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ORIGINAL CONTRIBUTION

Design and Implementation of an IoT-Based Smart Solar Photovoltaic Monitoring System with Cloud Analytics

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ABSTRACT

The growing dependence on renewable energy has established solar photovoltaic (PV) generation as one of the most widely deployed sustainable energy sources. The output of a PV installation, however, varies continuously with solar irradiance, ambient temperature, dust accumulation, partial shading, and module ageing, and faults that develop between manual inspections often remain undetected for extended periods. This study presents a low-cost IoT-based smart solar monitoring system that measures the electrical and environmental parameters of a PV panel in real time. A 0–25 V resistive voltage sensor and an ACS712 Hall-effect current sensor are interfaced with an ESP32 microcontroller, which digitises the readings, applies calibration coefficients, and computes instantaneous power and cumulative energy on the device itself. The processed values are transmitted over Wi-Fi to a cloud platform, where live readings and time-series trends for voltage, current, power, and energy are presented on a dashboard accessible from any browser or mobile device. A local display provides on-site indication, while threshold-based logic flags open-circuit, short-circuit, and low-yield conditions. Field testing on a small PV panel confirmed continuous logging and remote visualisation of the generated data. The system provides an affordable and scalable solution for performance supervision and early fault detection in domestic, institutional, and agricultural PV installations.

KEYWORDS: IoT, Solar Energy, Photovoltaic Monitoring, ACS712 Current Sensor, Cloud Dashboard.

1. INTRODUCTION

The rising demand for clean and renewable energy has made solar photovoltaic (PV) systems an important source of sustainable power for domestic, institutional, industrial, and agricultural applications. Unlike conventional generation, the output of a PV array is not constant: it varies continuously with solar irradiance, ambient and module temperature, humidity, dust deposition, partial shading, and the gradual ageing of the cells. Faults such as microcracks, string disconnection, connector corrosion, and converter failure further reduce the delivered power. In most small and medium installations these variations are never observed directly, because performance is assessed only from periodic energy-meter readings or occasional manual inspection. As a result, a degraded or partially faulty array may continue to operate at

reduced output for weeks before the loss is noticed. What such installations require is continuous, parameter-level visibility rather than aggregate readings taken long after the event.

The Internet of Things (IoT) offers a practical route to this visibility, since low-cost sensors, an inexpensive microcontroller with integrated wireless connectivity, and a cloud platform together make it possible to acquire, transmit, store, and visualise electrical parameters at short intervals and at negligible recurring cost. This study presents the design and implementation of an IoT-based smart solar monitoring system built around the ESP32 microcontroller. The system measures panel voltage, current, temperature, and light intensity, computes instantaneous power and accumulated energy locally, and transmits the results over Wi-Fi to a cloud dashboard that presents live values and historical trends. The

remainder of this paper reviews the related work and identifies the research gap, describes the proposed system architecture and hardware, sets out the methodology and implementation, and reports the experimental results before concluding with the limitations and future scope.

2. LITERATURE REVIEW

Swathi et al. [1] developed an IoT-based solar power monitoring system using an Arduino board. The system acquired panel parameters in real time and uploaded them to a monitoring platform, helping the user track generation and plan maintenance.

Sawashere et al. [2] proposed a solar panel monitoring and data-acquisition system for the real-time collection of solar power parameters. The recorded data were used to analyse panel performance and to improve overall energy management.

Nkinyam et al. [3] developed a low-cost IoT-based monitoring device for solar electric systems. The device enabled real-time observation of PV parameters and supported efficient management of the installation at a substantially lower cost than commercial monitoring hardware.

Trang et al. [4] designed a real-time system for monitoring and controlling solar power using IoT technology. In addition to remote observation, the system supported control actions, thereby improving the management of the solar energy resource.

Rao et al. [5] developed an IoT-based intelligent smart energy monitoring system for solar PV generation. The system tracked energy production continuously and applied the collected data to the analysis and improvement of plant performance.

Gopal et al. [6] proposed an IoT-based solar power monitoring system for the real-time observation of solar energy parameters. The work demonstrated that continuous parameter logging improves performance tracking and simplifies energy management.

