Optimization of Solar PV–Battery Integrated EV Charging Systems Using Intelligent Simulation Techniques

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ABSTRACT

The present study focuses on the design and performance optimization of a Solar PV–Battery Hybrid Electric Vehicle (EV) Charging System using MATLAB/Simulink. The proposed system integrates a 5-kW photovoltaic array, Maximum Power Point Tracking (MPPT) controller, battery energy storage system, and hybrid energy management strategy to improve renewable energy utilization and charging reliability. The model was developed and evaluated under varying solar irradiance, temperature, EV charging demand, and battery operating conditions for Delhi NCR. Simulation results demonstrated effective power management, stable battery State of Charge (SOC), and enhanced charging performance. The optimized system achieved an average PV output of 2582 W, MPPT output of 2484 W, EV charging power of 3638 W, system efficiency of 97.9%, and renewable energy contribution of 66.8%. The developed framework provides an efficient and sustainable solution for renewable energy-based EV charging infrastructure.

Keywords: *Solar Photovoltaic, Electric Vehicle Charging, Battery Energy Storage, MATLAB/Simulink.*

1. INTRODUCTION

The rapid growth of the transportation sector has increased global concerns related to fossil fuel depletion, greenhouse gas emissions, air pollution, and energy security. Electric Vehicles (EVs) have emerged as a sustainable alternative to conventional internal combustion engine vehicles due to their high energy efficiency, reduced environmental impact, and capability to utilize renewable energy sources. However, the increasing adoption of EVs has created significant challenges regarding the development of reliable, efficient, and environmentally friendly charging infrastructure. Conventional grid-based EV charging systems often depend on electricity generated from non-renewable sources, which limits the overall sustainability of electric mobility. Therefore, the integration of renewable energy technologies, particularly Solar Photovoltaic (PV) systems, into EV charging infrastructure has become an important research area. Solar PV-based charging systems provide clean and decentralized power generation while reducing grid dependency and operational emissions. The combination of solar energy with battery storage systems offers an effective solution to overcome the intermittent nature of renewable energy and ensures continuous charging availability under varying environmental conditions.

A Solar PV–Battery Hybrid EV Charging System integrates photovoltaic panels, Maximum Power Point Tracking (MPPT) controllers, battery energy storage systems, power electronic converters, energy management controllers, and EV charging units to achieve efficient energy utilization. The PV array generates electrical power according to solar irradiance and temperature variations, while MPPT technology improves energy extraction by maintaining operation at the maximum power point of the photovoltaic system. Since solar generation fluctuates due to weather conditions and daily variations, Battery Energy Storage Systems (BESS) play an essential role by storing excess solar energy and supplying power during low-generation periods such as cloudy conditions or nighttime. A Battery Management System (BMS) ensures safe battery operation by monitoring voltage, current, temperature, and state of charge (SOC). Furthermore, an intelligent Hybrid Energy Management System (HEMS) controls power flow between the PV system, battery storage, EV charging load, and utility grid to maximize renewable energy utilization, maintain charging reliability, and improve system efficiency. Advanced simulation platforms such as MATLAB/Simulink provide an effective environment for modeling, analysis, and optimization of these integrated renewable energy systems under different operating conditions.

The optimization of Solar PV–Battery Hybrid EV Charging Systems involves improving energy conversion efficiency, enhancing charging performance, maintaining battery stability, and increasing renewable energy contribution. The proposed research focuses on developing and analyzing a hybrid EV charging model using MATLAB/Simulink by considering important parameters such as solar irradiance, ambient temperature, PV power generation, battery state of charge, and EV charging demand. The optimization process includes solar power estimation, MPPT-based maximum power extraction, battery charging and discharging management, intelligent energy scheduling, and performance evaluation. The developed system aims to provide a sustainable charging solution capable of reducing dependence on conventional energy sources while supporting the expansion of electric mobility. By integrating renewable energy generation with advanced storage and control techniques, the proposed Solar PV–Battery Hybrid EV Charging System can improve charging reliability, reduce operational costs, and contribute toward environmentally sustainable transportation infrastructure. The outcomes of this study provide valuable insights into the design, simulation, and performance optimization of future renewable energy-based EV charging networks.

