to maximize photovoltaic self-consumption and minimize battery wear. Digital Twin simulations further enhance operational efficiency, reducing costs by 63.5 %. These technologies altogether improve grid resiliency, lower carbon footprints, and facilitate a decentralized, sustainable electric vehicle charging environment. Policymakers and industry leaders can further expedite the shift toward a cleaner, more efficient transportation and energy system using these technologies.

4. Research gap

Despite the large quantity of research on incorporating renewable energy into EV charging infrastructure, certain important gaps still exist. For one, while research has investigated single renewable sources such as solar (Sun et al.), wind (Kawashty et al.), and hydropower (Hrn íc et al.), there has been limited work investigating the best hybridization of these sources under a single EV charging framework. The absence of integrated models including several renewable sources in combination with energy storage, demand response, and grid interaction presents a chance for creating more efficient and more resilient systems. Second, despite the extensive discussions about V2G technology (Coban et al., Alsharif et al.), its massive implementation is less researched, especially its economic feasibility, regulatory issues, and real-time optimization issues. Third, technologies like blockchain-enabled P2P energy trading (Khan and Byun) and digital twin-based optimization (You et al.) hold great potential for increasing EV charging efficiency but are not yet empirically proven to be integrated into renewable-powered charging networks. Moreover, although various studies examine grid stability issues, the application of AI-based predictive analytics and deep reinforcement learning (Dorokhova et al.) in optimizing energy flows in EV charging systems is not adequately explored. Bridging these gaps will facilitate the creation of a comprehensive, data-driven, and scalable framework for sustainable EV charging infrastructure.

5. Findings and discussion

Even though there is great potential to enhance energy efficiency and

reduce carbon emissions by harnessing renewable sources of energy such as solar, wind, and water in EV charging systems, certain significant findings have been released in the literature. First of all, evidence shows that renewable sources can notably minimize the reliance on traditional grid power. For example, Heinisch et al. [35] show that smart charging plans can serve up to 62 % of charging demand from solar PV, underscoring the importance of renewable integration towards alleviating grid dependence. Additionally, charging stations powered by renewables can save costs as well as stabilize the grid. For instance, research by Langeroudi et al. [39] indicates that the incorporation of PEVs and hydrogen-based systems into a multi-energy microgrid leads to lower daily costs and system sustainability. Yet intermittency and grid reliability challenges still exist, which necessitates the importance of sophisticated storage options and demand response strategies. In terms of technical, economic, and regulatory issues, an important observation is that although various studies have outlined cutting-edge technologies such as V2G systems and energy storage (Bilal and Rizwan [36]), their large-scale implementation is marred by substantial obstacles. They consist of considerable upfront investment expenditure, the absence of regulatory support mechanisms to stimulate uptake, and the necessity of solid infrastructure growth. In addition, the task of combining disparate renewable energy sources in an optimal manner with EV charging infrastructure remains unexplored, and there is a requirement for more comprehensive models that account for different energy source combinations, storage, and grid interaction.

Several countries are highlighted in the manuscript where renewable powered EV charging has moved on from theory to real world feasibility. Countries like Norway, China and the US are very much leaders in the global electric vehicle (EV) adoption scene, as encouraged by a number of government incentives, zero emission mandates and ongoing infrastructure development. A solar powered EV charging system is shown to have practical viability as A. Singh et al. proved a system to reduce annual CO₂ emissions in India [27]. Allouhi and Rehman [16] similarly designed a hybrid PV-wind-battery system for EV charging in Dakhla, Morocco using HOMER software, resulting in low costing EV charging with high renewable energy integration. An off grid hybrid renewable energy system to meet local EV charging demands was experimentally validated in Spain, specifically in Valencia, as seen in Bastida-Molina et al. [24]. Meanwhile, other countries including Pakistan and Ukraine have performed feasibility analysis like Shafiq et al. [31] and Hnatov et al. [32], however, those countries are still at a pilot or conceptual stage. Yet, a considerable amount of the global literature still takes a simulation based approach using optimization models and virtual test environments, i.e., the MOPSO-TOPSIS model by Sun [50] and Digital Twin system by You et al. [53]. While these studies are valuable, they also demonstrate the need for wider empirically proven implementations to be performed to bridge the gap between theoretical potential and real world application.