Olayiwola et al. [7] presented a comprehensive analysis of the current-voltage (I-V) characteristic of photovoltaic modules, showing how irradiance and temperature reshape the characteristic curve and shift the maximum power point. Their analysis provides the theoretical basis

for interpreting measured voltage and current data.

Domínguez-Bolaño et al. [8] presented an IoT system for a smart campus in which solar photovoltaic energy monitoring is one of several deployed use cases. The work addressed data collection, storage, visualisation, and efficient energy management at the scale of an institutional campus.

While the reviewed studies demonstrate progress in solar parameter acquisition, low-cost IoT monitoring hardware, and cloud-based visualisation, most address these functions individually. Some concentrate on data acquisition without cloud analytics, others provide a dashboard without on-device computation of derived quantities such as accumulated energy, and comparatively few combine electrical and environmental sensing with automatic fault indication in a single low-cost unit. Limited attention has also been given to performing power and energy computation at the edge so that the cloud receives engineering values rather than raw counts. The proposed system addresses this gap by integrating voltage, current, temperature, and irradiance sensing, on-device calibration and energy integration, cloud transmission with time-series visualisation, and threshold-based fault flagging within a single affordable platform.

3. PROPOSED SYSTEM

3.1. System Architecture

The proposed system is organised as a layered architecture in which sensing, edge processing, network transport, and cloud visualisation are separated into distinct functional stages. As shown in Fig. 1, the solar panel supplies the measured quantities to a voltage sensor, an ACS712 current sensor, a temperature sensor, and a light-dependent resistor. These devices form the sensing layer and convert the physical quantities into analog electrical signals. The ESP32 microcontroller constitutes the edge layer: it digitises the analog signals through its internal ADC, applies the stored calibration coefficients, computes the instantaneous power and the accumulated energy, and evaluates the fault-detection conditions. A 16×2 LCD displays the current readings locally so that the installation can be checked without network access. The Wi-Fi

radio integrated in the ESP32 forms the network layer and transmits the processed values to the cloud at fixed intervals. The cloud and application layer stores the received records, maintains the time-series history, and renders the dashboard through which the user observes live values and past trends from a browser or mobile device.

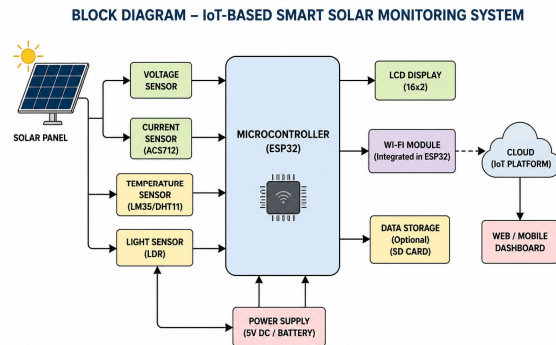


Figure 1: Block diagram of the proposed IoT-based smart solar monitoring system.

3.2. Hardware Components

Table 1 summarises the principal hardware components used in the system.

Table 1. Hardware Components

Components	
Solar PV Panel (20 W)	Voltage Regulator
ESP32 Microcontroller	Resistor
Voltage Sensor (0–25 V)	Capacitor
ACS712 Current Sensor	Diode
Temperature Sensor	Vero Board
Light Sensor (LDR)	PBT Connector
LCD Display (16 × 2)	Bug Strip
Power Supply (5 V DC)	Connecting Wires
SD Card / Enclosure	Signal Filter (RC)

3.3. Parameter Sensing and Signal Conditioning

Panel voltage is measured through a resistive divider that scales the panel terminal voltage into the 0–3.3 V input range of the ESP32 ADC, following the relation $V_{adc} = [R2 / (R1 + R2)] \times V_{pv}$. The panel current is measured by an ACS712 Hall-effect sensor whose output follows $V_{out} = V_{cc}/2 + (S \times I_{pv})$, where S is the device sensitivity. Because the sensor output is centred on half the supply voltage, the zero-current null point is measured at start-up and stored so that offset drift does not accumulate in the energy total. Small RC filters are placed on

both analog channels to suppress switching noise, and the readings are averaged over several consecutive samples before use. The overall measurement error is dominated by the ADC resolution, the tolerance of the divider resistors, and the temperature-dependent offset of the current sensor.

