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Design and Performance Analysis of Solar-Powered Electric Vehicle Charging Systems

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Abstract

Solar-powered electric vehicle charging systems combine photovoltaic electricity generation with charging infrastructure to reduce dependence on conventional grid electricity. Their performance depends on solar availability, charging demand, component efficiency, energy storage capacity, and the effectiveness of energy management. This article presents a design framework for a grid-connected photovoltaic charging station with optional battery energy storage. It discusses photovoltaic array sizing, charging equipment, power conversion, storage selection, and operational control. An illustrative calculation is used to estimate daily energy production and compare it with charging demand. A hypothetical graph shows the difference between solar generation and vehicle charging demand during the day. The analysis highlights the importance of matching charging schedules with solar availability and using storage or grid support when demand exceeds generation. Economic and environmental considerations are also discussed. The article concludes that the suitability of a solar-powered charging system must be evaluated using local weather data, realistic charging profiles, equipment costs, and applicable grid requirements.

Keywords

Solar photovoltaic energy, Electric vehicle charging, Battery energy storage, Energy management, Sustainable transportation

INTRODUCTION

The expansion of electric vehicles (EVs) creates opportunities to reduce the environmental effects of road transportation. However, the benefits of electric mobility depend partly on how the electricity used for charging is generated. When charging relies heavily on fossil-fuel-based electricity, some emissions are shifted from the vehicle to the power-generation system. Solar photovoltaic (PV) technology offers an opportunity to produce electricity close to the charging location. PV panels can be installed on building rooftops, parking structures, or ground-mounted systems. A solar-powered charging station may operate with a connection to the electricity grid, a battery energy storage system, or both. The integration of solar generation with EV charging

introduces design challenges. Solar output changes throughout the day and varies with weather, while vehicles may arrive at times when generation is low. Charging demand can also vary considerably depending on the number of vehicles, their battery capacity, and the time available for charging. Previous research has identified solar variability, charging demand, storage requirements, and economic feasibility as important considerations in station design ScienceDirect This article presents a conceptual framework for designing and assessing a solar-powered EV charging system. The numerical example and graph are illustrative and do not represent measurements from an operating station.

Solar-Powered Charging System Architecture:

A solar-powered EV charging system generally consists of a PV array, power converters, charging equipment, a control system, and a connection to the grid or a storage battery. The PV array converts sunlight into direct-current electricity. Power electronic devices regulate this electricity and make it suitable for the charging equipment or the grid. In a grid-connected configuration, solar generation supplies charging demand when available, while the grid provides electricity when solar output is insufficient. Surplus generation may be exported to the grid if local regulations and the connection agreement permit it. A battery can also be included to store electricity for use later in the day. The system architecture should be selected according to charging requirements, available space, local grid conditions, and project objectives. A workplace car park may benefit from daytime charging that coincides with solar generation. In contrast, a site with substantial evening demand may require more grid support or energy storage.

Electric Vehicle Charging Equipment:

EV charging equipment must be selected according to the expected vehicles and the time users can spend at the station. Alternating-current charging is often suitable for locations where vehicles remain parked for several hours, such as offices and educational institutions. Direct-current fast charging can supply higher charging power but may require larger electrical connections and more expensive equipment. The total rated power of chargers should not automatically be treated as the expected continuous demand. Charging patterns depend on vehicle arrivals, battery state of charge, charging limits, and user behavior. Nevertheless, the electrical design must consider the possibility of several vehicles charging simultaneously. A station with four 7 kW chargers, for example, has a combined rated charging capacity of 28 kW. If the grid connection or solar generation cannot supply that demand at all times, a load-management system can distribute available power among the connected vehicles.

Battery Energy Storage Integration:

A battery energy storage system can store electricity generated during periods of high solar output and provide it when solar output falls. Storage can also help manage short periods of high demand and reduce the maximum power drawn from the grid, subject to the system's capacity and operating strategy. Battery selection should consider usable energy capacity, power rating, efficiency, depth of discharge, expected lifetime, temperature conditions, and safety requirements. The capacity expressed in kilowatt-hours determines how much energy can be stored, while the power rating in kilowatts determines how quickly it can be delivered. Battery storage does not produce additional energy; it shifts energy from one time to another and introduces charging and discharging losses. Therefore, its value should be compared with its installation, maintenance, and replacement costs. Research on charging stations considers storage particularly relevant when solar generation and charging demand occur at different times. ScienceDirect

Energy Management and Charging Control:

An energy management system coordinates solar generation, vehicle charging, battery operation, and grid electricity. Its purpose may include increasing the use of locally generated solar energy, limiting grid demand, reducing electricity costs, or ensuring that vehicles receive the required energy before departure. A basic control strategy can prioritize solar electricity for EV charging, direct surplus solar generation to the battery, and use grid electricity when the combined solar and battery supply is insufficient. More advanced approaches can incorporate weather forecasts, electricity tariffs, vehicle arrival times, and battery operating limits. For example, a charging schedule can shift flexible workplace charging toward midday when PV generation is often higher. However, charging schedules must respect users' departure times. Research on grid-connected solar charging has examined scheduling as a way to improve the use of photovoltaic electricity while considering changing demand.

Performance Evaluation and Illustrative Analysis:

System performance can be assessed using indicators such as solar energy generation, charging energy delivered, grid imports, battery losses, equipment availability, and operating cost. Two useful indicators are:

Solar self-consumption: the share of PV generation used locally instead of being exported or curtailed.

Solar contribution to charging: the share of charging energy supplied by solar electricity, including electricity delivered through storage where properly accounted for.

