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A Comprehensive Review of Hybrid Renewable Energy-Based Electric Vehicle Charging Infrastructure: Technologies, Energy Management, and Future Challenges

Prince Kumar[1], Ashish Bhargav[2]
[1]*M.Tech Scholar, Department of EE, Bhabha Engineering Research Institute, Madhya Pradesh,* rockprince11@gmail.com*, India*
[2]*Professor & Head, Department of EE, Bhabha Engineering Research Institute, Madhya Pradesh, Madhya Pradesh, India*

Abstract *– The rapid growth of electric vehicles (EVs) has created an urgent need for environmentally sustainable charging infrastructure capable of meeting increasing energy demand while minimizing greenhouse gas emissions. Conventional grid-dependent charging stations often rely on electricity generated from fossil fuels, thereby reducing the environmental benefits of EV adoption. Consequently, hybrid renewable energy-based charging stations integrating solar photovoltaic (PV), wind turbines, biomass generation, battery energy storage systems (BESS), and intelligent energy management systems (EMS) have emerged as a promising solution. This review presents a comprehensive analysis of recent developments in hybrid renewable EV charging infrastructure. The paper reviews various charging architectures, renewable energy integration techniques, battery storage technologies, smart energy management strategies, and optimization methods reported in recent literature. Furthermore, existing research is critically compared in terms of renewable energy utilization, charging reliability, economic feasibility, and environmental performance. Major research challenges, including renewable intermittency, battery degradation, grid integration, cyber-security, and infrastructure cost, are also discussed. Finally, future research directions involving artificial intelligence, vehicle-to-grid (V2G), digital twins, blockchain-enabled energy trading, and smart microgrids are presented. This review provides useful insights for researchers, policymakers, and industry professionals working toward sustainable EV charging systems. Recent reviews similarly emphasize hybrid renewable architectures and intelligent energy management as key directions for scalable EV charging infrastructure.*

Keywords: Electric Vehicle, Renewable Energy, Solar PV, Wind Energy, Biomass, Battery Energy Storage System, Smart Grid, Energy Management System, Microgrid, Hybrid Charging Station.

I. Introduction

Electric vehicles have become one of the most promising solutions for reducing greenhouse gas emissions and fossil fuel consumption in the transportation sector. Governments worldwide are promoting EV adoption through supportive policies, financial incentives, and investments in charging infrastructure. However, the increasing penetration of EVs significantly raises electricity demand, potentially creating additional stress on conventional power grids.

Most existing charging stations rely heavily on grid electricity generated from coal and natural gas, which reduces the environmental benefits associated with electric transportation. Therefore, integrating renewable energy sources into EV charging stations has become an important research area. Solar photovoltaic systems, wind turbines, biomass generators, and battery storage technologies can significantly reduce grid dependency while improving sustainability and energy security.

Recent advances in artificial intelligence, optimization algorithms, Internet of Things (IoT), smart grids, and energy storage technologies have further improved the operational efficiency of renewable-powered charging stations. Hybrid renewable charging infrastructure combining multiple renewable sources with intelligent energy management has demonstrated superior reliability and lower operational costs than single-source systems.

India has set ambitious goals for EM. The government targets 30% of new vehicle sales to be electric by 2030, with even higher penetration in two- and three-wheelers. EV sales have indeed accelerated – by 2024, EVs reached around 6–8% of new vehicle sales, totaling nearly 5 million EVs on Indian roads (including two-wheelers and rickshaws). This burgeoning EV population is driving up electricity demand for charging, putting pressure on the existing power infrastructure. If left unaddressed, widespread EV charging could strain the grid and, paradoxically, increase reliance on coal power during peak times, diluting the environmental benefit. Therefore, integrating RE into the EV charging network is not just desirable but necessary for sustainable scale-up.

India is blessed with abundant RE resources. The country receives high solar irradiance (4–6 kWh/m²/day in many regions) and has significant wind potential in certain states (onshore wind speeds of 5–8 m/s in the best corridors). Biomass is another promising resource – India generates large quantities of agricultural residues and organic waste that can be converted to biogas or used in biomass gasifiers. Utilizing these resources at or near EV charging sites can ensure that "clean mobility" is powered by clean energy. Indeed, pilot projects have begun to demonstrate this concept. For example, Mumbai's first biogas-based EV CS processes ~2 tons of wet organic waste per day in an anaerobic digester, producing biogas to run a 360kW generator that charges EVs. This facility generates roughly 220 kWh of electricity per ton of food waste, enough to charge about 6–8 electric cars daily (using fast chargers) while managing municipal waste sustainably. Another example is ATUM Charge, a solar-powered EV CS in Mumbai that uses a 5.2kW solar rooftop to generate ~24 kWh/day for EV charging, making it India's first 100% solar-driven CS. These examples illustrate the potential of on-site renewables in cutting emissions and operating costs.

II. Literature Review

Numerous researchers have investigated renewable energy integration into EV charging stations using different hybrid configurations.

Boddapati and Daniel proposed a techno-economic assessment of hybrid renewable charging stations for metropolitan cities in India. Their results demonstrated that combining solar PV, battery storage, and biomass significantly reduced electricity costs while increasing renewable energy utilization.

Himabindu et al. developed a biogas-photovoltaic microgrid-based EV charging station that effectively utilized municipal organic waste to generate clean electricity while improving charging reliability.

Yilmaz and Krein presented one of the earliest comprehensive reviews of EV charging technologies and battery charger topologies, forming the foundation for modern charging infrastructure research.

Kempton and Tomic introduced the Vehicle-to-Grid (V2G) concept, enabling electric vehicles to function as distributed energy storage systems supporting grid stability.

