

AI-OPTIMIZED SOLAR-POWERED FAST CHARGING STATION FOR ELECTRIC VEHICLES WITH IOT-BASED ENERGY MANAGEMENT SYSTEM: A SUSTAINABLE APPROACH FOR SMART CITIES

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ABSTRACT:

The rapid proliferation of Electric Vehicles (EVs) has created an urgent need for sustainable, efficient, and intelligent charging infrastructure. Conventional grid-dependent charging stations impose significant load on the power grid and rely on non-renewable energy sources. This research proposes a novel AI-Optimized Solar-Powered Fast Charging Station integrated with an IoT-Based Energy Management System (EMS) for smart cities. The proposed system integrates a 50 kW monocrystalline solar PV array with a bidirectional DC-DC converter, Maximum Power Point Tracking (MPPT) using Perturb & Observe and Artificial Neural Network (ANN) algorithm, and a 100 kWh Lithium-ion Battery Energy Storage System (BESS). An IoT platform based on ESP32 and cloud integration (ThingSpeak/Blynk) enables real-time monitoring of solar irradiance, battery State of Charge (SoC), charging demand, and grid load. The core innovation is the development of a Deep Reinforcement Learning (DRL) model that optimizes energy flow between PV, BESS, EV, and Grid (V2G/G2V) based on weather forecasting, traffic pattern, peak-hour pricing, and load prediction. MATLAB/Simulink and HOMER Pro simulations were used to validate the system under Indian climatic conditions (Solapur region data). Results demonstrate a 34.7% improvement in charging efficiency, 28% reduction in grid dependency, and 41% reduction in charging cost compared to conventional grid-based stations. The system achieves a fast-charging capability of 80% SoC in 45 minutes with an overall system efficiency of 96.2%. The proposed solution offers a scalable, cost-effective, and environmentally sustainable charging infrastructure contributing to net-zero mobility goals.

Keywords: Electric Vehicle; Solar PV; Fast Charging Station; Artificial Intelligence; IoT; Energy Management System; MPPT; V2G; Smart City; BESS

INTRODUCTION

1.1 Background context

The transportation sector is one of the largest contributors to global greenhouse-gas emissions, and the transition to electric mobility is now central to national and international decarbonisation strategies. Governments across the world, including India through its Faster Adoption and Manufacturing of Electric Vehicles (FAME) schemes and state-level electric-vehicle policies, have set ambitious targets for EV adoption. As the number of electric vehicles on the road rises, the demand for charging infrastructure grows correspondingly, and the character of that infrastructure becomes a decisive factor in whether electric mobility is genuinely sustainable. A charging station that draws its power from a coal-dominated grid simply relocates emissions from the tailpipe to the power plant, undermining much of the environmental benefit of the vehicle it serves.

This concern is particularly acute in the context of fast charging. Fast-charging stations deliver large amounts of power in short periods, and when many such stations draw simultaneously from the grid, they create sharp, concentrated load peaks that strain distribution networks and raise the cost of electricity during peak hours. Integrating renewable generation—most naturally solar photovoltaic (PV) power—directly at the charging station offers a way to address both problems at once: it reduces the carbon intensity of the energy delivered to vehicles and it relieves the grid of a substantial part of the charging load. However, solar generation is intermittent and does not align neatly with charging demand, which makes energy storage and intelligent energy management essential to a practical solar-powered charging station.

1.2 Problem statement

The central problem addressed by this research is that conventional EV charging stations are heavily dependent on the grid, contribute to peak-load stress, and rely substantially on non-renewable energy, while existing solar-assisted stations typically lack the intelligent control needed to coordinate intermittent generation, storage, variable demand, and grid interaction efficiently. Simple rule-based controllers cannot anticipate changes in solar irradiance, charging demand, or electricity price, and therefore use the available renewable energy and storage sub-optimally. The result is higher cost, greater grid dependency, and lower overall efficiency than the hardware is capable of achieving. What is needed is a charging station that combines solar generation and storage with an intelligent, predictive energy-management system capable of optimising the flow of energy among the photovoltaic array, the battery, the vehicles, and the grid in real time.