The example below uses assumed values for preliminary design. It is an energy estimate, not the result of a field experiment or a complete simulation. Although the daily energy difference is 10 kWh, actual grid imports may be higher. This is because PV generation and charging demand do not necessarily occur at the same time, and batteries and power converters introduce losses. A time-based energy balance is therefore needed to estimate the real solar contribution.

Economic Assessment:

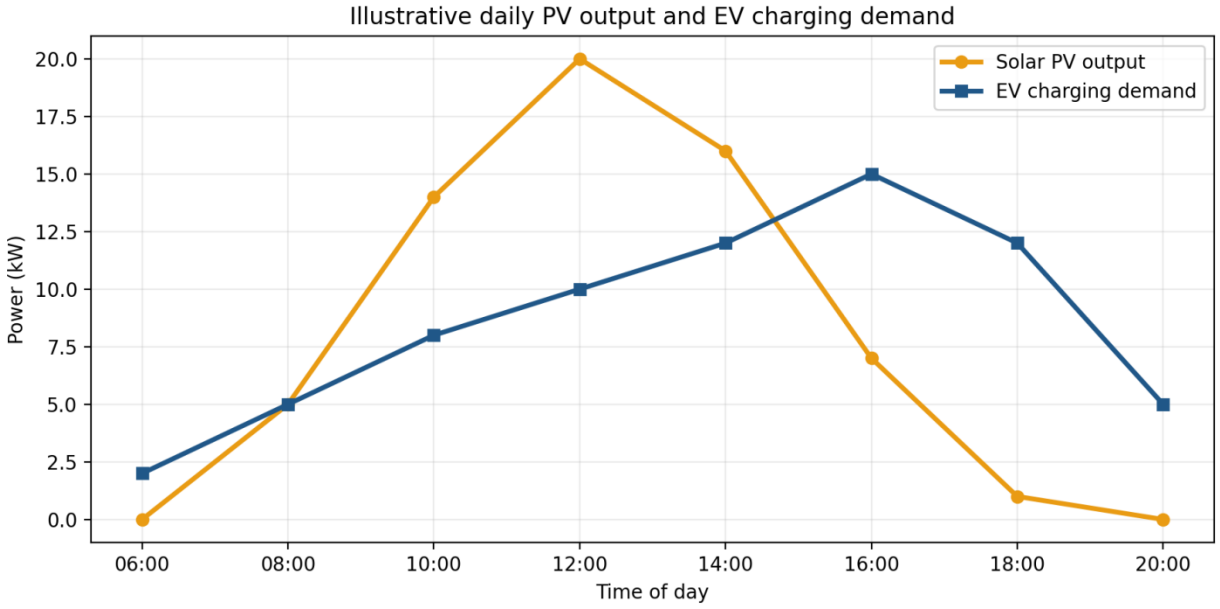
An economic assessment should include the initial cost of PV panels, mounting structures, charging equipment, power converters, batteries, installation, and grid connection. Ongoing costs may include maintenance, insurance, software, electricity purchases, and replacement of components. The economic value of the PV system depends on how much of its electricity can be used at the site, local electricity prices, export compensation, and the timing of demand. Storage may increase the use of solar electricity and reduce peak grid demand, but its financial benefit depends on battery costs, degradation, and the applicable electricity tariff. Common assessment methods include payback period, net present value, and lifecycle cost analysis. The results should be tested under different assumptions about energy prices, vehicle use, and solar output. A study of solar-integrated charging stations in Pakistani cities demonstrates the importance of evaluating technical and economic outcomes for specific locations. ScienceDirect

Environmental Impact and Sustainability:

Solar-powered charging can reduce dependence on grid electricity and potentially reduce emissions associated with vehicle charging. However, the size of the benefit depends on the electricity displaced, the amount of solar energy actually used, and the emissions associated with manufacturing and maintaining the equipment. A lifecycle assessment can consider emissions from PV panels, batteries, charging equipment, transport, installation, and end-of-life processing. Battery recycling and responsible management of electronic components are also relevant to the overall environmental performance of the system. Environmental claims should be based on the local electricity mix and a clear comparison with an alternative scenario. For example, a station using solar electricity during daytime may displace a different mix of generation than a station charging primarily at night.

Challenges and Future Research:

The main technical challenges include variable solar generation, uncertain vehicle demand, limited installation space, grid connection constraints, and the cost of battery storage. Charging stations must also maintain reliable service when the weather is poor or demand is unusually high. Future research can improve forecasting of solar generation and charging demand, develop control methods that protect battery life, and evaluate the interaction between charging stations and local electricity networks. Researchers can also investigate the use of solar carports, bidirectional charging, and coordinated charging across multiple sites. For practical deployment, future studies should use measured charging data and local weather records over extended periods. Comparisons across seasons and different user groups can help determine whether the proposed system performs reliably under real operating conditions.



Hypothetical values for illustration; not measured or simulated data.

Summary:

Solar-powered EV charging systems bring together renewable electricity generation, charging equipment, power conversion, and, where appropriate, battery storage. Their effectiveness depends on the relationship between solar output and charging demand, as well as the technical and economic characteristics of the site. The illustrative example shows that a 25 kW PV system could produce an estimated 90 kWh per day under the stated assumptions. However, daily generation alone does not establish how much charging demand can be supplied by solar power. A detailed evaluation must account for the timing of generation and demand, conversion losses, storage behavior, and grid operation. A well-designed system should combine suitable PV sizing, appropriate charging equipment, reliable controls, and a site-specific financial assessment. Further research based on real operating data is necessary to verify performance and support practical investment decisions.

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