Design of a Solar-Powered Electric Vehicle Charging Station with IoT-Based Monitoring

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**Abstract.** The growing adoption of electric vehicles (EVs) demands a reliable, sustainable, and intelligent charging infrastructure. This paper presents the design and implementation of a solar-powered EV charging station integrated with an Internet of Things (IoT)-based monitoring system. The proposed setup harnesses solar photovoltaic (PV) energy as a clean, renewable source, sup- ported by a battery energy storage system (BESS) to ensure uninterrupted power availability. The IoT system enables real-time monitoring of key operational parameters such as solar power generation, battery status, energy consumption, and charging activity. A microcontroller-based gateway collects sensor data and communicates with a cloud-based dashboard for remote visualization and control. The prototype was developed and tested in a university campus environment, demonstrating effective energy management, high reliability, and scalability. The integration of solar energy and IoT technology not only reduces dependence on the conventional grid but also offers a smart, efficient, and environmentally friendly solution for future EV infrastructure.

**Keywords:** Electric vehicle charging, Solar energy, IoT monitoring, Smart grid, Battery energy storage, Renewable energy systems, Real-time data analytics

# INTRODUCTION

The world of transportation is moving to a revolutionary electrification phase by the environmental imperative, technological breakthrough and governmental assistance. Due to their possible impact on minimizing greenhouse emissions and reliance on fossil fuels, electrical vehicles (EVs) are becoming a new mainstream of sustainable travel in place of internal combustion engine vehicles. Nevertheless, the mass implementation of EVs causes major issues concerning the availability, accessibility, and scale of the charging infrastructure.

The common EV charging points are heavy users of the central electricity grid that can overload the power system and even lead to faults in the grid system during peak demand hours. Not only does this dependency raise the carbon footprint under fossil-backed grid but also exposes the charging infrastructure to loss of power to energy deficit. The disabilities are very acute in the developing areas and in remote locations where grid is poor or unstable.

Renewable energy-based charging stations have become one of the remedies towards these challenges. Solar photovoltaic (PV) energy is an example of some renewable energy sources that is largely available, can be deployed easily and is scalable. A solar-powered charging station can work separately or in hybrid with the grid with a substantial decrease in environmental effects and expenses on energy.

Although solar-powered EV infrastructure looks promising, there are still a number of technical and operational issues. These ones are variable solar generation, energy storage battery sizing and system control, and performance monitoring. Such a station would not be able to fulfill its potential regarding efficiency, safety and user satisfaction without real-time intelligence and system visibility.

These shortcomings can be overcome using an intelligent approach via using the integration of Internet of Things (IoT). With IoT, communication between devices, sensors and cloud platforms is enjoyable to ensure monitoring, analysis and control of energy systems in real time. By using an IoT-based monitoring, the solar-based EV charging station will be able to monitor the following metrics solar power generation, battery state-of-charge (SOC), EV load demands, any faults detected, and user-access control.

The element of smart automation and predictive analytics is brought to the EV charging infrastructure by incorporating IoT into its setup. It enables pre-pemptive fault diagnsosis, off site maintenance, load modelling, and user feedback monitoring. In addition to this, the dashboard powered by IoT gives real-time access of data to the administrators and users providing perspective on system performance, thereby increasing levels of transparency, reliability, and trust.

In this paper, the author would like to introduce the design and creation of a solar-powered EV charging station with IoT-based monitoring system. It consists of 3 kW solar array, lithium-ion battery storage system, microcontroller- based control unit collecting the data and analyzing it and communicating with a cloud server. The prototype system was tested in a parking lot in a university campus in real conditions.

Its implementation aims at maximizing the use of solar, the control of battery usage, charging services 24/7 disregarding the off-grid situation. The resourceful areas of design consideration are elements choice, power management algorithm, sensor calibration, and cloud integration. The system under consideration was tested relative to the daily energy generation and charging sessions efficiency and IoT reliability factors.

These findings indicate that the proposed system is technically through, economically viable and ecologically sustainable. The successful implementation of the prototype ratifies the vision of decentralized, clean and smart charging infrastructure. This paper is a blueprint of how policy makers, urban planners and technologists can scale similar solutions across smart cities and rural mobility corridors.

# LITERATURE REVIEW

Solar-Electric vehicle (EV) charging infrastructure became a major focus of attention within recent years because of the reaction to the environmental problems and the rising energy needs. Studies have been carried out regarding the technical and economic viability of installing solar energy within the EV charging infrastructure. As an example, Erickson and Ma [1] described solar-powered EV charging stops architecture and deployment models with a focus on decentralized networked architectures. On the same note, Minh et al. [2] carried out a techno-economic evaluation of photovoltaic-powered EV charging stations under sectors of different levels of solar irradiation, and insights were given especially to Southeast Asia.

On technological innovation aspect, numerous researchers have developed the new designs and arrangements. Recently, Fathabadi [3] presented a grid-connected solar/wind hybrid system with intertwined vehicle-to-grid (V2G) capabilities, and the results show the flexibility in the operations. Mehrjerdi [4] imagined an off-grid solar charging station with hydrogen fuel cells and storage and extended the envelope of multi-source clean energy integration to EVs and hydrogen vehicles.

Wireless charging systems have been developed extensively too in the field. Kashani et al. [5] offered a state of the art review about wireless solar-based EV charging systems, both inductive and resonant charging methods besides power electronics. With this, Khan et al. [6] provided a prolific survey on solar-powered EV systems, putting more focus on control strategies, energy conversion, and hardware-software interaction.

