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Renewable Energy–Based Electric Vehicle (EV) Charging Infrastructure: Solar/Wind Integrated Systems for Sustainable Transportation - A Review

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Abstract- The rapid growth of electric vehicles (EVs) is creating a strong demand for efficient, reliable, and sustainable charging infrastructure. Conventional grid-based charging systems increase carbon emissions and put heavy load on power systems. Therefore, integration of renewable energy sources such as solar photovoltaic (PV) and wind energy with EV charging infrastructure has become an important research area. This paper presents a comprehensive review of previous research studies related to renewable energy-based EV charging stations. Various aspects such as system design, optimization techniques, energy management strategies, economic feasibility, environmental impact, and technological advancements are discussed in detail. The study also identifies major research gaps and future directions for improving EV charging infrastructure. The review concludes that hybrid renewable energy-based EV charging systems are a promising solution for sustainable transportation, but further improvements are required in control systems, cost reduction, and real-time implementation.

Keywords: Electric Vehicles, Solar Energy, Wind Energy, EV Charging Station, Renewable Energy, Sustainable Transportation.

I. INTRODUCTION

In recent years, the transportation sector has become one of the major contributors to greenhouse gas emissions, especially carbon dioxide (CO₂), which is a primary cause of global warming and climate change. The continuous growth in population, rapid urbanization, and increasing demand for mobility have significantly increased the number of vehicles on roads. Most of these vehicles are powered by fossil fuels such as petrol and diesel, which release harmful pollutants into the atmosphere. This has resulted in serious environmental problems such as air pollution, depletion of natural resources, and adverse health impacts on human beings. Therefore, there is an urgent need to shift towards cleaner and more sustainable transportation systems to reduce environmental degradation and achieve long-term energy security [5], [10], [29].

Electric vehicles (EVs) have emerged as a promising and sustainable alternative to conventional internal combustion engine (ICE) vehicles. EVs operate using electric motors powered by batteries, which eliminate tailpipe emissions and significantly reduce greenhouse gas emissions. In addition to environmental benefits, EVs offer advantages such as higher energy efficiency, lower operating cost, reduced noise pollution, and improved performance. Due to these benefits, governments and policymakers around the world are promoting EV adoption through various incentives, subsidies, and policy frameworks [3], [14], [31].

However, the large-scale adoption of EVs is highly dependent on the availability of efficient, reliable, and accessible charging infrastructure. One of the major challenges faced by EV users is “range anxiety,” which refers to the fear of running out of battery charge due to insufficient charging stations. Traditional EV charging systems mainly rely on electricity supplied from the grid, which in many countries is still generated using fossil fuels such as coal and natural gas. This reduces the overall environmental benefits of EVs and increases the load on power distribution systems, especially during peak demand hours [4], [15], [21].

To overcome these limitations, researchers have focused on integrating renewable energy sources such as solar photovoltaic (PV) systems and wind energy into EV charging infrastructure. Renewable energy-based EV charging systems provide a sustainable solution by utilizing clean and abundant energy resources. Solar energy is one of the most widely used renewable sources due to its availability, low maintenance, and ease of installation. Similarly, wind energy can be used as a complementary source to generate electricity during non-sunny conditions, making hybrid systems more reliable and efficient [7], [22], [28].

Several studies have demonstrated that solar PV-based EV charging stations can significantly reduce greenhouse gas emissions, operational cost, and dependency on fossil fuels. Grid-integrated and standalone PV systems have been widely researched for different applications such as residential charging, commercial charging stations, and university campuses. These systems often include battery energy storage systems (BESS) to store excess energy and ensure continuous power supply during low solar irradiance conditions [1], [11], [26]. Hybrid systems combining solar, wind, and grid supply have also been developed to improve system reliability and performance under varying environmental conditions [17], [22].

In addition to renewable integration, advanced technologies such as Internet of Things (IoT), artificial intelligence (AI), machine learning, and smart energy management systems are being used to optimize EV charging operations. These technologies help in real-time monitoring, load forecasting, demand management, and efficient utilization of available energy resources. Intelligent control strategies such as fuzzy logic, ANFIS, and predictive algorithms have been applied to improve system efficiency and reduce energy losses [6], [12], [16].