3.4. On-Device Data Processing

The ESP32 converts the filtered ADC counts into engineering units and computes the derived quantities locally rather than transferring raw values to the cloud. The instantaneous DC power is obtained as $P(t) = V(t) \times I(t)$, and the energy generated over a period is obtained by numerical integration of the power samples, $E = \sum [P(t) \times \Delta t]$, evaluated by the trapezoidal rule over the sampling interval Δt . Performing this computation at the edge keeps the accumulated energy correct even when a transmission is missed, and reduces the volume of data sent over the network.

3.5. Cloud Transmission and Alerting

The processed readings are assembled into a record and transmitted over Wi-Fi to the cloud platform, where each measured quantity is written to a separate channel field. The dashboard renders the received records as live values and as time-series charts, so that the daily generation profile and any departure from it can be observed remotely. Threshold-based logic is applied to the same values to flag abnormal conditions: an open circuit is indicated by a current close to zero while the terminal voltage remains near the open-circuit value during daylight, a short circuit or string fault by a collapsed voltage with current still flowing, and soiling or degradation by a sustained fall in the delivered power under comparable irradiance conditions. When such a condition persists, a notification can be issued so that the fault is addressed before a significant quantity of energy is lost.

4. METHODOLOGY

The development of the proposed system followed a structured, iterative engineering approach consisting of the following stages.

1. Requirement Analysis and Component Selection: The system specifications, including the voltage and current ranges, the required accuracy, and the data update interval, were

defined first. The ESP32, the voltage and current sensors, the temperature and light sensors, and the supporting components were then selected on the basis of cost, accuracy, and mutual compatibility.

2. **Circuit Design and Sensor Interfacing:** The sensors were connected to the appropriate microcontroller pins. A resistive divider was used for safe voltage measurement, and suitable analog interfaces were provided for the current, temperature, and light sensors. The circuit was powered from a regulated 3.3 V supply.

3. **Firmware Development:** Firmware was written in Arduino C++ to initialise the sensors and the Wi-Fi interface, acquire the sensor readings, convert them into engineering units, and compute the instantaneous power and the accumulated energy. The processed data were then formatted for transmission to the cloud.

4. **Cloud Platform and Dashboard Configuration:** A cloud channel was created to receive the transmitted data, with a separate field allocated to each measured quantity. The dashboard was configured to display live values together with time-series charts for voltage, current, power, and energy.

5. **Alerting Mechanism:** Threshold-based rules were implemented to detect abnormal operating conditions and low power output. When a threshold is crossed, a notification is generated so that the condition can be investigated.

6. **Testing, Calibration and Validation:** The assembled system was tested first with a regulated DC supply and subsequently with an actual solar panel. The sensor readings were compared against a calibrated multimeter and the calibration coefficients were adjusted accordingly. Continuous operation and simulated fault conditions were then exercised to verify the stability of the logging and the correctness of the alert logic.

5. IMPLEMENTATION

The system was assembled on a Vero board carrying the ESP32, the voltage-divider network, the ACS712 current sensor, the temperature and light sensors, the LCD module, the voltage regulator, and the associated passive components. The solar panel was connected to the sensing network through PBT connectors, with the voltage divider placed across the panel terminals

and the current sensor placed in series with the load, so that the delivered power could be computed from simultaneous measurements of the two quantities. The ESP32 was programmed to sample the sensors at a fixed interval, convert the readings, compute the power and energy, update the local display, and publish the record to the cloud channel. A demonstration model was constructed in which the monitored panel supplies a small lighting load, allowing the relationship between the generated power and the connected load to be observed directly during testing. The assembled prototype is shown in Fig. 2. Before deployment, the assembly was verified for correct sensor polarity, stable supply voltage, and reliable Wi-Fi association, and the null point of the current sensor was recorded with the load disconnected.