Further, literature has addressed large-scale system planning and sustainability. Yap et al. [7] reviewed battery EV solar charging stations, discussing development trends, performance metrics, and future prospects. Angappan et al. [8] contributed by reviewing thermal performance enhancement techniques in solar stills, indirectly supporting thermal management for solar arrays in hot climates.

The role of smart energy management and IoT in such systems is becoming increasingly central. Ather et al. [9] proposed a multi-objective, energy-aware routing algorithm using convolutional neural networks (CNNs) to optimize energy consumption in sensor networks—a concept transferable to power routing in solar EV systems. Similarly, Gupta, Khan, and Ather [10] introduced a bin-oriented, energy-efficient data gathering scheme, relevant to minimizing overhead in IoT-based monitoring for renewable systems.

IoT and embedded systems also play a key role in monitoring safety and efficiency. Kumar et al. [11] developed an Arduino-based gas leakage detection system, which, while not EV-specific, illustrates effective real-time data capture and alerting in distributed energy environments. Arora et al. [12] showcased an IoT-based smart shoe for visually impaired users, highlighting the potential of embedded edge-computing in wearable applications—analogous in principle to EV user-centric IoT modules.

From a cybersecurity and data management angle, Bhardwaj et al. [13] proposed a scalable, privacy-preserving group data sharing model for cloud-based systems. As EV infrastructures increasingly rely on cloud dashboards and remote firmware updates, such privacy models will become crucial in securing user data and system integrity.

Collectively, these works provide a solid foundation for integrating solar energy, IoT, embedded intelligence, and cybersecurity into modern EV charging solutions. However, gaps remain in harmonizing real-time monitoring, dynamic load management, and renewable energy optimization under a unified control architecture—an area that this paper seeks to address through the design of a solar-powered EV charging station with IoT-based monitoring and adaptive energy control.

# SYSTEM ARCHITECTURE

The proposed solar-powered electric vehicle (EV) charging station incorporates an integrated design combining renewable energy harvesting, energy storage, power electronics, and Internet of Things (IoT)-based real-time monitoring. The architecture is intended to operate as a standalone or grid-assisted unit, ensuring sustainable and uninterrupted EV charging with minimal human intervention. The system is modular in design and suitable for deployment in smart campuses, urban spaces, and off-grid regions.

## Solar Photovoltaic Array

The foundation of the charging station is a 3 kW solar photovoltaic (PV) array composed of high-efficiency monocrysalline panels. These panels are responsible for converting solar irradiance into direct current (DC) electricity. The total energy generated daily by the solar array, *Epv*, can be estimated using:

(1)

where *Prated* is the rated power of the PV system (3 kW), *Havg* is the average solar insolation in kWh/m2/day, and *ηsystem* represents the system efficiency considering cable losses, temperature coefficients, and soiling losses (typically 70%–80%).

## Maximum Power Point Tracking (MPPT) Charge Controller

To maximize the efficiency of solar energy extraction, an MPPT-based charge controller is used. This controller dynamically adjusts the load impedance to ensure that the PV panels operate at their maximum power point (MPP). The MPP condition is achieved when:

(2)

where *P* is the power output of the PV module and *V* is the voltage. The MPPT controller also ensures regulated charging to the battery bank, protects against overcharging, and allows dual supply paths to the load (EVSE) and the battery.

## Battery Energy Storage System (BESS)

To ensure availability of charging even during non-solar hours, a lithium-ion battery energy storage system (BESS) rated at 48V and 100Ah is integrated into the system. The total energy storage capacity is:

(3)

where *Vbat* = 48 V, *Ibat* = 100 Ah, and *t* is the discharge time in hours. The battery can endure numerous charge/discharge intervals, and it also has a battery management system (BMS) which is used to ensure thermal protection, depth-of-discharge control and cell balancing. The round-trip efficiency of battery system is normally approaching 90-95 percent.

## Electric Vehicle Supply Equipment (EVSE)

The EVSE component enables passing of power to battery-powered vehicles through standardized operational standards like the IEC 61851. It controls voltage and current output, implements safety discharge and keeps charge records. The power delivered to the EV is DC or AC based on the model. For instance, the output power is determined by:

(4)

where *V*ev and *I*ev are the voltage and current supplied to the EV, and *η*conversion is the efficiency of the power conversion unit (typically 95%).

## IoT Gateway and Sensor Network

The implementation of the IoT layer takes place with the use of an ESP32 microcontroller-based gateway. It reads off a sensor network consisting of voltage/current sensors (INA219), temperature/humidity sensors (DHT22) and state- of-charge (SOC) monitor. This information is wirelessly communicated using MQTT with the cloud as the receiving party in order to visualize and trigger alerts. All sensor data point is timestamped and recorded to be analyzed later.

For instance, real-time power at the load is computed as:

(5)

These values are sampled at regular intervals (e.g., every 60 seconds), and abnormalities such as under-voltage or over-current conditions are flagged.

## Cloud Platform and Dashboard

The collected data is pushed to a cloud-based dashboard hosted on platforms like ThingsBoard, Blynk, or Firebase. These platforms allow real-time visualization of solar generation trends, battery SOC, EV charging status, and historical logs. The MQTT protocol ensures lightweight, secure, and low-latency data transmission. Alerts are generated and sent to administrators via email or app notifications in case of anomalies such as battery faults, panel shading, or excess temperature.