Emerging technologies like blockchain based energy trading and energy related technologies like Vehicle to Grid (V2G) systems, however, introduce critical cybersecurity and integration challenges which need to be addressed if these are going to be widely adopted. The V2G system provides a means to data integrity VTAitting, spoofing control commands and unauthorized access to grid vehicle. Blockchain platforms, although they're transparent and run via consensus mechanisms and smart contracts, suffer from software bugs, delayed consensus, network latency, data privacy and all of these that have been tested in an energy trading environment. There are also problems with integration beyond security, in that there is no interoperability on different auto OEMs (OEMs: Car manufacturers) and charging standards (CHAdeMO vs. CCS) and a lack of agreement on grid communication protocols. Seamless integration is complicated by the absence of standardized bidirectional communication protocols for V2G energy exchange. However, real-time trading and therefore demand response coordination, may not be suitable in the blockchain systems due to scalability and latencies. These factors emphasize the critical requirement for

regulatory harmonization, strong cybersecurity frameworks and creation of standardised solutions for enabling the secure, scalable and interoperable deployment of smart charging and energy trading technologies.

New technologies like blockchain and AI-based optimization models are poised to make renewable-powered EV charging systems more scalable and viable. For instance, Khan and Byun [51] A peer-to-peer energy trading system based on blockchain technology offers an affordable and environmentally friendly way to distribute extra energy. The incorporation of these technologies into workable EV charging systems and their compatibility with existing grid systems, however, need further investigation. Recent research efforts in 2025 increasingly focus on integrating renewable energy into electric vehicle (EV) charging systems, with several studies [59–61] exploring innovative approaches and advancements in this domain.

Several overarching trends are identified across the published reviewed literature. This thesis first focuses on solar PV integration in renewable-powered EV charging solutions for its scalability, cost effectiveness and global applicability and wind and hydropower are usually supplementary options with favorable climatic conditions. Systems that utilize hybrid combinations of multiple renewable sources, coupled with energy storage, provide resilience and reliability at the price of system complexity and higher capital cost. Vehicle to Grid (V2G), smart charging, blockchain and other technologies hopefully can improve the efficiency, power demand and power stability of grid, mostly through pilot projects or simulation study. In terms of differences across regions, Norway, China, India, Spain represent countries with practical progress through pilot deployments or validated testbeds, while other regions remain at earlier exploratory stages of deployment. We identified a major trade off between cost and system complexity: superior performance is associated with more sophisticated, adaptive systems, but the price is higher investment in infrastructure and in regulatory support. A significant research gap in cross technology integration models not only experiment with different renewables and storage together, but also examine, in its totality, what the adoption of these resources will look like in realistic scenarios complemented by AI control and appropriate policy frameworks. Likewise, only limited empirical validation of blockchain enabled P2P trading and Digital Twins systems exists although these ideas are conceptually strong. The way these gaps are bridged is essential in informing regionally specific high scale strategies for the global transition to green mobility.

The Fig. 2 demonstrates how dependence on the conventional electricity grid reduces with higher penetration of renewable energy with time. The X-axis denotes the years 2020–2040, while the Y-axis denotes the grid dependency percentage. The figure reflects a linear reduction in the dependence on fossil fuel-based grids as more renewable sources are included, with the dependency reducing from 80 % in 2020 to 20 % in 2040. This trend focuses on the long-term contribution of renewables in cutting carbon emissions and ensuring energy independence in charging systems for EVs.