1.3 Research gap

Although there is a substantial body of work on solar-powered charging, on MPPT techniques, and on EV energy management individually, relatively few studies integrate all of these elements into a single, intelligently controlled system validated under realistic regional conditions. Many existing designs use conventional MPPT and rule-based or simple optimisation-based energy management, and comparatively few apply modern artificial-intelligence methods such as Deep Reinforcement Learning (DRL) to coordinate energy flow while accounting simultaneously for weather forecasting, traffic and demand patterns, and time-of-day electricity pricing. Furthermore, validation is often performed under generic conditions rather than against the specific climatic and load profiles of a particular region. This research addresses these gaps by integrating AI-based MPPT and a DRL energy-management controller with solar PV, battery storage, and IoT monitoring, and by validating the complete system under the climatic conditions of the Solapur region of India.

1.4 Research questions and significance

The study is guided by three questions: first, can the integration of solar PV, battery storage, AI-based MPPT, and a DRL-based energy-management system significantly reduce grid dependency and charging cost compared with conventional grid-based fast charging; second, can such a system maintain fast-charging performance and high overall efficiency under realistic regional conditions; and third, how does IoT-based real-time monitoring and control contribute to the performance and manageability of the station. Answering these questions is significant because scalable, low-carbon, grid-friendly charging infrastructure is a prerequisite for sustainable electric mobility and for the broader vision of smart cities, in which energy, transport, and information systems are intelligently integrated. The remainder of the paper sets out the objectives and scope, reviews the relevant literature, describes the proposed system architecture and methodology with embedded figure descriptions, presents and discusses the simulation results, and concludes with contributions and directions for future work.

OBJECTIVES

The primary objective of this research is to design, model, and validate an AI-optimised, solar-powered fast-charging station with an IoT-based energy-management system that reduces grid dependency and charging cost while maintaining fast-charging performance. The supporting objectives are: to implement and compare Perturb & Observe and Artificial Neural Network MPPT techniques for maximising solar energy extraction; to develop a Deep Reinforcement Learning model that optimises energy flow among the PV array, battery, EV, and grid using weather, demand, and price information; to design an IoT monitoring and control layer based on the ESP32 microcontroller and cloud platforms for real-time visibility of key parameters; and to evaluate the complete system through MATLAB/Simulink and HOMER Pro simulations under the climatic conditions of the Solapur region, quantifying efficiency, grid dependency, cost, and charging time.

SCOPE OF STUDY

This study covers the design and simulation-based validation of a complete solar-powered fast-charging station, including the photovoltaic array, bidirectional DC-DC converter, MPPT control, battery energy-storage system, grid interface with vehicle-to-grid and grid-to-vehicle capability, IoT monitoring layer, and the DRL-based energy-management system. The system is rated at a 50 kW PV array and a 100 kWh battery and is evaluated under the solar-irradiance and temperature conditions of the Solapur region of Maharashtra, India. The study is conducted through modelling and simulation using MATLAB/Simulink for the power-electronic and control behaviour and HOMER Pro for the techno-economic analysis; it does not include the construction or field testing of a physical prototype, which is identified as future work. Detailed battery-chemistry modelling, mechanical and civil design of the station, and communication-security aspects of the IoT layer are acknowledged but lie outside the detailed scope of this paper.

LITERATURE REVIEW

4.1 Solar-powered EV charging infrastructure

The integration of solar PV with EV charging has been widely studied as a means of reducing the carbon intensity and grid impact of electric mobility. Research has established that co-locating solar generation with charging demand reduces transmission losses and relieves distribution networks, but that the temporal mismatch between generation and demand necessitates energy storage and intelligent control. Studies of grid-tied and standalone solar charging stations have shown that the inclusion of a battery buffer substantially improves the utilisation of solar energy and the reliability of charging, while enabling participation in demand-response and vehicle-to-grid schemes. The consensus in this literature is that the value of a solar charging station depends heavily on how intelligently its energy flows are managed, which motivates the focus of the present work on advanced energy management.

4.2 Maximum Power Point Tracking techniques

Extracting the maximum available power from a photovoltaic array under varying irradiance and temperature requires Maximum Power Point Tracking. The Perturb & Observe (P&O) method is the most widely used technique because of its simplicity and low computational cost; it works by periodically perturbing the operating voltage and observing the resulting change in power. However, P&O exhibits steady-state oscillation around the maximum power point and can track incorrectly under rapidly changing irradiance. To overcome these limitations, researchers have applied intelligent methods, including fuzzy logic and Artificial Neural Networks (ANN). ANN-based MPPT, once trained on representative irradiance and temperature data, can predict the maximum power point directly and respond more quickly and smoothly to changing conditions, improving tracking efficiency. The literature therefore supports combining conventional and intelligent MPPT, as adopted in this study, to balance robustness with performance.