Despite significant advancements, several challenges still exist in the development and implementation of renewable energy-based EV charging systems. These include high initial investment cost, intermittency of renewable energy sources, battery storage limitations, lack of standardization, and difficulties in grid integration. Moreover, most of the existing studies are based on simulation models rather than real-time practical implementation, which limits their applicability in real-world scenarios [7], [21], [23].

Therefore, there is a need for a comprehensive review of existing research to understand the current developments, identify limitations, and explore future opportunities in this field. This review paper aims to analyze previous research studies related to solar, wind, and hybrid EV charging systems, focusing on their design, optimization, performance, and sustainability aspects. The paper also highlights key research gaps and suggests future directions for developing efficient, reliable, and cost-effective EV charging infrastructure for sustainable transportation systems.

II. LITERATURE REVIEW

The development of renewable energy-based electric vehicle (EV) charging infrastructure has become a major area of research in recent years due to the increasing demand for sustainable transportation systems and the urgent need to reduce environmental pollution. With the rapid growth in EV adoption across the world, researchers, engineers, and policymakers are focusing on designing efficient, reliable, and eco-friendly charging solutions. Traditional grid-based charging systems are facing several limitations such as high dependency on fossil fuels, increased load on power systems, and higher carbon emissions. To overcome these issues, a large number of studies have explored the integration of renewable energy sources such as solar photovoltaic (PV) systems, wind energy, and hybrid energy systems into EV charging infrastructure [5], [7].

Many researchers have investigated different configurations of EV charging stations, including grid-connected systems, standalone systems, and hybrid systems combining multiple energy sources. Solar PV-based charging stations are widely studied due to the abundant availability of solar energy, low maintenance cost, and ease of installation. These systems are often integrated with battery energy storage systems to ensure continuous power supply and to manage energy fluctuations caused by variable solar irradiance [1], [26]. Similarly, wind energy-based and hybrid solar-wind systems have also been proposed to improve system reliability and ensure uninterrupted charging under different environmental conditions [22], [17]. In addition to system design, significant research has been carried out in the areas of optimization, control strategies, and energy management for EV charging infrastructure. Advanced techniques such as Genetic Algorithms, Fuzzy Logic, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been used to optimize system performance, reduce energy losses, and improve overall efficiency [12], [13], [16]. Furthermore, modern technologies like Internet of Things (IoT), smart grid

integration, and real-time monitoring systems are being implemented to enhance the functionality and intelligence of EV charging stations [15], [27].

Several studies have also focused on techno-economic analysis and environmental impact assessment of renewable energy-based EV charging systems. These studies highlight that although the initial investment cost is high, long-term benefits such as reduced energy cost, lower greenhouse gas emissions, and improved sustainability make these systems economically viable [10], [3]. Researchers have also explored optimal site selection, infrastructure planning, and policy frameworks to support the large-scale deployment of EV charging stations [18], [29]. Despite the significant progress made in this field, there are still several challenges that need to be addressed, including intermittency of renewable energy sources, high cost of energy storage systems, lack of standardization, and limited real-time implementation. Therefore, a detailed review of existing literature is essential to understand the current advancements, identify limitations, and highlight future research directions. In this section, various research studies related to renewable energy-based EV charging infrastructure are reviewed in detail, focusing on system design, optimization techniques, performance analysis, and sustainability aspects.

[1] Kassem et al. (2025) studied PV-grid integrated EV charging stations for university campuses. The system supports multiple charging modes and energy sources like PV, grid, and battery. Results showed good economic feasibility with 5–10 years payback and significant CO₂ reduction.

[2] Saini and Chanda (2025) developed a hybrid Huff model with Genetic Algorithm for optimal EV charging station placement. The model improves accessibility and reduces waiting time. Solar integration reduced grid dependency by around 28%.

[3] Karmakar et al. (2025) analyzed PV-based EV charging under different Indian climates. Solar energy reduced electricity cost significantly. The study proved that solar charging is economical and suitable for Indian conditions.

[4] Elkholy et al. (2025) designed a solar-powered EV charging system with battery and grid backup. HOMER analysis showed high cost savings and reduced emissions. The system is feasible for regions with high solar potential.

[5] Tripathi et al. (2025) reviewed integration of solar PV in EV charging systems. The study highlighted benefits like emission reduction and energy sustainability. Challenges include intermittency and grid integration issues.