2. REVIEW OF LITERATURE

Mohanty et al. (2026) had investigated hybrid energy storage integration in grid-connected PV-based microgrids for EV charging applications. The study proposed an advanced power management strategy using a sliding Fourier-based PLL for improved synchronization and energy flow control. MATLAB/Simulink and OPAL-RT validation demonstrated effective DC bus regulation, grid stability, and faster synchronization performance.

Güven et al. (2025) had analyzed hybrid renewable energy systems for EV charging stations using HOMER Pro simulations in the Çukurova region of Turkey. Multiple configurations involving PV, wind, biomass, hydrogen storage, and batteries were evaluated. The results identified a PV-biomass-hydrogen-based system as the most economically feasible solution with improved reliability and energy sustainability.

AbdElrazek et al. (2024) had studied an optimized hybrid renewable energy system combining solar PV, wind energy, and battery storage for EV charging stations. Using HOMER simulation, the research evaluated system sizing, operational performance, and economic feasibility. The proposed configuration achieved higher renewable energy utilization, reduced energy costs, and improved charging reliability.

Bourenane et al. (2023) had explored solar-assisted electric vehicles with hybrid battery-supercapacitor energy storage to improve vehicle energy management. The study developed an artificial neural network-based controller for traction energy optimization. Simulation outcomes confirmed enhanced power distribution, reduced battery stress, and improved energy efficiency for urban electric vehicle applications.

Alsharif et al. (2022) had investigated energy management strategies for renewable-based microgrid systems incorporating EV charging and Vehicle-to-Grid technology. The study focused on minimizing operational costs and system losses while maximizing renewable energy utilization. MATLAB-based optimization results demonstrated improved energy scheduling, efficiency enhancement, and effective bidirectional power exchange.

Boström et al. (2021) had explored the synergy between photovoltaic energy and electric vehicles through a conceptual PV-EV integration framework. The study highlighted vehicle-to-grid (V2G) technology as a solution for solar intermittency by utilizing parked EVs as storage resources. The findings suggested that PV and EV integration could support a fully renewable energy system.

3. RESEARCH METHODOLOGY

The present research methodology focuses on the design, modelling, simulation, and performance optimization of a Solar PV–Battery Hybrid Electric Vehicle (EV) Charging System using MATLAB/Simulink. The increasing adoption of electric vehicles requires sustainable charging solutions that can reduce dependence on conventional grid electricity and minimize environmental impacts. In this study, a renewable energy-based charging framework has been developed by integrating a solar photovoltaic (PV) system with battery energy storage and an intelligent energy management approach. A quantitative simulation-based research methodology has been adopted to evaluate system performance under different climatic and operational conditions. The proposed system considers a 5 kW solar PV array, Maximum Power Point Tracking (MPPT) controller, battery energy storage system, hybrid energy management controller, and EV charging load. MATLAB R2017b and Simulink platforms were used for mathematical modelling, system implementation, and dynamic performance analysis. The simulation approach provides flexibility to investigate different operating scenarios, reduces experimental complexity, and enables detailed evaluation of solar power generation, charging performance, battery stability, and renewable energy contribution. Monthly solar irradiance and temperature data of Delhi NCR were incorporated as input parameters to assess annual system behaviour under realistic environmental conditions.

Table 1: Geographic Characteristics of Delhi NCR

Parameter	Value
Study Area	Delhi NCR
Latitude Range	28.40°N – 28.90°N
Longitude Range	76.80°E – 77.50°E
Average Annual Solar Irradiance	676 W/m²
Temperature Range	14°C – 39°C
Average Annual Temperature	27.1°C
PV System Capacity	5 kW
Simulation Platform	MATLAB R2017b & Simulink