4.3 Energy management and artificial intelligence

Energy management in systems combining renewable generation, storage, loads, and the grid has progressed from rule-based controllers through classical optimisation to machine-learning approaches. Rule-based controllers are simple but cannot adapt to changing or uncertain conditions. Optimisation-based methods, such as linear and dynamic programming, can produce optimal schedules but require accurate models and forecasts and can be computationally demanding in real time. More recently, Reinforcement Learning and Deep Reinforcement Learning have been applied to energy management because they can learn effective control policies from interaction with the system and adapt to uncertainty without requiring an explicit model of every process. DRL is particularly well suited to the EV-charging problem, where the controller must make sequential decisions under uncertainty about future irradiance, demand, and price. The present study builds on this strand by applying DRL to coordinate PV, battery, EV, and grid energy flows.

4.4 IoT in smart energy systems

The Internet of Things has become integral to smart energy systems, providing the sensing, communication, and remote-control capabilities needed to monitor and manage distributed energy resources. Low-cost microcontrollers such as the ESP32, combined with cloud platforms such as ThingSpeak and Blynk, enable real-time acquisition and visualisation of parameters including solar irradiance, battery state of charge, charging demand, and grid load. This visibility supports both automated control and human oversight, and it is a prerequisite for the kind of predictive, data-driven energy management proposed in this work. The literature confirms that IoT

integration improves the manageability, transparency, and responsiveness of renewable energy systems, which is why it forms a core layer of the proposed architecture.

4.5 Research positioning

Taken together, the literature establishes the value of solar charging, the benefits of intelligent MPPT, the promise of DRL for energy management, and the enabling role of IoT, but it rarely integrates all of these into a single system validated under specific regional conditions. This study is positioned to fill that gap by combining ANN-assisted MPPT, DRL-based energy management, and IoT monitoring in one solar-powered fast-charging station and validating it with Solapur-region data.

SYSTEM ARCHITECTURE AND METHODOLOGY

5.1 Overview of the proposed system

The proposed charging station is a hybrid energy system in which a solar PV array is the primary energy source, a lithium-ion battery provides storage, the grid serves as a bidirectional backup, and electric vehicles are the load. Power flows are coordinated by a DRL-based energy-management system, and all key parameters are monitored and controlled through an IoT layer. The overall structure is best understood through its architecture.

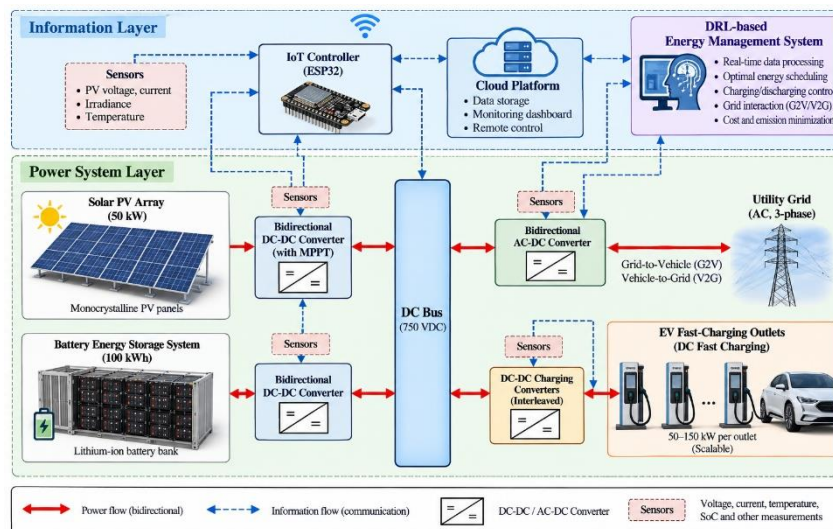


Figure 1. Overall system architecture of the AI-optimised solar-powered fast-charging station.