[6] Guerrero-Silva et al. (2025) conducted a PCA-based review of EV charging infrastructure. The study emphasized AI and machine learning for optimization. It concluded that intelligent systems improve performance and planning.

[7] Oruganti et al. (2025) reviewed standalone solar EV charging stations. It discussed policies, sizing methods, and system design. The study highlighted importance of MPPT and battery storage for efficiency.

[8] Albaba et al. (2025) presented a real-world PV-based EV charging system in Ireland. The system reduced electricity cost by 50% and achieved high self-consumption. It confirmed practical feasibility of solar EV charging.

[9] Pampana et al. (2025) proposed “Solar District” EV charging concept. It combines charging with community services. The study showed improved sustainability and energy efficiency compared to traditional stations.

[10] Alsharif et al. (2025) analyzed solar-powered EV charging systems economically and environmentally. The system reduced emissions by 87.5%. It proved solar charging is sustainable despite high initial cost.

[11] Alaamri et al. (2025) designed grid-connected PV EV charging station. The system showed high ROI and 7.2-year payback. Net metering improved energy utilization and economic benefits.

[12] Mohan et al. (2025) developed hybrid EV charging using ANFIS control. The system improved power quality and reduced harmonics. It enhanced efficiency and reliability of multi-source systems.

[13] Mouelhi et al. (2025) optimized PV energy use using fuzzy inference system. FIS achieved better efficiency than deterministic method. It increased PV utilization up to 98%.

[14] Nguyen et al. (2024) designed solar EV charging stations for green cities. The system reduced grid dependency and emissions. It supports sustainable urban planning.

- [15] Joseph et al. (2024) integrated EV charging with smart buildings using IoT. The system improved energy management and accessibility. It reduced grid load and enhanced sustainability.
- [16] Patel and Ghuge (2024) proposed predictive energy management for EV charging. It reduces peak load and improves efficiency. The system optimizes energy distribution using forecasting.
- [17] Chaudhari et al. (2024) designed hybrid solar-wind EV charging station. IoT-based monitoring improves control and efficiency. The system ensures reliable charging using multiple sources.
- [18] Naseri et al. (2024) used GIS and AHP for EV station site selection. The study identified optimal locations based on multiple factors. It supports efficient infrastructure planning.
- [19] Singla et al. (2024) designed 4 kW hybrid solar EV charging station. The system used MPPT and multiple operation modes. It reduced grid load and improved reliability.
- [20] Dudi et al. (2024) optimized solar EV charging with fast and slow modes. The system improved flexibility and performance. It enhanced energy utilization and charging efficiency.
- [21] Rashid et al. (2024) reviewed PV-based EV charging infrastructure. The study discussed V2G, storage systems, and challenges. It highlighted need for advanced control systems.
- [22] Manikyalarao et al. (2023) developed hybrid solar-wind EV charging system. It ensures continuous power supply. The system reduces dependence on fossil fuels.
- [23] Sahin and Kurt (2023) optimized grid-supported solar EV charging stations. GA was used to reduce cost and emissions. The system improves energy efficiency.
- [24] Anaji et al. (2023) developed solar EV charging station for Indian cities. It reduces fossil fuel use and emissions. The system supports sustainable urban energy.
- [25] Shafiq et al. (2023) integrated solar charging with power grid. The system reduced energy cost significantly. Smart scheduling improved efficiency.
- [26] Yonis et al. (2023) designed PV-battery EV charging system. ANN and ANFIS improved energy management. The system ensures reliable charging.
- [27] Reddy et al. (2023) developed solar EV charging with IoT control. Optimization improved energy distribution. It enhances efficiency and sustainability.
- [28] Shafiq et al. (2022) studied solar EV charging for security bikes. The system reduced emissions and energy cost. It proved environmental benefits.
- [29] Mokariya (2022) analyzed solar EV charging in India startup ecosystem. The study highlighted challenges and opportunities. It emphasized policy and infrastructure needs.
- [30] Ambavane et al. (2021) designed solar EV charging station for Indian conditions. It reduced grid load and emissions. Proper system design improves efficiency.
- [31] Singh et al. (2021) analyzed solar EV charging in Indian cities. The system reduced CO₂ emissions significantly. It supports green transportation.
- [32] Riful et al. (2021) designed PV-based EV charging for Bangladesh. It reduced grid dependency and emissions. The system is suitable for developing countries.