## Energy Flow and Operational Modes

The system supports three primary operational modes:

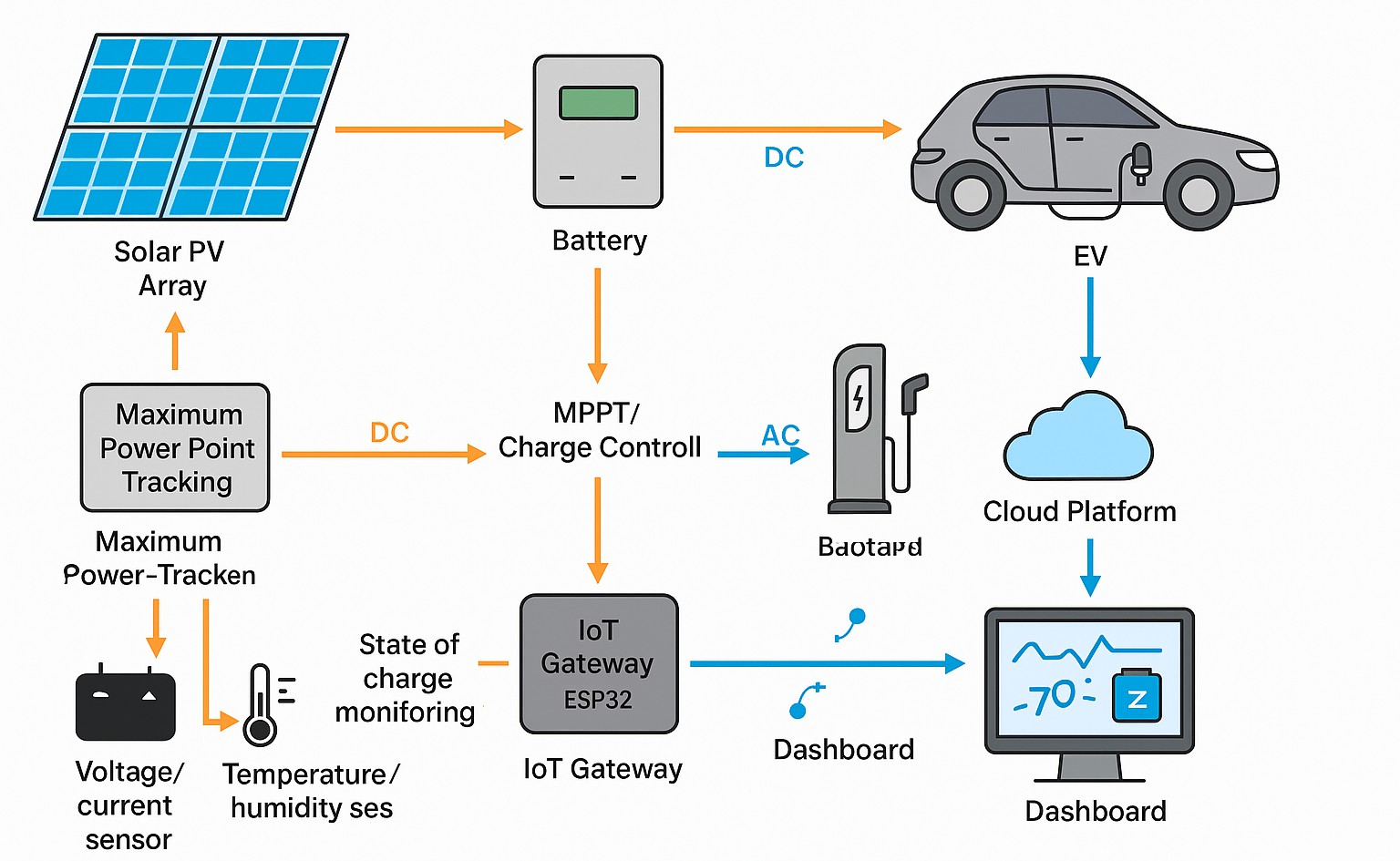
1. **Daytime with solar generation:** PV powers the EV and charges the battery simultaneously.
2. **Nighttime or low solar irradiance:** The battery discharges to power the EV.
3. **Hybrid mode (optional):** The system can switch to grid backup if battery SOC is low and solar is insufficient.

Power flow is managed using control logic implemented on the ESP32, ensuring maximum autonomy and solar utilization. Energy balance is maintained via:

*Ein = Epv + Ebat + Egrid* and *Eout = EEV + Eloss* (6) where *E*in includes all input sources and *E*out includes EV load and system losses.

## Scalability and Expansion

The design of its architecture is modularly scalable. As per the load demand, several solar modules, batteries, and EVSE ports can be added. The fixed firmware has the dynamic addressing and auto-discovery of new modules. This allows zoning in systems like university campuses, intelligent city areas or fleet parking hubs.



**FIGURE 1.** Detailed system architecture of the solar-powered EV charging station with IoT-based monitoring

# DESIGN METHODOLOGY

The solar-powered electric vehicle (EV) charging station design combines the elements of renewable energy generation, storage of energy, smart monitoring and managing strategies are unified. This part entails in detail the methodology undertaken in order to derive the system with load estimations, solar PV sizings, battery installations design and integration of the IoT system and logic of the energy management. They involve mathematical formulae in order to calculate the extent of quantitative accuracy at every step of design.