The heatmap in Fig. 3 illustrates the variations in EV charging demand over various locations and at various times of the day. The X-axis indicates various time slots (e.g., morning, afternoon, evening, night), while the Y-axis indicates various locations like urban areas, residential areas, highways, and commercial areas. The colour intensity indicates the charging demand, with darker intensities showing higher demand and lighter intensities showing lower demand. The information indicates that city centres and roads have their peak charging demand during the morning and evening peaks, while residential neighbourhoods experience increased demand at night through home charging. This visualization aids in the optimization of where to install charging stations, enhancing energy distribution and peak load management effectively. It also aids policymakers and energy companies in planning for the integration of renewable sources to handle different demand patterns efficiently.

Fig. 4 further shows that the energy sources in renewable powered

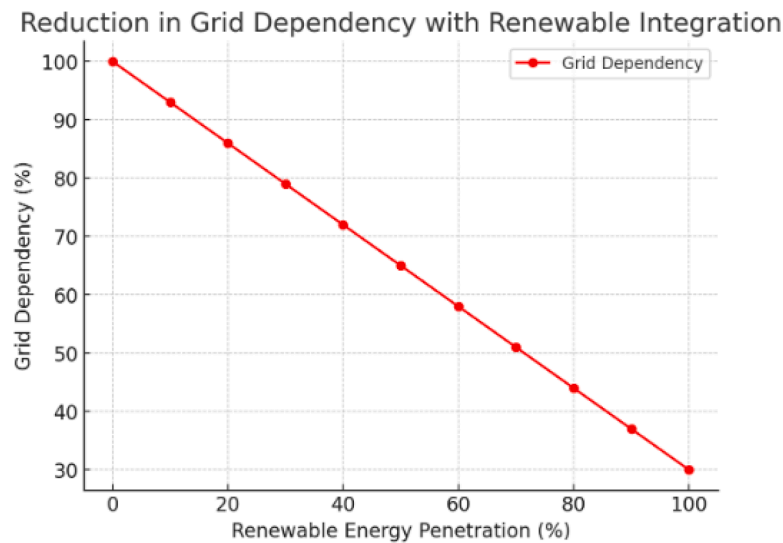


Fig. 2. Reduction in Grid Dependency with Increased Renewable Penetration.

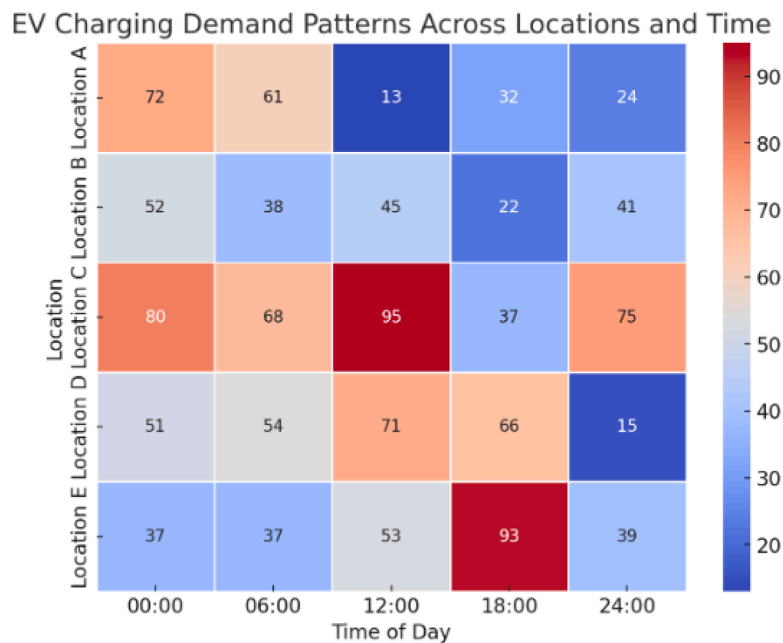


Fig. 3. EV Charging Demand Patterns Across Different Locations and Timel.