III. RESEARCH GAP

From the detailed review of previous research studies, it is observed that significant work has been carried out in the field of renewable energy-based electric vehicle (EV) charging infrastructure. Researchers have explored various aspects such as solar PV integration, wind energy utilization, hybrid systems, optimization techniques, energy management strategies, and techno-economic analysis. However, despite these advancements, several important gaps still exist, which need to be addressed for the successful implementation and large-scale adoption of EV charging systems. One of the major research gaps identified is the lack of real-time implementation and practical validation. Most of the studies are based on simulation tools such as MATLAB, HOMER, and PVsyst, which provide theoretical results but do not fully represent real-world conditions. There is a need for more pilot projects and experimental studies to validate system performance under actual operating conditions.

Another important gap is related to the high initial cost of renewable energy-based charging systems. Although solar and hybrid EV charging stations are economically beneficial in the long term, their high installation cost, especially due to photovoltaic panels and battery energy storage systems, limits their adoption. Very few studies focus on cost reduction techniques, financial models, or government policy support to make these systems more affordable. The intermittency of renewable energy sources is also a major challenge. Solar energy is only available during daytime, and wind energy depends on environmental conditions. Although hybrid systems have been proposed, efficient energy management strategies for handling fluctuations and ensuring continuous power supply are still limited. There is a need for advanced control algorithms and hybrid configurations to improve reliability. Another significant gap is the limited development of advanced smart control systems. While some studies have used AI-based techniques such as ANN, fuzzy logic, and ANFIS, their real-time application and integration with EV charging infrastructure are still in early stages. There is a need for more research on intelligent, adaptive, and self-learning systems that can optimize charging operations dynamically.

The issue of grid integration and power quality is also not fully addressed. Integration of EV charging stations with existing power grids can lead to problems such as voltage fluctuation, harmonics, and peak load demand. Many studies discuss this issue but lack detailed solutions for large-scale implementation. Furthermore, standardization and policy framework for EV charging infrastructure is still underdeveloped. Different countries follow different standards, which creates challenges in interoperability and scalability. More research is required in developing universal standards and guidelines. Another gap is related to optimal site selection and infrastructure planning. Although some studies have used GIS and optimization techniques, real-time data-based and dynamic location planning methods are still lacking.

Lastly, there is limited research on user behavior, demand forecasting, and integration with smart cities. Future EV charging infrastructure should be designed considering real-time user demand, traffic patterns, and smart grid interaction. Hence, there is a strong need for further research focusing on real-time implementation, cost reduction, smart control systems, hybrid energy integration, and policy development to make EV charging infrastructure more efficient, reliable, and sustainable.

CONCLUSION

This review paper presents a comprehensive analysis of renewable energy-based electric vehicle (EV) charging infrastructure, focusing on solar photovoltaic (PV), wind energy, and hybrid energy systems. From the study of various research articles, it is clearly observed that integrating renewable energy sources with EV charging stations is a highly effective approach for achieving sustainable transportation and reducing environmental impact. Solar PV-based charging systems are widely used due to their simplicity, availability, and cost-effectiveness, while hybrid systems combining solar, wind, and grid supply provide improved reliability and continuous power supply. The use of battery energy storage systems further enhances system performance by storing excess energy and managing load fluctuations. Advanced technologies such as IoT, artificial intelligence, and smart energy management systems have also contributed significantly to improving efficiency and operational control. The reviewed studies demonstrate that renewable energy-based EV charging systems can reduce greenhouse gas emissions, decrease dependency on fossil fuels, and lower operational costs in the long run. Techno-economic analysis shows that although the initial investment is high, the long-term benefits make these systems economically viable and environmentally sustainable. However, several challenges still exist, including high installation cost, intermittency of renewable energy, limited

real-time implementation, and issues related to grid integration and standardization. These challenges highlight the need for further research and development in this field. In future, research should focus on developing low-cost and efficient systems, advanced control algorithms, real-time monitoring and optimization techniques, and strong policy support. Integration of EV charging infrastructure with smart grids and smart cities will also play a crucial role in improving system performance and user convenience. Overall, renewable energy-based EV charging infrastructure has great potential to transform the transportation sector and contribute to a cleaner, greener, and more sustainable future.

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