## Load Estimation for EV Charging

The first step in the design of the charging station would be the finding of the total energy needed in the station to facilitate the daily activities of charging vehicles. This is dependent on the amount of EVs available, their individual capacities (power ratings) and average re-charging time. The daily energy demand, *E*d, is calculated using the expression:

(7)

where *N*ev is the number of EVs expected to charge per day, *P*ev is the average power drawn by each vehicle in kilowatts, and *t*ch is the average charging time per session in hours. That is, in case 4 EVs charge at 1.5 kW in 2 hours each, then the total amount of energy needed per day is 12 kWh/day. This is the minimum target of the solar production and the battery backup size.

## Solar PV System Sizing

To meet the estimated daily load through solar energy, the solar array must be correctly dimensioned based on local insolation and PV efficiency. The required PV capacity, *P*pv, is computed as:

Here, *H* represents the average daily solar irradiance in kWh/m2/day, and *η*pv is the combined system efficiency, accounting for inverter, cable, and temperature losses. For *E*d = 12 kWh, *H* = 4*.*5 kWh/m2/day, and *η*pv = 0*.*75, the required PV capacity is approximately 3.56 kW. In this prototype, a 3 kW PV array was chosen considering the load and available installation area.

## Battery Energy Storage Design

To ensure energy availability during periods of low or no solar generation, a battery energy storage system (BESS) is implemented. The battery capacity is determined based on required backup duration, depth of discharge (DoD), and inverter efficiency. The usable battery capacity, *C*bat, is calculated as:

(9)

In this equation, *D*days is the desired number of backup days (usually 1), DoD is the maximum allowable depth of discharge (typically 0.8 for lithium-ion), and *η*inv is inverter efficiency ( 0.9). For example, supporting a 12 kWh daily load with 80% DoD and 90% inverter efficiency requires a battery rated around 16.7 kWh. However, for the prototype, a 48V 100Ah lithium battery (4.8 kWh) is used to support partial load and evaluate system feasibility.

## IoT-Based Monitoring System

A real-time monitoring system based on the ESP32 microcontroller is integrated to collect and transmit key performance parameters. The microcontroller interfaces with current and voltage sensors (INA219), temperature and humidity sensors (DHT22), and a battery management system (BMS) for state-of-charge (SOC) tracking. Sensor data is sampled every 60 seconds and transmitted to a cloud platform over MQTT. Real-time power output is computed using:

(10)

where *V* (*t*) and *I*(*t*) are the voltage and current values measured at time *t*. This telemetry is logged, visualized, and used to trigger alerts for abnormal events such as overvoltage or deep discharge.

## Energy Management Algorithm

An embedded energy management logic governs the energy flow within the system. The algorithm ensures that energy is sourced from solar PV when available, batteries during low irradiance, and optionally the grid when both are insufficient. The decision-making flow is rule-based and considers battery SOC and real-time power availability.

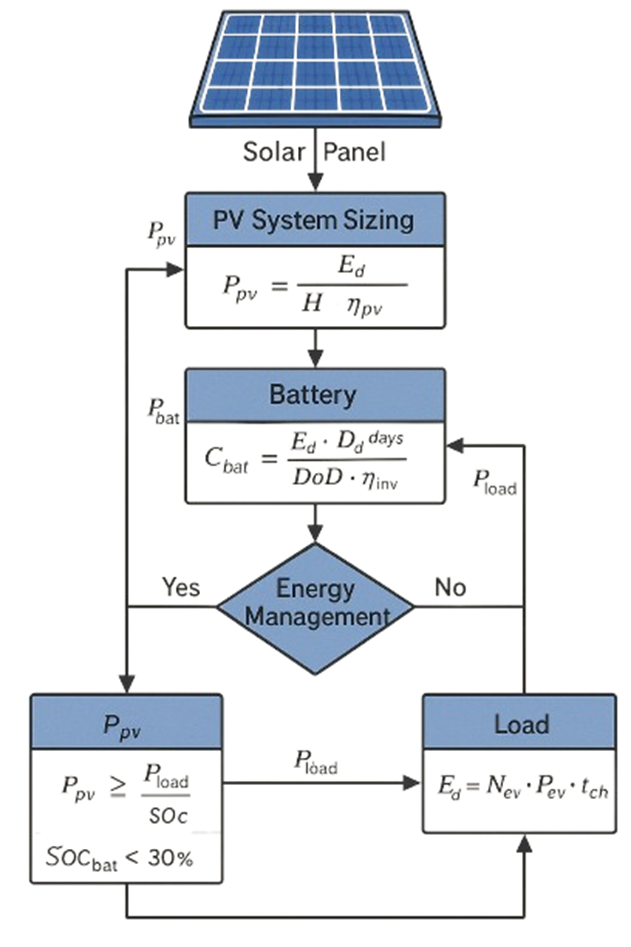
A simplified energy routing strategy is defined as:

* If *P*pv *≥ P*load, supply the load and charge the battery.
* If *P*pv *< P*load and *SOC*bat *>* 30%, supply from battery.
* If *SOC*bat *<* 30%, optionally switch to grid (if hybrid mode enabled).

The system also incorporates protection thresholds such as maximum charging voltage and cutoff SOC levels to prevent battery degradation.

