

Grid-Connected Renewable Energy–Based Electric Vehicle Charging Station

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Abstract: The rapid electrification of road transport is increasing the demand for dependable electric-vehicle (EV) charging infrastructure. Conventional grid-only charging can increase feeder loading, peak demand and dependence on carbon-intensive electricity. Grid-connected renewable-energy charging stations provide an alternative by combining photovoltaic (PV) generation, power electronic converters, optional battery energy storage, intelligent energy management and a utility-grid interface. This literature review synthesizes research on the architecture, operating modes, control methods, grid interaction, energy storage, charging strategies and future directions of renewable-energy-based EV charging stations. Recent reviews consistently identify PV-grid systems as attractive because the grid can maintain charging availability when renewable generation is insufficient, while PV generation can reduce imported energy during periods of solar availability. Research also emphasizes MPPT, bidirectional converters, smart charging, demand response, vehicle-to-grid (V2G), forecasting and optimization. The reviewed results indicate that the most practical near-term architecture is a grid-connected PV station with a coordinated energy-management controller and, where economics justify it, battery storage. Remaining challenges include renewable intermittency, power-quality constraints, high-power fast charging, interoperability, battery degradation, cybersecurity and optimal sizing. The review concludes with a conceptual station architecture and research recommendations for reliable, low-carbon EV charging.

Keywords: Electric vehicle charging station; photovoltaic energy; grid-connected system; renewable energy; MPPT; battery energy storage; smart charging; V2G; energy management

Introduction

The Electric mobility is moving the transport sector toward a closer relationship with the electricity system. The environmental benefit of an EV depends partly on how its electricity is generated; consequently, coupling charging infrastructure with renewable resources is an important pathway toward lower-carbon mobility. Recent literature reviews describe renewable-energy-powered EV charging as a rapidly developing field covering system design, converter topologies, optimization, charging management and grid interaction. A 2024 review concluded that renewable resources have significant potential for supplying EV charging stations, while performance depends on technology selection, site conditions, operating conditions and control design. [1]

Solar PV is particularly suitable for charging stations because generation can be located at the charging site, reducing the amount of energy that must be imported from the distribution network. PV-EV systems can be implemented as standalone, hybrid or grid-connected configurations. The grid-connected configuration is especially useful when continuous charging service is required: when PV

power is inadequate, the grid supplies the deficit; when PV production is high, local renewable power can supply EV demand and, depending on the control strategy, charge stationary storage or support export. A recent comprehensive review of PV-grid charging architectures identifies the grid connection as a practical solution for maintaining supply during low solar availability. [2]

The establishment of a renewable-energy-based EV charging station therefore requires more than installing solar panels beside chargers. It involves coordinated design of the PV generator, DC-DC conversion and MPPT, DC-link regulation, inverter synchronization and power quality, EV charger interface, battery energy storage where applicable, protection, communication and supervisory energy management. The objective is to maximize renewable utilization while maintaining safe charging, acceptable voltage and frequency behavior, limited harmonic distortion, and economically sensible grid power exchange.

Literature Review and System Architecture

Renewable-energy integration

Earlier PV-EV research established the main technical building blocks: PV arrays, DC-DC converters, maximum-power-point tracking, charging control and grid-connected or hybrid interfaces. A widely cited review identified converter topologies and charging/control mechanisms as central themes for both PV-grid and PV-standalone systems. [3] More recent reviews extend this scope to smart charging, storage, V2G and intelligent control. [4, 5].

For a grid-connected station, PV generation is variable because solar irradiance and temperature change throughout the day. MPPT algorithms are consequently required to operate the PV array near its maximum power point. The DC-DC stage provides voltage adaptation and isolates PV operating conditions from the DC-link requirements. The grid-side inverter regulates active and reactive power, maintains synchronization and can be controlled to satisfy power-quality requirements. If storage is installed, the battery can absorb surplus PV power and discharge during charging peaks or low-PV periods, reducing rapid changes in grid demand.