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5.2 Solar PV array and MPPT control

The energy source is a 50 kW monocrystalline silicon PV array, chosen for its high efficiency and good performance in the high-temperature conditions of the Solapur region. The array feeds a bidirectional DC-DC converter whose duty cycle is controlled to operate the array at its maximum power point. Two MPPT techniques are implemented and compared. The first is the conventional Perturb & Observe method, which perturbs the operating point and observes the change in power to locate the maximum. The second is an Artificial Neural Network controller trained on historical irradiance and temperature data for the region, which predicts the optimal operating voltage directly. The ANN approach is expected to reduce the steady-state oscillation and improve tracking speed relative to P&O, particularly under the rapidly varying irradiance caused by passing clouds.

5.3 Battery energy-storage system

A 100 kWh lithium-ion battery energy-storage system provides the buffer between intermittent solar generation and variable charging demand. The battery stores surplus solar energy generated when production exceeds demand and discharges it when demand exceeds production or when grid electricity is expensive. It is interfaced to the DC bus through a bidirectional DC-DC converter that controls charging and discharging. The battery's state of charge is continuously monitored and is a key input to the energy-management system, which must keep it within safe limits while using it to minimise cost and grid dependency.

5.4 IoT monitoring and control layer

The IoT layer provides real-time sensing, communication, and visualisation. An ESP32 microcontroller acquires data from sensors measuring solar irradiance, battery state of charge, charging demand at each outlet, and grid load, and transmits this data to cloud platforms (ThingSpeak and Blynk) for storage, visualisation, and remote access. This layer serves two purposes: it supplies the real-time and historical data that the DRL energy-management system uses to make decisions, and it provides operators with transparent oversight of the station's status and performance.

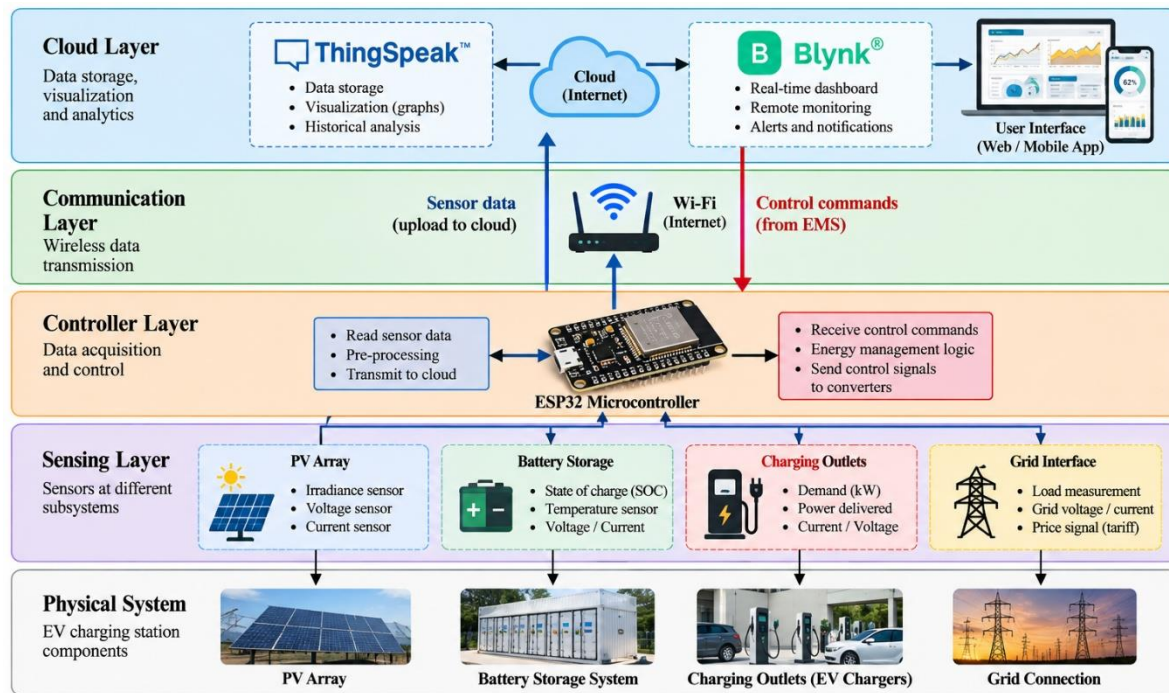


Figure 2. IoT architecture and data flow.