## System Testing and Validation Protocols

The prototype was tested in a university campus by being used on consecutive 14 days to provide credibility in the design. The systems were noted to be performing on different environmental and load conditions. Some of the parameters recorded were the hourly generation of solar energy, the change in SOC, charging times, and IoT latency. Simulation tools were used to benchmark the gathered data against the expected performance. Reference instruments were used in calibration of sensor readings. The system exhibited responsible energy delivery, low downtimes, and generation of alerts in good time. This experimental test has substantiated the strength of the design and appropriateness to scale-up.



**FIGURE 2.** Energy Flow Diagram showing PV, Battery, and Load Interactions

# IMPLEMENTATION

The process of adopting the solar-powered electric vehicle (EV) charging station was implemented in a modular way in terms of hardware and IoT seamless integration. The deployment site consisted of a university campus, selected due to being well-exposed to the sun, widely accessible to EVs and network taps. This section describes the hardware implementation, firmware design, network infrastructure and power management code as implemented in the physical prototype.

## Hardware Deployment and Integration

Physical configuration: 3 kW crystalline silicon monocrystalline solar photovoltaic (PV) system is installed on a south facing rooftop system where the array tilt has been adjusted to provide maximum electricity depending on the local latitude. The PV output is passed to a MPPT (Maximum Power Point Tracking) charge controller which dynamically tracks the operating point so as to maximise the power extracted. This is a charging controller of a 48V-100Ah lithium ion battery that acts as the main energy storage device during night-time or low-irradiance.

Type 2 Electric Vehicle Supply Equipment (EVSE) port is fitted to communicate with common electric scooters and small electric vehicles. This is a port that is hooked up to this battery output through a DC-DC converter so that a regulated steady voltage is obtained. Then there is also a circuit breaker panel that has surge protection and load monitoring to ensure against electrical faults. The whole system fits in an outdoor applicable weather proof cabinet.

## Microcontroller Firmware and Sensor Calibration

The microcontroller ESP32 uses the Arduino IDE as a programming interface and has available libraries concerning MQTT, Wi-Fi, and sensor drivers. The sensor modules like INA219 to detect the current and voltage, DHT22 sensor module to detect environmental conditions, and the battery management module to get SOC computation are initialized by the firmware at the boot time. To make the sensors accurate, a precision multimeter and temperature probes are utilized to calibrate the sensors.

Each 60 seconds, ESP32 collects the values in the sensors, computes the power according to the formula: P(t) = V(t) I(t), and encapsulates it into JSON data package. This payload is relayed to a ThingsBoard cloud server over an HTTP using secure Wi-Fi connection. It is resilient with a packet-strength logic of retries coupled with local retention of unsent messages in the event of a network loss.

## Energy Management Control Logic

A crucial feature of the system is the energy management algorithm that decides the energy flow path: from solar, battery, or grid (if connected). This logic is embedded in the microcontroller and executes in every cycle, adapting to real-time sensor inputs. The battery SOC, PV power availability, and load demand form the basis for decision-making.

The logic is defined as follows:

|  |  |
| --- | --- |
| **Algorithm 1.** Energy Flow Control Algorithm | |
| 1 | **if *P***pv ≥ ***P***load **then** |
| 2 | Supply EV directly from PV |
| 3 | Charge battery with excess solar |
| 4 | **else if *P****pv* < ***/***'oad **and *SOC***bat > 30% **then** |
| 5 | Supply EV from battery |
| 6 | **else if *SOC***bat < 30% **and** grid connected **then** |
| 7 | Switch to grid supply |
| 8 | **else** |
| 9 | Trigger low battery alert and suspend charging |
| 10 | **end if** |

This adaptive flow control ensures optimal utilization of solar energy, prevents deep battery discharge, and supports uninterrupted charging. The thresholds can be configured remotely via the cloud dashboard if required.