EV charging station distributed 50 % of which from solar energy, 30 % from wind energy and 20 % from hydropower. Solar energy is the dominant renewable EV infrastructure driver which scales, cost decreases and is readily available, but is mitigated by geographically and temporally based factors. Furthermore, wind energy (30 percent), a complementary technology, contributes when the additional solar production is low and demonstrates how these two sources work together. Hydro power, the stalwart of the energy mix at 20 %, stabilizes, supplying reliable, consistent energy as solar and wind production is stop and go. Diversification of energy sources and methods of supply to meet requirements for energy security, reliability and resilience is evident in this balanced mix of energy sources. Moreover, it outlines strategic opportunities to incorporate advanced storage systems and to optimise hybrid models for variability. In addition, the dependance on regional resources raises the requirement for bespoke energy policies that compliment a region’s renewable potential which in turn enhances the efficiency and sustainability canvas of EV charging systems.

Fig. 5 shows a consistent positive correlation between smart charging strategies and reduction of grid load, reflecting both demand scheduling and vehicle to grid (V2G) technologies. We observe that as charging efficiency improves from 70 % to 95 %, the grid load reduction varies from about 10 % to 40 %, reflecting the potential of well-formed charging patterns to lighten grid stress. The trend here serves to reinforce the significance of widespread smart charging as a tool to more effectively deal with energy demands and peak loads. These strategies can help stabilize the grid by matching vehicle charging times with off peak hours and by enabling bidirectional energy flows that use vehicle batteries to share excess clean power produced by renewable energy sources with a home or community facility. Finally, the graph emphasizes the essential role of innovative technologies in defining the role of sustainable energy infrastructures for the upcoming electric vehicle ecosystem. Research question and key findings shown in Table 11.

Distribution of Energy Sources in a Renewable-Powered EV Charging Station

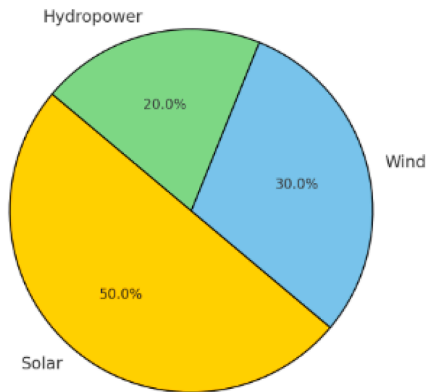


Fig. 4. Distribution of Energy Sources in an EV Charging System.

Correlation between Smart Charging Strategies and Grid Load Reduction

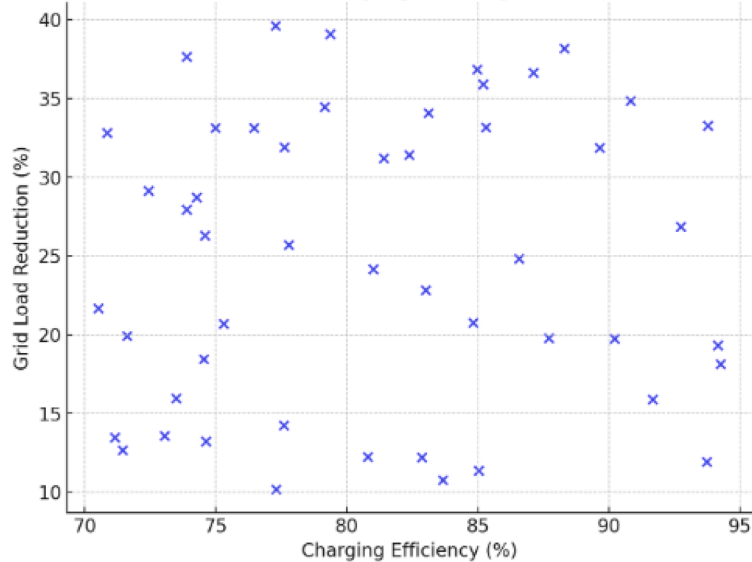


Fig. 5. Relationship Between Smart Charging and Grid Load Reduction.

6. Conclusion and future works

This study underscores the pivotal role of renewable energy sources—such as solar, wind, and hydropower—in improving the energy efficiency of EV charging infrastructure and minimizing carbon footprints. The integration of Vehicle-to-Grid (V2G) networks and smart charging strategies represents a transformative step toward sustainable EV infrastructure. However, significant challenges such as grid stability, energy intermittency, high capital costs, and regulatory barriers must be addressed for effective large-scale deployment.