EV charging technologies

EV charging can be broadly organized into AC and DC charging. AC charging generally relies on the vehicle's onboard charger, whereas DC charging supplies controlled DC power directly to the battery through an off-board power converter. For public and high-utilization stations, DC charging can provide higher charging power but also produces greater instantaneous demand on the electrical system. The literature therefore increasingly considers charging power, station capacity, transformer constraints, demand response and smart scheduling together rather than as independent design decisions. [2, 5]

Interoperability is also essential. Charging stations must coordinate electrical protection, communication, connector requirements, battery management and user authorization. Current research additionally considers V2G and vehicle-to-home operation, where bidirectional chargers allow EV batteries to act as distributed energy resources. These functions can provide flexibility, but they require suitable tariffs, communication, battery-degradation models and grid-support controls. [5]

Grid-connected operating modes

A grid-connected renewable charging station normally operates in several modes. In renewable-priority mode, available PV power is directed first toward EV charging. In hybrid mode, PV and the grid jointly supply the charging load. In storage-support mode, surplus renewable energy is stored and later discharged to reduce grid imports. In grid-support or V2G mode, controlled reverse power flow can provide selected services when technical and regulatory conditions permit. Smart energy management selects among these modes according to PV availability, EV state of charge (SOC), charger demand, electricity price, battery SOC, grid limits and user requirements. The literature emphasizes that sophisticated control can increase renewable share and reliability in grid-connected configurations. [1,2]

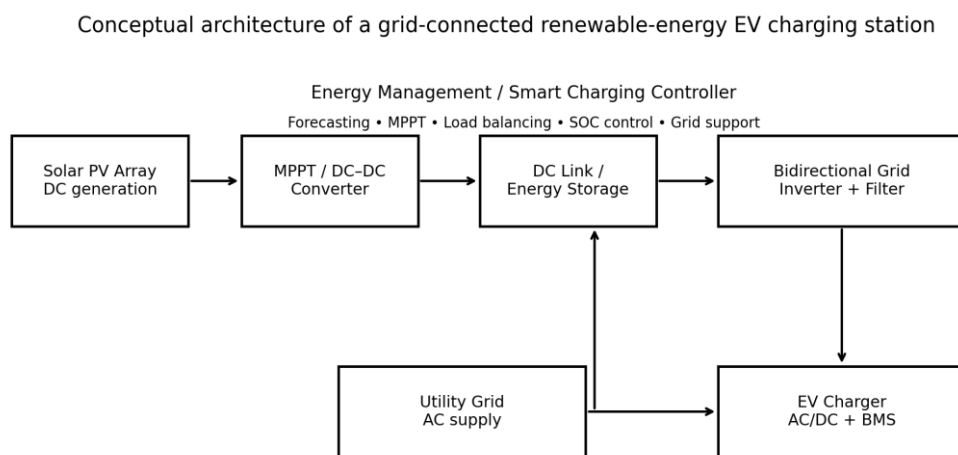


Figure 1. Proposed conceptual architecture for a grid-connected renewable-energy EV charging station

Results and Comparative Synthesis

The reviewed literature shows a consistent progression from simple PV-assisted charging toward integrated, intelligent charging stations. The principal result is that a grid connection and renewable source are complementary rather than competing resources. PV generation can reduce imported electricity when available, while the grid preserves charging continuity when solar production is insufficient. This hybrid arrangement is one reason grid-connected PV-EV architectures are frequently favored over purely standalone systems for dependable public charging. [2]

A second result concerns energy management. Renewable generation is intermittent, whereas EV arrivals, requested charging power and departure times are uncertain. Consequently, fixed charging rules can produce unnecessary peaks or curtail renewable energy. Forecast-assisted scheduling, dynamic charging and demand-response methods are increasingly used to coordinate these uncertainties. Recent reviews identify AI/ML, predictive control and optimization as important emerging approaches for demand forecasting, anomaly detection and real-time charging management. [4,5]

A third result is the growing role of storage. Battery energy storage can buffer the mismatch between PV generation and EV demand, smooth rapid power changes and reduce peak grid imports. However,

storage adds capital cost, conversion losses, thermal management requirements and battery degradation. Thus, storage should not be assumed to be beneficial in every station; its value depends on tariff structure, PV-to-load ratio, charging demand, grid capacity and required reliability. This conclusion is consistent with review studies that classify grid-plus-renewable-plus-storage as a distinct design option rather than a universal solution. [6]

The fourth result is that grid impact must be considered at the station design stage. High-power charging can create large short-duration loads and may affect transformer loading, feeder voltage, losses and power quality. Power converters with appropriate control, filtering and reactive-power capability can mitigate some impacts. Smart charging can further flatten the load profile by shifting flexible charging away from network peaks. Research on EV-grid interaction has long highlighted the challenge of coordinating variable renewable resources with EV charging demand. [7-9]

Finally, V2G offers a potential transition from one-way charging to bidirectional energy services. The vehicle fleet can become a distributed storage resource capable of supporting the grid. However, implementation requires bidirectional hardware, communication standards, appropriate compensation mechanisms and explicit consideration of battery aging. Current reviews also highlight cybersecurity, interoperability and real-time coordination as important barriers to large-scale intelligent charging. [5].