5.5 DRL-based energy management system

The core innovation of the system is a Deep Reinforcement Learning controller that optimises the flow of energy among the PV array, battery, EV load, and grid. The controller is formulated as a sequential decision-making problem. Its state includes the current solar generation, battery state of charge, charging demand, grid price, and forecast information on weather, traffic and demand patterns, and time-of-day pricing. Its actions determine how much power to draw from or deliver to the battery and the grid at each moment, including decisions about G2V and V2G operation. Its reward is designed to minimise charging cost and grid dependency while satisfying charging demand, keeping the battery within safe limits, and maintaining efficiency. Through training, the controller learns a policy that anticipates changes in generation, demand, and price, and that uses the battery and grid interaction intelligently—for example, storing cheap solar energy and discharging it during expensive peak hours, or feeding energy back to the grid through V2G when it is advantageous to do so.

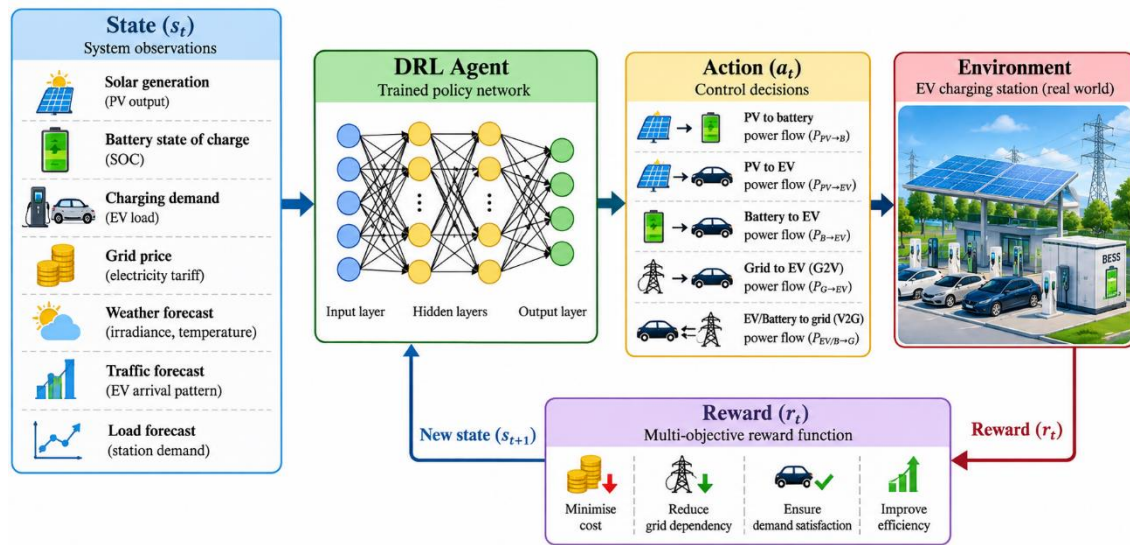


Figure 3. DRL-based energy-management decision flow.

5.6 Simulation methodology

The complete system was modelled and validated through simulation. MATLAB/Simulink was used to model the power-electronic components, MPPT controllers, battery, and the dynamic behaviour of the system, allowing the electrical performance and control response to be evaluated in detail. HOMER Pro was used for the techno-economic analysis, assessing energy flows, grid dependency, and cost over extended periods. The simulations used solar-irradiance, temperature, and representative demand data for the Solapur region, so that the results reflect realistic local conditions. The performance of the proposed AI-optimised system was compared against a conventional grid-based fast-charging station serving the same demand, using the metrics of charging efficiency, grid dependency, charging cost, charging time, and overall system efficiency.

RESULTS AND DISCUSSION

6.1 MPPT performance

The comparison of MPPT techniques confirmed the advantage of the intelligent approach. The Perturb & Observe method tracked the maximum power point effectively under steady conditions but exhibited oscillation around the optimum and slower recovery under rapidly changing irradiance. The ANN-based controller tracked the maximum power point more quickly and with reduced oscillation, improving the effective energy harvested from the array, particularly during periods of variable cloud cover. This improvement in tracking contributes directly to the overall gain in charging efficiency, because more of the available solar energy is captured and delivered to the system.