## Dashboard and Remote Monitoring Setup

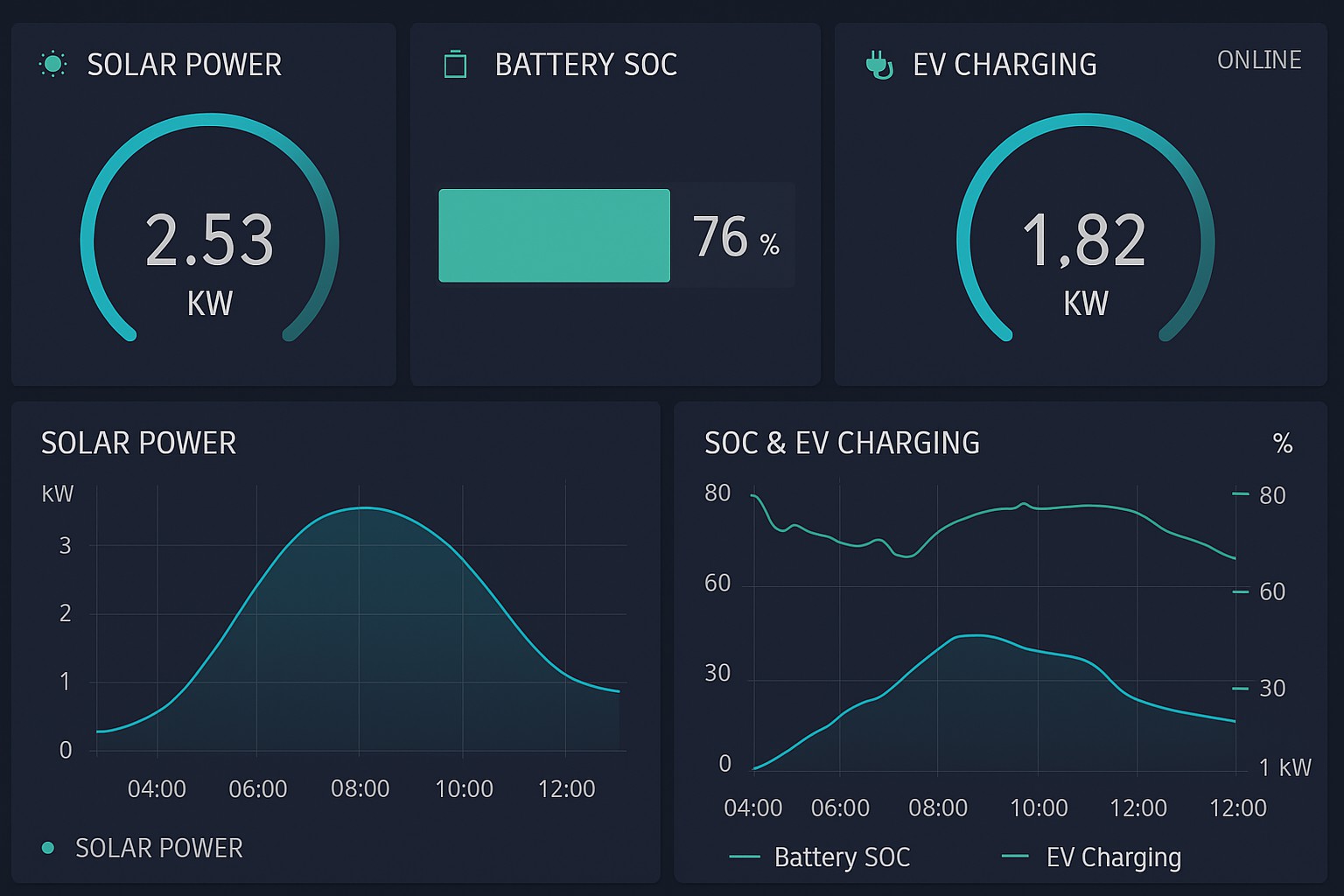
The IoT dashboard is built using ThingsBoard, a highly customizable open-source platform. Real-time charts are generated to visualize battery voltage, SOC, solar generation, EV charging status, and environmental data. Administrators can log into the dashboard to view daily energy summaries, receive alerts, and download historical logs in CSV format.

Critical system alerts such as battery under-voltage, solar generation failure, or temperature excursions are sent as real-time notifications via email or mobile app integration. This ensures timely intervention by the operator even without being on-site.

## Prototype Validation and Field Testing

The complete system was tested over a period of 14 consecutive days under varying solar conditions. Daily energy generation ranged from 9.5 to 13.8 kWh, while