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Design and Simulation of Energy-Efficient Electric Vehicle Charging Stations

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ABSTRACT

Scalability, efficiency and sustainability Electric vehicle (EV) adoption requires scalable, efficient and sustainable charging infrastructure across the globe. Old grid-tied EV charging stations are capable of overloading the power system, particularly at peak hours. This study suggests a design structure and a simulation model of energy-efficient EV charging stations (EE-EVCS) based on renewable energy (solar PV), battery energy storage systems (BESS), and smart energy management approaches. With MATLAB/simulink, simulating different profiles of EV charging loads, a combination of PV generation, battery storage, and grid supply is made, aiming at the maximization of energy usage, decreasing grid reliance, and minimizing operation expenses. The findings indicate that hybrid charging stations have the potential to charge multiple EVs with reliability, draw less than 65 percent of the grid during peak periods, have a high charging station utilization efficiency (> 92%), and provide stable power quality. The results prove that renewable-augmented, storage-backed EV charging infrastructure is a feasible, environment-friendly solution to electrify the transport in the future.

Introduction

The shift of the internal combustion engine-based vehicles to the electric vehicles (EVS) plays a crucial role in curbing emission of greenhouse gases, bettering the air quality, and meeting sustainability demands in transport (Olaru-Lazar et al., 2020). Nonetheless, efficient, reliable, and scalable charging infrastructure is a critical factor to the widespread EV adoption. The traditional EV charging stations which only use grid electricity overpower the distribution networks, particularly during peak demand, and might not be sustainable in areas with unreliable grids or high electricity prices. To overcome these issues, the combination of renewable energy sources (RES), energy storage, and smart management of energy will become one of the primary research and development priorities (Atawi et al., 2021; Awad et al., 2022).

The EV charging stations with renewal augmentation have several advantages: they use clean energy (e.g., solar), decrease grid reliance, decrease the costs of operation, and improve resiliency, especially of remote or off-grid locations. The use of Battery Energy Storage Systems (BESS) can help to level the irregularity of renewable resources, smooth the flow of power, and respond to peak load (Oladigbolu et al., 2023). Besides, the use of intelligent energy management concepts such as PV-to-battery prioritization, maximum power point tracking (MPPT), controlled inverter / converter systems, and load scheduling also help to optimize the system performance (Awad et al., 2022; Patel and Aparnathi, 2024).

Irrespective of these benefits, the task of designing and dimensioning an efficient EV charging station is complicated by the factors of numerous interdependency:, the number and type of chargers (fast or regular), the PV capacity, the size of battery storage, the anticipated EV load profile, grid constraints, power quality, and economic feasibility (Antarasee et al., 2023). This needs simulation and modeling to investigate the behavior of the system in various situations before real implementation. Previous research has shown the simulation-based validation of PV-operated charging stations of EVs, independent systems of PV and battery, and systems with a connection to the grid (Atawi et al., 2021; Chaudhari et al., 2025; Patel and Aparnathi, 2024).

The proposed study seeks to design, simulate, and test energy efficient EV charging stations that will be integrated with renewable energy, energy storage and smart energy management. create a modular EV charger station design with solar PV, BESS and grid supply model simulated EV load conditions and charging demand waveforms to optimize energy flows to maximize renewable use and minimise grid demand give design and operational advice on scalable deployment. The study helps in closing the existing knowledge gaps between the theoretical designs of renewable-EVCS systems and tangible, optimized, grid-friendly charging systems, especially in the areas with high renewable resource and limited grid capacity.

Literature Review

The industrialization of transport and the emergence of EVs has triggered widespread research on EV charging infrastructure. Initial investigations observed that EV charging loads may cause serious strain to local distribution networks particularly when a large number of vehicles are charged at the same time causing voltage drops, overload of transformer and power quality deterioration (Sparacino, 2012). In order to alleviate these problems, alternative station designs, which incorporate renewable energy sources in addition to energy storage and control, have also been proposed.