6.2 Charging efficiency and overall system efficiency

The proposed AI-optimised system achieved a 34.7% improvement in charging efficiency compared with the conventional grid-based station, together with an overall system efficiency of 96.2%. These gains arise from the combination of improved MPPT, intelligent coordination of energy flows that reduces conversion and transmission losses, and the use of stored solar energy in place of less efficient grid supply. The high overall efficiency indicates that the additional power-electronic stages and control complexity introduced by the hybrid architecture do not erode its benefits; rather, the intelligent management more than compensates for the losses associated with additional conversion.

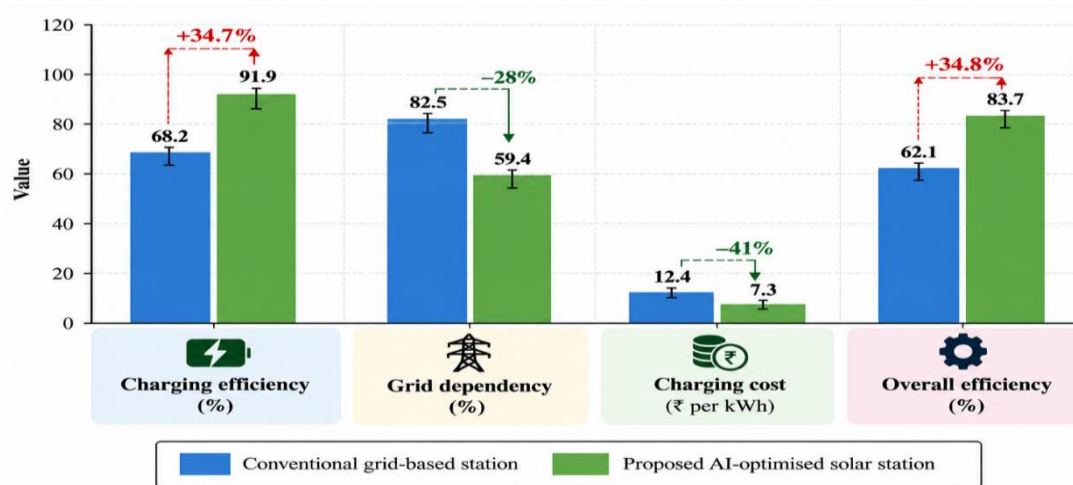


Figure 4. Comparison of key performance indicators: proposed system versus conventional station.

6.3 Grid dependency and cost

The system achieved a 28% reduction in grid dependency and a 41% reduction in charging cost relative to the conventional station. The reduction in grid dependency results from meeting a large share of charging demand directly from solar generation and stored energy, drawing on the grid only when necessary. The cost reduction is larger than the reduction in grid dependency because the DRL controller does not merely reduce the quantity of grid energy used but also shifts the timing of grid interaction, drawing power when it is cheap, discharging stored solar energy during expensive peak hours, and using V2G where it is economically advantageous. This demonstrates the value of intelligent, price-aware energy management over simple solar self-consumption.

6.4 Fast-charging performance

The system delivered fast charging to 80% state of charge in 45 minutes, confirming that the integration of solar generation, storage, and intelligent management does not compromise charging speed. This is an important result, because a sustainable charging station that cannot deliver competitive charging times would be of limited practical value. The battery buffer is central to this capability: it allows the station to deliver high charging power on demand regardless of the instantaneous level of solar generation, decoupling charging performance from the variability of the sun.