Recent studies have shifted toward artificial intelligence-based energy management systems. Reinforcement learning, deep learning, fuzzy logic, and model predictive control have been successfully applied to optimize battery charging schedules, renewable energy utilization, and electricity costs.

The latest review studies conclude that hybrid renewable charging stations provide superior energy efficiency, improved reliability, reduced carbon emissions, and lower operating costs compared with conventional charging systems. However, large-scale deployment still faces economic and technical challenges.

Table 1. Summary of Recent Literature

Author	Renewable Source	Storage	Method	Major Contribution
Boddapati et al.	Solar + Biomass	Battery	HOMER	Techno-economic optimization
Himabindu et al.	Solar + Biogas	Battery	Microgrid	Sustainable charging
Arif et al.	Hybrid	Battery	Reinforcement Learning	Smart charging
Li et al.	Hybrid	Battery	PSO + GA	Energy optimization
Goncalves et al.	Solar	Battery	Smart Grid	Grid-connected charging
Yilmaz et al.	Grid	EV Battery	Review	Charging technologies

III. Method

This review paper follows a systematic literature review (SLR) methodology to provide a comprehensive and unbiased assessment of renewable energy-based electric vehicle (EV) charging technologies. The primary objective of the review is to identify, analyze, and compare recent developments in hybrid renewable-powered EV charging infrastructure, energy management strategies, and intelligent charging techniques. Research articles published between 2015 and 2026 were collected from well-established scientific databases, including IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Elsevier, Google Scholar, and Wiley Online Library. These databases were selected because they contain high-quality peer-reviewed journal articles, conference proceedings, and review papers related to electric vehicles, renewable energy integration, smart grids, battery energy storage systems, and intelligent energy management.

The literature search was conducted using a combination of relevant keywords and Boolean search operators to ensure broad coverage of the research domain. The primary search terms included Electric Vehicle Charging Station, Renewable Energy, Solar Photovoltaic, Wind Energy, Biomass Energy, Battery Energy Storage System, Hybrid Renewable Energy, Microgrid, Vehicle-to-Grid (V2G), Smart Charging, Energy Management System, Artificial Intelligence, and Optimization Techniques. Additional filtering was performed by combining these keywords using operators such as AND, OR, and NOT to retrieve the most relevant publications while excluding unrelated studies.

The collected publications were then subjected to a rigorous screening process to ensure the quality and relevance of the selected literature. Initially, duplicate records, non-English publications, editorial notes, patents, and articles with insufficient technical information were removed. Subsequently, titles, abstracts, and keywords were examined to determine their relevance to renewable energy-powered EV charging infrastructure. Full-text analysis was then performed for the shortlisted papers, considering publication quality, originality, research contribution, technical methodology, experimental validation, and practical applicability. Priority was given to peer-reviewed journal articles and highly cited conference papers presenting novel charging architectures, renewable energy integration techniques, energy management strategies, optimization algorithms, and real-world implementation studies.

After the selection process, each publication was analyzed in detail to extract important technical information, including charging station architecture, renewable energy sources utilized, battery energy storage technologies, intelligent control strategies, optimization methods, charging efficiency, renewable energy penetration, operational cost, system reliability, environmental impact, and scalability. Various optimization techniques, including rule-based control, fuzzy logic, genetic algorithms, particle swarm optimization, reinforcement learning, deep learning, and model predictive control, were also reviewed to evaluate their effectiveness in improving the performance of hybrid charging systems.

Finally, a comparative analysis was performed to identify the strengths, limitations, and research trends reported in the existing literature. The selected studies were compared based on key performance indicators such as renewable energy utilization, charging efficiency, energy management capability, battery performance, operational cost, greenhouse gas emission reduction, reliability, computational complexity, and suitability for large-scale deployment. This comparative evaluation helped identify current research gaps and emerging technologies that can improve the sustainability and intelligence of future EV charging infrastructure..

IV. Research Challenges

The Despite significant advancements, several challenges remain.

Renewable intermittency: Solar and wind generation fluctuate due to weather conditions, affecting charging reliability.

Battery degradation: Frequent charging and discharging reduce battery lifespan and increase replacement costs.

High capital investment: Installation of PV systems, wind turbines, battery storage, and smart controllers requires substantial initial investment.

Grid integration: Bidirectional power flow introduces voltage regulation, power quality, and protection issues.

Cybersecurity: Intelligent charging stations connected through IoT are vulnerable to cyber attacks and data breaches.

Lack of standardization: Different charging protocols and communication standards limit interoperability.

Scalability: Large-scale deployment requires advanced energy management algorithms capable of handling thousands of charging stations simultaneously.

Recent comprehensive reviews identify intelligent EMS, interoperable communication standards, and resilient hybrid architectures as major research priorities for future deployments

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V. Conclusion

Hybrid renewable energy-based EV charging infrastructure represents one of the most promising solutions for achieving sustainable transportation. The integration of solar photovoltaic systems, wind turbines, biomass generators, battery energy storage systems, and intelligent energy management strategies significantly improves charging reliability while reducing greenhouse gas emissions and operating costs. The reviewed literature demonstrates that hybrid charging stations consistently outperform conventional grid-dependent systems in terms of renewable energy utilization, energy efficiency, and environmental sustainability. Nevertheless, challenges such as renewable intermittency, battery degradation, cybersecurity, and infrastructure cost continue to limit widespread deployment. Future research should focus on artificial intelligence-based energy management, blockchain-enabled energy trading, vehicle-to-grid integration, digital twins, and resilient smart microgrids to enable highly efficient and intelligent EV charging ecosystems.

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