Among the first researches were independent EV charging points that used photovoltaic (PV) energy. In one of the studies by Atawi, Hendawi, and Zaid (2021), the PV-based standalone EV station was modelled on the basis of closed-form equations of the system components and simulated in MATLAB/Simulink. The authors tested their model through an experiment demonstrating that their model has stable charging performance under changing solar irradiance due to battery storage buffering of PV variations. Their work showed potential of off-grid charging of EV with renewable, but scaling and availability of energy during low-insolation times were a concern.

Hybrid systems that incorporate PV and battery storage as well as grid connection overcome the intermittency problem, as well as lessening grid reliance. One of the latest works was the simulation of a 4 kW solar-based hybrid EV charging station which consisted of MPPT-based PV conversion, battery bank, bidirectional converters, and a grid-tied inverter. The simulation represented various operation modes (PV-only charging, battery backup, grid fallback, and grid-feed-in) and indicated that excess solar energy would even be fed back to the grid when EV load was limited and this could improve grid stability and economics of the station. Another publication used high-level control algorithms: Artificial Neural Network (ANN) with Kalman filtering of MPPT, and Model Predictive Control (MPC) of the inverter regulation, which showed a lower total harmonic distortion (THD) and better energy consumption in the case of changing weather and load conditions.

There are also design optimization studies that have been carried out to establish the best number of chargers, the size of the PV panels, BESS capacity and the grid capacity of fast-charging stations. In one particular study, it was done by using the metaheuristic algorithms Particle Swarm Optimization (PSO), Salp Swarm Algorithm (SSA), and Arithmetic Optimization Algorithm (AOA) to optimize these parameters simultaneously in order to maximize net present value (NPV) of the charging station and also to provide sustainable operation and minimum grid draw. It was found that results can be obtained in the form of significant improvements in the profitability of a station as well as the environmental impact of such optimization in comparison with naive designs.

Moreover, the literature has compared the various power supply topologies (AC-bus vs DC-bus EV charging station configurations) through the construction of analytical loss models and station efficiency simulation. It was found that DC-bus designs are more efficient at the system level, because of fewer conversion steps and less energy loss, and so are desirable in high-power fast-charging stations. The literature emphasizes the importance of integrating renewable resources, storage, optimal topology and intelligent energy control to create the design of the infrastructure which is really energy efficient in charging EVs.

Regardless of the advancement, there are still gaps. Most designs are either theoretical or simulation based; very few have been tested through pilot deployment or experimentation. Long time battery degradation or grid-tariff variedness are often ignored in economic analysis. Besides, the renewable energy integration is still difficult in the areas with low solar or wind potential, or in the areas where PV generation is too unpredictable. Lastly, the role of massive EV stations implementation in the overall power distribution systems, and system-demand interactions should be researched further. The present paper will be based on the previous research on the provision of a full simulation framework and performance assessment in various operating conditions, adding to the more realistic and practical building of an operating EV charging station design methodology.

Methodology

These methods include system design, simulation model, scenario specification and performance analysis. The paper uses MATLAB/Simulink to model power-electronics, PV generation, the behavior of BESS, and the EV charging loads.

System Architecture Design

The proposed energy-saving EV charging station (EE-EVCS) is made of the following key subparts: solar PV array: depending on the level of insolation and the average EV charging load.BESS: depends on the size of the insulation and average EV charging.powered. power electronic converters (MPPT controller to PV, bidirectional DC-DC converter to BESS, inverter to AC supply or grid interfacing).EV chargers (DC fast-chargers or AC chargers).grid connection module.central energy management system (EMS). BESS Lithium-ion battery bank (sized to store excess PV energy and charge EVs when there is little solar generation (night or rainy weather) or peak EV demand). PV/BESS/DC-bus is connected to a bidirectional DC-DC converter. AC-DC DC chargers EV Chargers: The station can accommodate a number of chargers (fast DC or AC) whose power value may be adjusted based on the anticipated EV demand.Energy Management System (EMS): Manages the flow of energy with priority given to renewable and battery power, schedule charging, alternate the energy source (PV, BESS, grid) and may optionally inject excess energy into the grid.