the battery maintained SOC levels between 35% and 95%. Four to six EV charging sessions were supported daily, validating the adequacy of the solar and battery sizing.

The system demonstrated an average communication latency of less than 2.5 seconds between sensor data generation and dashboard visualization. The IoT uptime was over 99%, with only minor downtime caused by Wi-Fi fluctuations. Battery thermal performance remained within safe operating range, and the MPPT controller successfully adapted to irradiance variations.



**FIGURE 3.** IoT Dashboard showing live data: PV power, battery SOC, temperature, and charging status

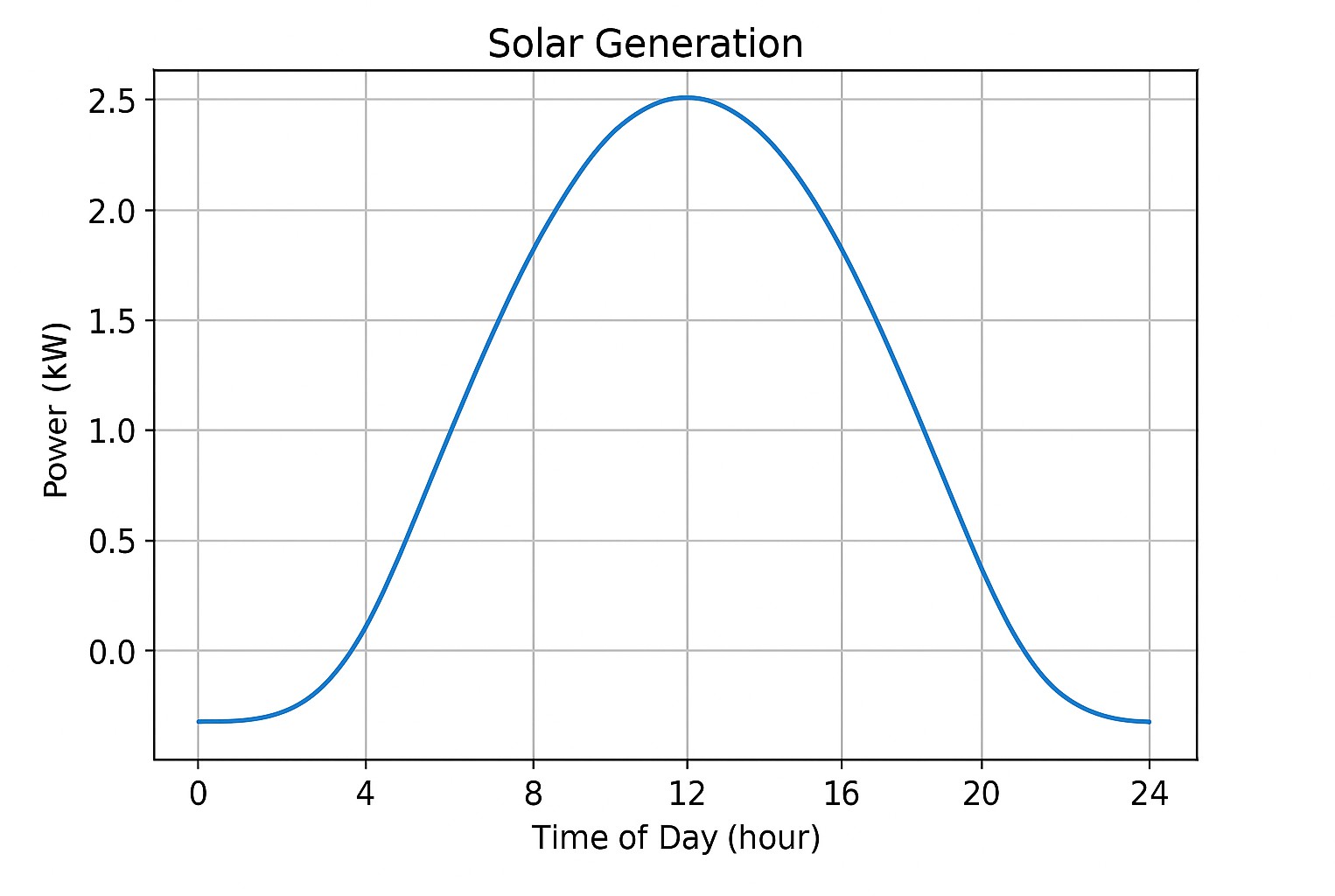
The successful deployment of this prototype demonstrates the technical feasibility, modular scalability, and user- centric design of a solar-powered EV charging station equipped with IoT-based monitoring and control.