Emerging technologies like blockchain, AI-driven energy management, and digital twins are reshaping the landscape of EV charging and renewable energy systems. Blockchain ensures secure, decentralized peer-to-peer energy transactions, fostering trust and operational transparency. However, its scalability and energy-intensive consensus mechanisms require advanced solutions. V2G technology, which enables bi-directional energy flow between EVs and the grid, transforms EVs into mobile energy storage units, aiding in grid stabilization, energy dispatch optimization, and renewable energy utilization. This approach, while promising, necessitates advancements in battery longevity, standardization of communication protocols, and supportive regulatory frameworks to ensure seamless integration. AI-driven optimization

methods play a critical role in energy management by leveraging predictive algorithms and machine learning models to forecast energy demand, optimize load distribution, and align EV charging schedules with renewable energy availability. For instance, reinforcement learning (RL) has shown potential in managing real-time grid fluctuations and reducing battery degradation. These methods enhance grid efficiency and minimize operational inefficiencies but require robust computational infrastructure and high-quality datasets for reliable implementation. Additionally, digital twins offer real-time simulation and predictive modeling of energy systems, providing valuable insights for system operators to optimize performance and mitigate potential issues proactively. Despite their immense potential, deploying digital twins requires significant investment and alignment between virtual models and physical systems.

Future work should include the development of intelligent, AI driven control algorithms of dynamic energy management that allows for allocation of renewable energy to EV charging stations given the variability of supply and demand to follow. Hybrid renewable energy based charging systems integrating solar, wind and biomass must be pilot tested in different geographical locations, to examine feasibility, efficiency and scalability. Furthermore, modeling and optimization of hybrid energy storage systems like lithium ion battery–hydrogen fuel

Table 11
Research Question and its Key Findings.

Research Question	Key Finding
RQ1. How can renewable energy sources like solar, wind, and hydropower be optimally integrated into EV charging systems to maximize energy efficiency and minimize carbon emissions?	Integration of renewable energy, particularly solar PV, can minimize reliance on traditional grid electricity and enhance charging efficiency. Intelligent charging techniques can provide as much as 62 % of the demand from renewable sources. Integrating energy sources such as wind, solar, and hydrogen-based systems provides more energy efficiency and sustainability.
RQ2. What are the primary technical, economic, and regulatory challenges associated with deploying renewable-powered EV charging systems, and how can they be effectively addressed?	Technical issues are grid stability and energy intermittency, whereas economic impediments are expensive initial investment costs and the demand for strong infrastructure. There is a lack of regulatory frameworks in place to stimulate large-scale usage. Sophisticated technologies such as V2G and energy storage can address such issues, though more research should be conducted.
RQ3. What role do emerge technologies, such as V2G systems and advanced energy storage solutions, play in enhancing the feasibility and scalability of renewable energy-powered EV charging infrastructure?	Emerging technology like V2G systems and newer energy storage solutions can improve the stability of the grid, enable renewable energy integration, and improve scalability. For example, V2G systems can lower peak loads, while blockchain facilitates peer-to-peer energy trading. Additional research is required in order to incorporate these technologies into viable infrastructure solutions.

cell should be placed higher on the agenda to reduce the costs of deployment, smooth out the intermittences of renewable energy resources and investigate their integration with Vehicle to Grid technology for stabilizing the grid and redistributing the energy. Integrating the targeted research in these areas will be critical to creating sustainable, resilient and scalable EV charging infrastructure.

CRediT authorship contribution statement

Govindaraj Ramkumar: Writing – original draft, Methodology, Investigation, Funding acquisition. **Sathish Kannan:** Validation, Supervision, Conceptualization. **Vinayagam Mohanavel:** Writing – review & editing, Formal analysis. **S. Karthikeyan:** Writing – review & editing, Formal analysis. **Anita Titus:** Writing – review & editing, Software, Data curation.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data availability

The data used to support the findings of this study are included within the article.

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Further readings

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