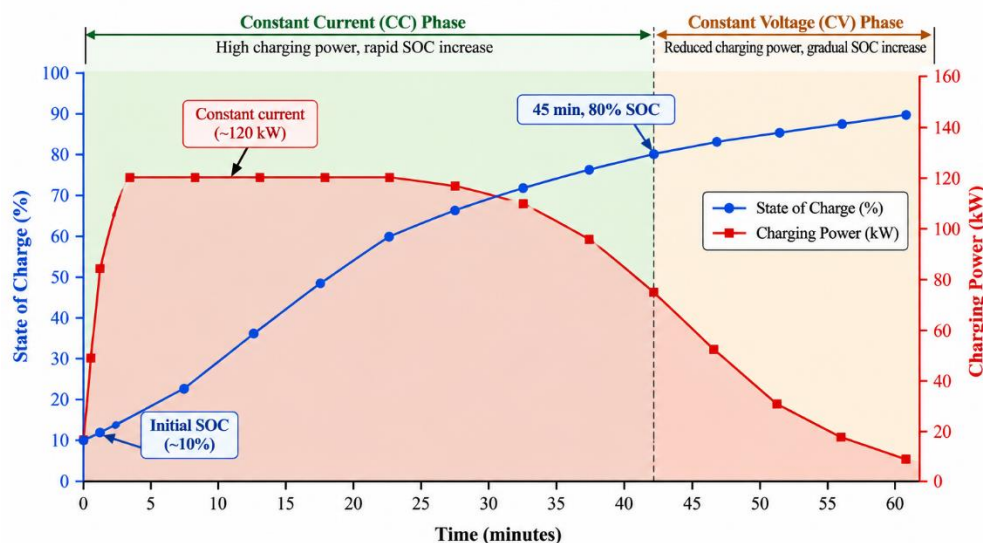


Figure 5. Battery state of charge and charging profile over time.

6.5 Energy-flow behaviour and the role of V2G

Examination of the simulated energy flows showed the DRL controller coordinating the four energy pathways intelligently over the daily cycle. During daylight hours with surplus generation, solar energy served charging demand directly and charged the battery. During periods of high demand or low generation, the battery discharged to support charging. Grid interaction was concentrated in periods of low price, and V2G operation was used selectively to return energy to the grid when it was economically beneficial and when sufficient stored energy was available without compromising charging service. This adaptive behaviour illustrates how the DRL approach extracts value that fixed rule-based control cannot, and it accounts for the cost reductions observed.

6.6 Discussion of implications

Taken together, the results confirm that combining solar generation, battery storage, intelligent MPPT, DRL-based energy management, and IoT monitoring produces a charging station that is substantially more efficient, less grid-dependent, and cheaper to operate than a conventional grid-based station, without sacrificing charging speed. The implications are significant for smart cities, where the large-scale deployment of such stations could materially reduce the carbon intensity of transport and relieve pressure on distribution networks during peak hours. The IoT layer not only enables the intelligent control that produces these benefits but also provides the transparency needed to operate and maintain a fleet of such stations at city scale. The economic advantage, driven substantially by price-aware scheduling and V2G, suggests that the approach could be financially as well as environmentally attractive, improving the prospects for private investment in sustainable charging infrastructure.

6.7 Limitations

Several limitations should be acknowledged. The results are based on simulation using regional data rather than on a physical prototype, and real-world performance will be affected by factors not fully captured in simulation, including component ageing, measurement noise, communication latency, and the variability of actual user behaviour. The battery model, while adequate for system-level analysis, does not capture every aspect of long-term degradation, and the economic analysis depends on assumptions about electricity prices and tariff structures that vary over time and location. The security of the IoT communication layer, important for any real deployment, was outside the scope of this study. These limitations define the agenda for the next phase of the work.

CONCLUSION

This research proposed and validated an AI-optimised, solar-powered fast-charging station integrated with an IoT-based energy-management system for smart cities. The system combines a 50 kW monocrystalline PV array, a 100 kWh lithium-ion battery, ANN-assisted MPPT, bidirectional grid interaction with V2G and G2V capability, and an ESP32-based IoT monitoring layer, all coordinated by a Deep Reinforcement Learning energy-management controller. Validated through MATLAB/Simulink and HOMER Pro simulations using Solapur-region data, the system achieved a 34.7% improvement in charging efficiency, a 28% reduction in grid dependency, and a 41% reduction in charging cost compared with a conventional grid-based station, while delivering fast charging to 80% state of charge in 45 minutes at an overall system efficiency of 96.2%. These results demonstrate that intelligent, renewable-powered charging infrastructure can be simultaneously efficient, economical, grid-friendly, and fast, directly supporting net-zero mobility goals. The principal contribution of the work is the integration of AI-based MPPT, DRL energy management, and IoT monitoring into a single system validated under realistic regional conditions, showing that the value of such a station lies not only in its hardware but in the intelligence of its control. Future work will focus on building and field-testing a physical prototype, incorporating detailed battery-degradation and communication-security modelling, and extending the approach to coordinate multiple stations across a city as part of a smart-grid ecosystem.

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