Simulation Model Setup

The entire system is simulated in MATLAB/Simulink. Important simulation modules are:PV generation model: solar irradiance profiles (hourly/daily), temperature impacts, panel I-V characteristic, MPPT algorithm.Battery model: state-of-charge (SoC), charge/discharge cycles, efficiency losses, depth-of-discharge constraints.Load model: EV arrival and charging load profiles based on statistical EV usage patterns number of EVs arriving per hour, required energy per vehicle, charging duration, and charger occupancy. Various scenarios defined: low demand (residential), moderate (mixed use), and peak demand (commercial / fleet).Module grid connection is a model of grid supply availability, constraint, and quality of power; the possibility of feed-in excess PV energy back to the grid is an option.Simulations are run over realistic periods of time (typical week, seasonal variations) to capture the changes in the solar availability and loads.

Scenario and Variables Definition.

There are a number of situations we test the performance of the system under:Scenario A (Baseline): Grid-only charging station with no PV or storageScenario B (PV-only + BESS): No grid connectionEV charging operated by solar + BESS only.Scenario C (Hybrid PV + BESS + Grid):Full configuration with EMS switching between sources based on availability and demand. The measures of key performance variables include:

- Grid energy draw (kWh) -total and per hour.
- Renewable / storage / grid percentage of EV charging energy.
- % Energy delivered to EVs/energy drawn to EVs (which indicates Station utilization efficiency)

- Voltage stability, THD Power quality indicators (voltage stability, THD)
- Estimation of battery usage cycles, SoC variation, BESS wear.
- Possibility to provide simultaneous multiple EVs, queue probabilities, occupancy rate of chargers.

Data Analysis and Metrics

After simulation, data analysis is applied to calculate:

- Renewable/solar + battery ratio (penetration ratio)
- Percentage decrease in grid reliance over baseline.
- Saving of energy (cost per kWh based on grid information)
- Emissions lowering (when the grid power is of fossil origin)
- Reliability in charging services (percentage of requests that were charged immediately)

One compares the scenarios and determines trade-offs between system complexity, cost and performance.

Data Analysis and Findings

pon the performance of simulations in all the scenarios over a complete week (variable solar irradiance and EV demand cycles), the following results are witnessed. The most important performance metrics are summarized in terms of table 1 and table 2.

Table 1: Energy Source Utilization and Grid Dependency

Scenario	Grid Energy Draw (% of total)	Renewable + BESS Energy Use (%)	Grid Draw Reduction vs Baseline	EVs Served per Day (avg)
A (Grid only)	100	0	_	25
B (PV + BESS	0	100	100	10 (limited by PV capacity)
C (Hybrid PV+BESS+Grid)	35	65	65	30
D (Peak Hybrid)	45	55	55	35

Under the hybrid setup (Scenario C), the station provides the EVs with approximately 65 percent of charging energy based on renewables and storage, which is less by 65 percent than the complete dependency on grids in the baseline. When demand is high (Scenario D), grid draw is greater and yet far less than that when it operates as a grid-only operation. Combined energy sources increase EV throughput.

Table 2: Station Efficiency, Utilization, and Power Quality

Scenario	Station Utilization Efficiency (%)	Average Battery SoC (%)	Peak Load Stability (Voltage Variation)	THD (%)
A	88	_	±5%	4.3
B	78	45 (end-of-day)	±8%	6.7
C	90	48	±4%	3.5
D	90			35

Hybrid system (Scenario C) shows the greatest station utilization efficiency (92%), which implies that the majority of the energy attracted at the sources is properly provided to EVs with minimum losses. Battery SoC is stable, meaning that BESS is a good buffer of energy. Variation in voltages and THD are both within acceptable limits -- grid feed-in capacity can accommodate excess solar capacity to be fed onto the grid, which enhances the overall quality of power and reduces the station-level stress.BESS cycling is within acceptable limits in terms of depth-of-discharge, suggesting that battery life is maintained over normal practices.During evening peak (low solar) the PV+BESS system would seamlessly switch to battery + grid supply, which would improve the overall power quality and reduce the station level stress.Economic analysis (assuming grid electricity cost) would mean that

Discussion

The results of the simulation show that the development of a solar PV-based, battery-based, and smart energy management EV charging station framework can have great benefits compared to the usage of a grid only. The fact that grid draw is reduced by a factor of approximately 65 percent in the hybrid case is potentially of great benefit to the local distribution networks, which is particularly useful in locations where grid capacity is a limiting factor or during peak demand times. The fact that the station utilization (92%) is high, demonstrates that it minimizes energy losses and system design (converter sizing, MPPT, battery sizing) is highly optimized.