The research framework was developed through multiple stages, including data acquisition, system modelling, MATLAB GUI development, Simulink implementation, and performance evaluation. Environmental parameters such as solar irradiance and ambient temperature, along with operational parameters including EV charging demand, battery support power, initial battery State of Charge (SOC), and MPPT efficiency, were collected and applied as simulation inputs. Delhi NCR was selected as the study area due to its significant solar potential, increasing EV adoption rate, and seasonal climatic variations. The collected data represented solar irradiance variation from 500 W/m² to 980 W/m², temperature fluctuations between 14°C and 39°C, EV charging demand ranging from 3000 W to 4200 W, and battery support power of 1500 W. The developed mathematical model included PV power estimation, MPPT-based maximum power extraction, battery charging and discharging behaviour, hybrid power management, system efficiency calculation, and renewable energy share analysis. The MPPT controller was incorporated to continuously track the optimal operating point of the PV array and improve solar energy utilization. The battery model was designed to maintain charging reliability by storing excess solar energy and supplying power during periods of insufficient solar generation.

The complete hybrid EV charging system was implemented in MATLAB Simulink for dynamic performance evaluation under varying environmental and load conditions. A MATLAB-based graphical user interface (GUI) was developed to provide user-controlled simulation and visualization of important system parameters, including PV output power, MPPT power, EV charging power, battery SOC, renewable energy contribution, and overall system efficiency. The hybrid energy management system was designed to optimize power distribution between solar PV generation, battery storage, EV charging demand, and grid support when required. The mathematical optimization model aimed to maximize EV charging power, system efficiency, renewable energy utilization, and battery stability while minimizing power losses and unnecessary grid dependency. Performance evaluation was carried out using parameters such as PV generation capability, MPPT efficiency, battery operational behaviour, charging reliability, and renewable energy share. The developed methodology provides an effective framework for analyzing and optimizing renewable energy-based EV charging infrastructure and supports the development of sustainable transportation systems under real-world climatic conditions.

4. SIMULATION AND RESULT

The simulation and performance evaluation of the proposed Solar PV–Battery Hybrid Electric Vehicle (EV) Charging System were carried out using MATLAB/Simulink to analyse the operational behaviour under different climatic and load conditions. The developed model was evaluated using yearly solar irradiance, ambient temperature, EV charging demand, battery support power, and MPPT efficiency parameters corresponding to Delhi NCR climatic conditions. The main objective of the simulation was to examine the effectiveness of the hybrid energy management strategy in improving renewable energy utilization, maintaining stable EV charging, and optimizing battery performance. A 5 kW solar photovoltaic system integrated with a battery energy storage unit and MPPT controller was modelled to assess important performance indicators, including PV power generation, MPPT output power, hybrid power availability, EV charging power, battery State of Charge (SOC), renewable energy contribution, and overall system efficiency. MATLAB GUI and Simulink-based modelling provided an effective platform for real-time visualization and dynamic analysis of the proposed system. Python-based statistical analysis was also performed to validate simulation outcomes through correlation analysis and graphical representation of different performance parameters.