Table 1. Comparative analysis of PV, grid, BESS, V2G

Design option	Main benefit	Main limitation	Literature implication
Grid-only EVCS	High supply availability; simpler renewable interface	Higher grid dependence and peak demand	Useful where renewable resource or site area is limited
PV + grid	Renewable contribution with grid backup	PV intermittency	Strong practical option for reliable public charging
PV + grid + BESS	Peak shaving and higher renewable utilization	Additional cost, losses and degradation	Best when demand peaks and tariffs justify storage
PV + grid + V2G	Bidirectional flexibility and grid services	Battery degradation, standards and control complexity	Promising for future smart-grid integration

Key Research Gaps and Future Scope

The literature indicates five major research directions. First, accurate short-term forecasting of solar generation and EV charging demand is needed for predictive energy management. Second, hybrid storage combining batteries with high-power technologies such as supercapacitors may reduce battery stress during rapid charging transitions. Third, AI-based optimization should be evaluated using real operational data rather than only simulations. Fourth, V2G needs coordinated market mechanisms, interoperable communication and battery-degradation-aware control. [4, 5]

For future projects, researchers should report comparable performance indicators such as renewable-energy utilization, grid-energy reduction, peak-demand reduction, charging efficiency, conversion efficiency, annual energy throughput, battery cycling, cost of energy and emissions reduction.

Reporting these metrics under common weather and charging-demand scenarios would make results across different studies easier to compare.

Conclusion

The literature supports grid-connected renewable-energy-based EV charging stations as a technically promising pathway for combining electric mobility with cleaner electricity. PV generation can reduce grid energy requirements, while the utility connection provides reliability during periods of low renewable output. Energy storage can further improve flexibility and peak management, although its economic value depends on site-specific conditions. Smart charging, predictive control and V2G can transform the station from a passive electrical load into an actively managed energy resource. Overall, the recommended architecture for a practical station is a PV array with MPPT, controlled power converters, a grid-synchronized inverter, EV charging units, optional battery storage and a supervisory energy-management system. The strongest future opportunities lie in predictive and AI-assisted control, coordinated storage, V2G, interoperable communication,. These developments can improve renewable utilization while maintaining charging reliability, power quality and distribution-grid compatibility.

References

- [1] S. S. et al., "Electric vehicle charging by use of renewable energy technologies: A comprehensive and updated review," *Computers and Electrical Engineering*, vol. 118, 109401, 2024.
- [2] Alok Jain, Suman Bhullar, "Operating modes of grid integrated PV-solar based electric vehicle charging system—A comprehensive review," *e-Prime—Advances in Electrical Engineering, Electronics and Energy*, vol. 8, 100519, 2024.
- [3] Abdul Rauf Bhatti, Zainal Salam, Mohd Junaidi Bin Abdul Aziz, Kong Pui Yee, Ratil H. Ashique, "Electric vehicles charging using photovoltaic: Status and technological review," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 34–47, 2016.
- [4] Zia Ullah, Kotb M. Kotb, Mohamed R. Elkadeem, Laiqing Yan, Tahir Khan, Hasan Saeed Qazi, Fazal Badshah, Mohammad A. Abido, "Integrating electric vehicles and renewable energy in modern power systems: A review of EV charging station design, control strategies, and emerging trends," *Ain Shams Engineering Journal*, vol. 16, no. 10, 103592, 2025.
- [5] M. Ranjbar, H. R. Baghaee, and A. Ramezani, "Intelligent electric vehicle charging infrastructure: A comprehensive review of optimization, control, and grid integration strategies for sustainable mobility," *Energy Strategy Reviews*, vol. 64, 102124, 2026.
- [6] Rajanand Patnaik Narasipuram, Subbarao Mopidevi, "A technological overview & design considerations for developing electric vehicle charging stations," *Journal of Energy Storage*, Vol.43, 103225, 2021. DOI: 10.1016/j.est.2021.103225.
- [7] Liansheng Liu, Fanxin Kong, Xue Liu, Yu Peng, Qinglong Wang, "A review on electric vehicles interacting with renewable energy in smart grid," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 648–661, 2015.
- [9] S. G. Motlagh, J. Oladigbolu, and L. Li, "A review on electric vehicle charging station operation considering market dynamics and grid interaction," *Applied Energy*, vol. 392, Art. no. 126058, 2025.
- [10] T. Yuvaraj, K. Devabalaji, J. A. Kumar, S. B. Thanikanti, and N. I. Nwulu, "A comprehensive review and analysis of the allocation of electric vehicle charging stations in distribution networks," *IEEE Access*, vol. 12, pp. 5404–5461, 2024.