Figure 2: Hardware implementation of the prototype with the monitored panel and connected load.

6. RESULTS AND DISCUSSION

The developed system was tested outdoors with the solar panel exposed to natural sunlight, and it operated continuously for the duration of each test without loss of connectivity. The panel voltage, current, power, and accumulated energy were acquired at the configured interval, displayed locally, and transmitted successfully to the cloud channel. The field arrangement and the resulting cloud dashboard are shown in Fig. 3, in which the four channel fields correspond to the measured voltage, the measured current, the computed power, and the accumulated energy.



Figure 3: Field deployment of the monitored panel and the corresponding cloud dashboard.

The recorded voltage and current traces fluctuated continuously about their mean values over the observation window. These fluctuations follow the variation of incident irradiance caused by passing cloud and by the changing solar angle, and confirm that the system resolves short-term changes in generation rather than merely reporting an average. The power channel, being the product of the two measured quantities, reflected the same variation, while the energy channel increased monotonically as the power samples were integrated, with a discontinuity corresponding to the point at which the accumulator was reset during testing. The ability to observe these traces remotely is the principal practical benefit of the system, since a comparable manual measurement campaign would require continuous attendance at the installation.

The interpretation of the measured data follows directly from the electrical characteristic of a photovoltaic module. As shown in Fig. 4, the current remains nearly constant over the lower part of the voltage range and then falls sharply as the open-circuit voltage is approached, so that the product of current and voltage passes through a maximum power point. Because the operating point of a directly connected load does not generally coincide with this maximum, the measured power is expected to lie below the peak of the characteristic; the recorded traces are consistent with operation on the rising portion of the power curve. The characteristic also explains the observed sensitivity of the output to irradiance and temperature, since a fall in irradiance lowers the current plateau while a rise in cell temperature reduces the open-circuit voltage.

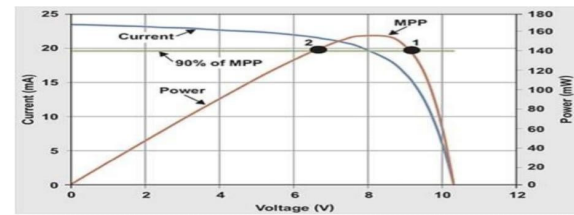


Figure 4: Current–voltage and power–voltage characteristics of a photovoltaic module showing the maximum power point.

Comparison of the sensor readings with a calibrated multimeter during the validation stage showed agreement within a few per cent for both voltage and current, consistent with the expected error budget arising from the ADC resolution, the divider tolerance, and the offset of the current sensor. The architecture also scales without redesign: because each unit publishes independently to its own cloud channel, additional panels can be monitored by replicating the node rather than by modifying the system structure. Overall, the results demonstrate that the proposed system provides a practical and inexpensive means of observing photovoltaic performance continuously and of detecting deviations early, although the accuracy of the measurements depends on careful calibration, and continuity of operation depends on the stability of the Wi-Fi connection and of the supply to the monitoring node.

7. CONCLUSION

This work presented the design and implementation of an IoT-based smart solar monitoring system built around the ESP32 microcontroller. The system measures the voltage, current, temperature, and light intensity associated with a photovoltaic panel, computes the instantaneous power and the accumulated energy at the edge, displays the values locally, and transmits them over Wi-Fi to a cloud dashboard that provides live readings and historical trends together with threshold-based fault indication. Field testing confirmed continuous acquisition, correct computation of the derived quantities, and reliable remote visualisation of the recorded data. The system therefore converts photovoltaic monitoring from a periodic, manual record-keeping exercise into a continuous and remotely accessible process, at a cost appropriate to domestic, institutional, and agricultural installations. Future work will extend the platform with maximum power point tracking,

longer-term storage for seasonal performance analysis, and automated diagnosis of the fault signatures identified in this study.

ACKNOWLEDGMENT

The authors gratefully acknowledge the guidance of Dr. Ritwik Haldar, Department of Electronics & Communication Engineering, Haldia Institute of Technology, throughout this work, and the Department for providing the laboratory facilities used to build and test the prototype.

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