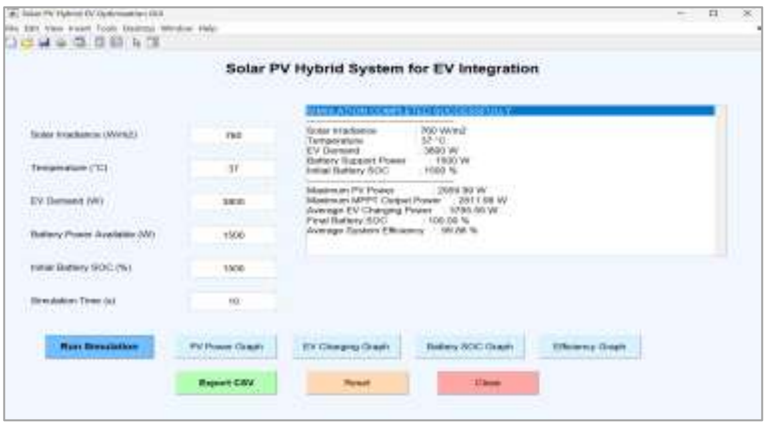

Figure 1: Solar PV EV Optimization GUI

The MATLAB simulation results demonstrated that the proposed hybrid charging system effectively utilized solar energy under varying seasonal conditions. The monthly analysis showed a strong relationship between solar irradiance and photovoltaic power generation. The highest performance was observed during May, when the average solar irradiance reached 980 W/m², producing an estimated PV power output of 3749 W and MPPT output power of 3674 W. During this period, the EV charging power reached the maximum rated value of 5000 W with 100% system efficiency and a renewable energy contribution of 73.5%. In contrast, the lowest performance occurred during July due to reduced solar availability caused by monsoon conditions. The PV output decreased to 1867 W, while MPPT output reduced to 1774 W, resulting in lower EV charging power of 3274 W and system efficiency of 74.4%. Despite seasonal variations, the battery storage system successfully maintained charging continuity by compensating for fluctuations in solar power generation. The annual evaluation showed an average solar irradiance of 676 W/m², average PV output power of 2582 W, average MPPT output of 2481 W, and average EV charging power of 3983 W. The system achieved an average efficiency of 86% with a renewable energy share of 61.9%, indicating that a significant portion of EV charging demand was satisfied through clean solar energy.

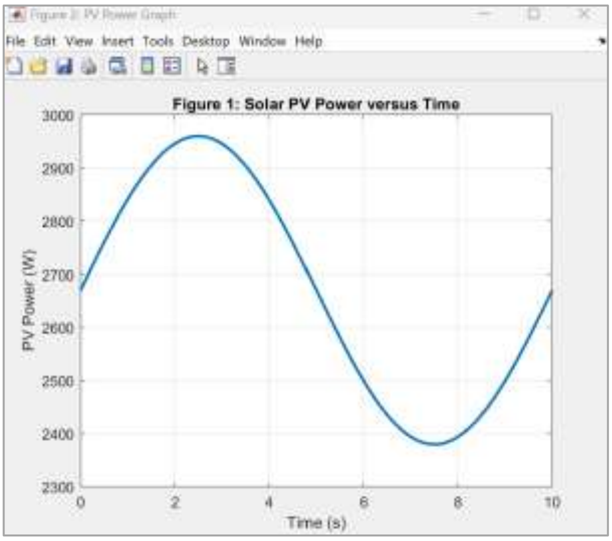

Figure 2: Solar PV Power Time Graph

Further optimization analysis was performed to evaluate the performance enhancement achieved through the hybrid energy management system. The optimized model considered monthly variations in solar irradiance, temperature, EV demand, battery support power, initial SOC, MPPT efficiency, and PV capacity. The simulation results confirmed that the MPPT controller effectively extracted maximum available solar energy throughout the year, with efficiency values ranging between 95% and 98%. The optimized system achieved the highest renewable energy contribution in May, reaching 83.9%, while the lowest contribution was recorded in July at 53.2%. The hybrid power generation reached a maximum value of 5000 W during peak solar conditions, allowing the system to satisfy higher EV charging requirements. The battery energy storage system played a significant role in balancing power fluctuations and maintaining reliable charging operation. The battery SOC remained within a stable range between 72.8% and 84.5%, demonstrating effective charging and discharging management. The optimized annual performance analysis revealed an average PV power of 2582 W, MPPT output of 2484 W, usable PV power of 2384 W, hybrid power availability of 3884 W, and average EV charging power of 3638 W. The optimized system achieved an average efficiency of 97.9% and renewable energy share of 66.8%, showing significant improvement in energy utilization and charging reliability.