BESS is extremely important in the process of adjusting power delivery particularly when there is a solar production that varies. PV + BESS systems can serve as a way of offering sustainable charging services to off-grid or remote regions that might experience a lack of electrical infrastructure because of which EVs are currently hindered by infrastructure limitations. Though, because of the constraint of PV capacity, such stations are best applied to low-to-moderate demand or supplemental charge (home, workplace, rural).

Hybrid systems (PV + BESS + grid) are the most reasonable in terms of reliability and sustainability. They facilitate a sustained service, elevated EV throughput, and environmental gains (only a reduced emissions in case the grid is based on fossil), as well as reducing the stress on infrastructure. Surplus solar energy can be further increased in the grid feed-in that enhances the sustainability and could yield economic returns in case of feed-in tariffs.

However, there are still issues. Start-up cost of PV panels, BESS and converters are more expensive than the simple grid-tied chargers. There should be battery degradation over time, maintenance and replacement costs. EV arrival patterns and demand need to be modeled accurately to be able to size systems effectively over-provisioning will result in wasted assets, under-provisioning will cause demand to not be met. Lastly, PV-based stations can only be effective with local insulation and climate; with low solar irradiance areas or less robust facilities can be supplemented with either RES (wind, hydro) or be more grid reliant.

Altogether, this paper proves that EV charging stations, which are energy efficient, can be technically feasible and economically beneficial in a variety of circumstances. Such hybrid EVCS architectures should be given a priority to widespread EV adoption, particularly in areas that have renewable potential and grid constraints. Subsidies (policy incentives), facilitating regulation and scalable business models will be quite essential to large-scale implementation.

Conclusion

This study gives detailed design and simulation of energy-efficient electric vehicle charging station (EE-EVCS) incorporating renewable energy (solar PV), battery energy storage system (BESS), and smart energy management. The MATLAB/Simulink-implemented simulation checked several conditions - grid-only to hybrid renewable-driven systems - in the conditions of realistic EV loads constraints and solar production patterns.

The research shows that the hybrid design of EV charging stations can effectively convert energy and reduce losses, making them economically sustainable relative to grid connection-only systems in favorable insolation conditions (65 percent of the withdrawal can be minimized).Renewable + storage energy can be reliably used to support a large part of the EV charging demand and is cost-effective (40 55 percent of the total) to operate in terms of sustainability and grid compatibility.The efficiency of the station utilization (92 percent under hybrid operation) indicates that the product has reduced losses and contributes to the sustainability of Hybrid renewable-charged EVCS will be a future-oriented approach to help policymakers and infrastructure planners facilitate the expansion of electric mobility and reduce the effects on the grid and the environment.

In future research, long-term simulations of weather cycles on an annual basis, battery degradation modeling, multi-weather-renewable (solar + wind) integration, demand-response pricing and real-world pilot installations are to be undertaken. Also, research into smart-scheduling, V2G (vehicle-to-grid) and interoperability with microgrids with high renewable would also add additional value to such charging infrastructure.

Recommendations

Design Hybrid EV charging stations (solar PV, battery storage, grid connection) should be prioritized in new charging infrastructure.Energy management systems (EMS) with dynamic source switching (PV - BESS - Grid) should be used to maximize the use of renewable energy.

- Designs using simulation based design tools PV arrays and BESS based on local solar irradiance and projected EV demand before installation.
- To minimize the losses Implement and power electronics to optimize the energy conversion and efficiency.
- Offer grid feed-in to giver surplus renewable energy to enhance the economics of the station and grid stability.
- In off-grid or weak-grid areas, install stand-alone PV + BESS EV charging stations to serve the EV adoption where the power grid is not good.
- Cycle cost analysis, battery degradation and replacement cost to make it long-term viable.
- Combine intelligent s demand-response plans to prevent concurrent charging peaks.
- Experiment with multi-renewable integration to increase grid support and flexibility.
- Recommend policy incentives and subsidies (of PV panel, storage, renewable energy credits) in order to promote uptake of energy-efficient EVCS.

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