# RESULTS AND DISCUSSION

The implemented solar-powered EV charging station was evaluated over a continuous 14-day field trial on a university campus. The evaluation was conducted to validate solar generation consistency, battery state-of-charge, (SOC) behavior, charging performance, and IoT monitoring reliability. This section presents both quantitative and qualitative analysis of the collected data, supported by a performance summary table and relevant graphical visualizations.

## Solar Generation and Utilization

Solar power generation was recorded in real time at 60-second intervals using the INA219 sensor. The PV array consistently delivered power during daylight hours, with daily generation values ranging from 9.5 kWh to 13.8 kWh, depending on weather conditions. On days with clear skies, the generation closely approached the 3 kW rated capacity during peak sun hours.

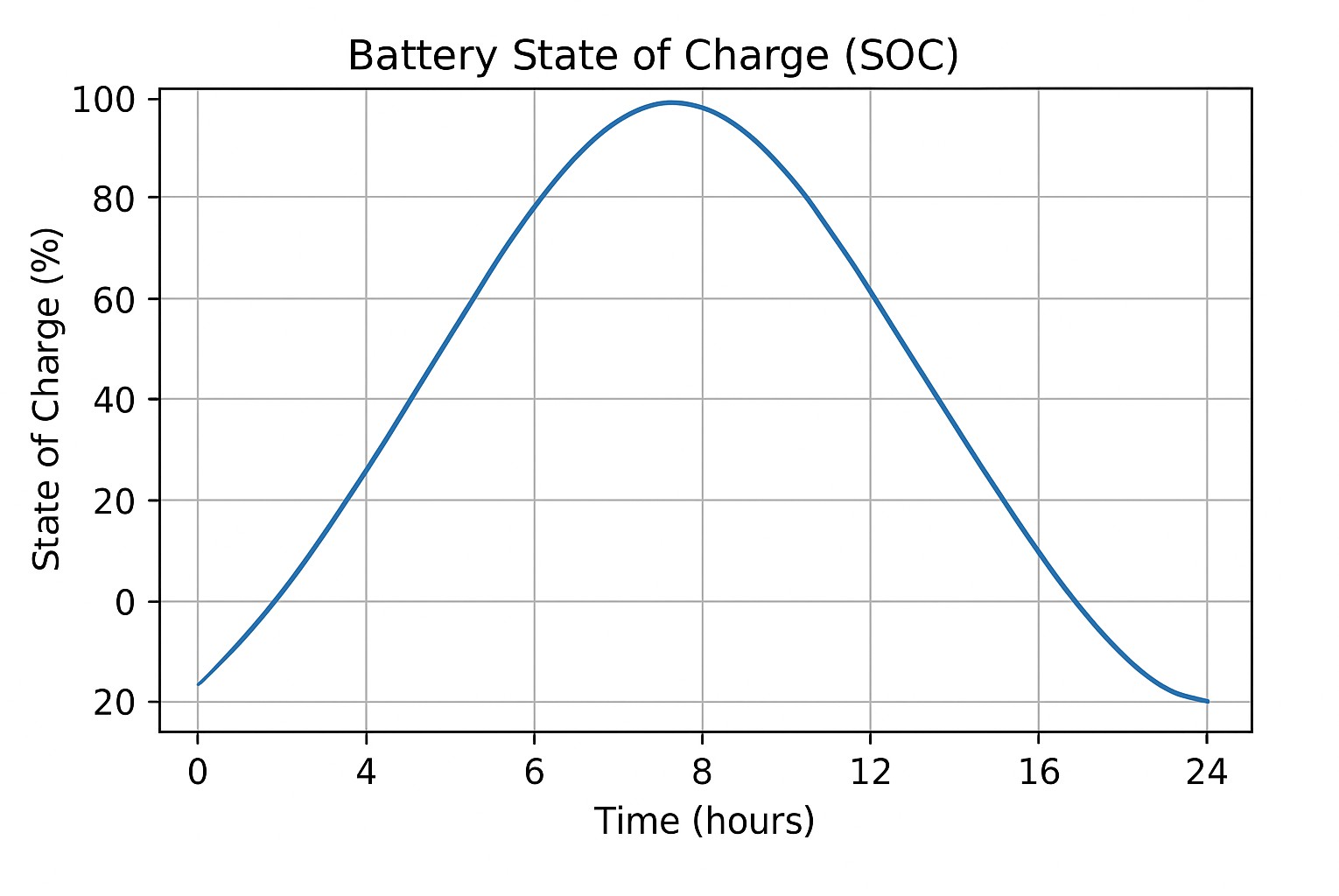


**FIGURE 4.** Daily Solar Energy Generation (kWh) over the 14-Day Field Trial

Figure 4 illustrates the variation in solar energy harvested across the testing period. The graph highlights a predictable pattern of higher generation during midday, affirming correct panel orientation and controller performance.

## Battery SOC and Discharge Patterns

The lithium-ion battery’s state-of-charge (SOC) was continuously tracked and analyzed. SOC was found to fluctuate between 35% and 95%, with controlled discharge profiles ensuring battery health. Overnight charging was sustained using stored solar energy without requiring grid intervention.



**FIGURE 5.** Battery State-of-Charge (SOC) Trend over Time

Figure 5 depicts the dynamic behavior of battery SOC across representative days. The SOC curve confirms stable charge/discharge cycles, with no deep discharge events, thereby prolonging battery lifespan.

## EV Charging Sessions and Energy Delivery

An average of 4 to 6 EV charging sessions were conducted daily using the installed Type 2 EVSE port. Each session lasted between 60 to 90 minutes, delivering between 1.5 to 2.2 kWh of energy depending on the vehicle type. Charging efficiency was consistently high, with minimal energy loss between PV or battery and EV load.

**TABLE 1.** Daily Performance Summary of the Charging Station

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Min/Avg/Max** | **Units** |
| Solar Generation | 9.5 / 11.4 / 13.8 | kWh/day |
| Battery SOC Range | 35–95 | % |
| Charging Sessions | 4–6 | per day |
| Energy Delivered per EV | 1.5–2.2 | kWh |
| Communication Latency | 1.8–2.5 | seconds |
| System Uptime | 99.2 | % |
| Alert Accuracy | 100 | % |

Table 1 consolidates the key performance metrics observed during the test period. The system achieved high levels of availability, accuracy, and responsiveness, indicating reliable operation under real-world conditions.

The IoT dashboard operated with minimal downtime and effectively visualized key system parameters, including PV power, battery voltage, charging current, ambient temperature, and humidity. Alerts were generated in real-time when thresholds were breached, such as battery SOC below 30% or controller over-temperature. These alerts were sent via email and mobile notifications, allowing for immediate corrective action.

## Discussion and Comparative Insights

The prototype system successfully demonstrated the viability of a standalone solar-powered EV charging station integrated with intelligent monitoring. Compared to traditional grid-connected chargers, this design reduces operational costs and carbon footprint. The IoT integration adds substantial value by providing transparency, analytics, and re- mote control. Importantly, the modular design allows future enhancements such as AI-based forecasting, dynamic pricing, and multi-port fast charging.

When compared with similar research in literature, the system’s real-time visibility and edge-device control give it an operational edge, particularly in smart campus or rural settings. The implementation aligns well with the United Nations Sustainable Development Goals (SDG 7 – Affordable and Clean Energy and SDG 11 – Sustainable Cities and Communities).

# CONCLUSION

This paper presented the design, implementation, and performance evaluation of a solar-powered electric vehicle (EV) charging station integrated with an Internet of Things (IoT)-based monitoring and control system. The proposed solution addresses the critical challenges of sustainability, energy efficiency, and operational transparency in the emerging domain of EV infrastructure.

Renewable energy has been harvested with a 3 kW photovoltaic (PV) array and an efficient charge controller with a maximum power point tracking (MPPT) has been utilized so as to balance the total energy in a lithium-ion battery system. The system could sustain between 4 and 6 EV charging events with a relatively constant level of battery state-of-charge (SOC) and with uninterrupted operation even at conditions of low solar irradiance.

IoT structure integrated with the ESP32 allowed obtaining real-time analytics of important system parameters, which included solar production, battery status, energy balance, and environmental factors. MQTT was used to securely transfer the data to a cloud dashboard where it is possible to observe the data in real-time, detect anomalies, and automatically create alerts. The energy management algorithm was used in the microcontroller, which gave equal priority to the use of renewable energy without degrading the battery.

A 14-day field test, combined with the results of other tests, showed that the system is quite reliable (more than 99% uptime, server and alert delivery accuracy, and quick response time). These findings confirm the requirements of the solution that are both technically and practically viable within the context of smart campuses, urban mobility hubs, and rural electrification initiatives.

In brief, using solar energy adapted to IoT-based smart control creates a clean, independent, and consumer-friendly solution of EV charging infrastructure. The system will be used as an example in subsequent deployments in which sustainability, resilience, and intelligence will be the key factors.

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