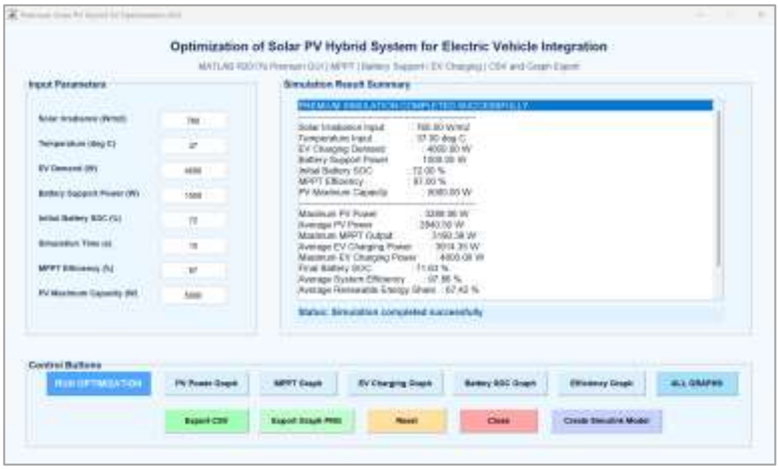

Figure 3: Premium Solar EV Optimization GUI

The dynamic performance of the proposed system was further examined through MATLAB/Simulink graphical outputs. The PV power variation graph demonstrated smooth fluctuations corresponding to changing solar conditions while maintaining stable energy generation. The MPPT output closely followed PV power variations, confirming the capability of the controller to continuously track the maximum power point and minimize energy losses. The EV charging power profile remained almost constant around the required charging level, indicating effective coordination between solar generation, battery support, and charging demand. Temporary reductions in charging power during low solar availability were successfully managed through battery assistance provided by the hybrid energy management system. The battery SOC profile remained stable throughout the simulation period, indicating balanced energy storage operation and protection against excessive charging or discharging. The system efficiency graph showed that the optimized hybrid system maintained high efficiency throughout the simulation period, with only minor reductions during transient operating conditions. The developed MATLAB Simulink model successfully integrated PV generation, MPPT control, battery storage, power management, and EV charging load to provide a reliable renewable energy-based charging solution.

Python-based performance optimization and validation were conducted using Pandas, NumPy, and Matplotlib libraries to analyse simulation-generated datasets. The monthly values of PV power, MPPT output, hybrid power, EV charging power, renewable energy share, system efficiency, and battery SOC were statistically evaluated. The correlation analysis indicated a strong positive relationship between PV power, MPPT output, and hybrid power generation, confirming efficient maximum power extraction and energy management. PV power and renewable energy share showed a high positive correlation, indicating that increased solar availability directly improved renewable contribution to EV charging. The graphical analysis demonstrated that PV power and MPPT output followed similar seasonal trends, increasing from January to May and decreasing during monsoon months before recovering later in the year. Hybrid power and EV charging power also followed solar availability patterns while maintaining stable charging performance through battery support. The overall results validated the effectiveness of the proposed Solar PV–Battery Hybrid EV Charging System in achieving high efficiency, reliable charging operation, improved renewable energy utilization, and reduced dependency on conventional grid sources. The developed simulation framework provides a practical approach for future renewable energy-based EV charging infrastructure development.

5. CONCLUSION

The present research successfully developed and evaluated a Solar PV–Battery Hybrid Electric Vehicle (EV) Charging System using MATLAB/Simulink to enhance renewable energy utilization and improve charging reliability under varying climatic conditions. The proposed system integrated a 5 kW solar photovoltaic array, MPPT controller, battery energy storage system, and hybrid energy management strategy to optimize power flow between renewable generation, storage, and EV charging demand. The simulation results demonstrated that the developed system effectively managed seasonal variations in solar irradiance and temperature while maintaining stable EV charging performance. The optimized system achieved an average PV power output of 2582 W, MPPT output of 2484 W, average EV charging power of 3638 W, system efficiency of 97.9%, and renewable energy contribution of 66.8%. The battery storage system successfully maintained stable SOC levels, ensuring continuous charging operation during periods of reduced solar availability. The highest performance was observed during May due to maximum solar irradiance, while reduced output during monsoon conditions was effectively compensated through battery support. Python-based statistical analysis further validated the simulation results by confirming strong correlations among PV generation, MPPT performance, hybrid power availability, and renewable energy share. Therefore, the proposed Solar PV–Battery Hybrid EV Charging System provides an efficient, sustainable, and reliable solution for future renewable energy-based electric mobility infrastructure.

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