Jurnal Kejuruteraan 38(7) 2026: 3483-3494
https://doi.org/10.17576/jkukm-2026-38(7)-26

# Integration of IoT Technologies for Real-Time Monitoring and Communication Assessment in Remote PV Systems

Zhao Wenya & Muhammad Hafeez Mohamed Hariri*

*School of Electrical & Electronic Engineering, Tuanku Syed Sirajuddin Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.*

*Corresponding author: muhammadhafeez@usm.my*

*Received 8 January 2026, Received in revised form 1 June 2026*
*Accepted 1 July 2026, Available online 30 October 2026*

ABSTRACT

*Conventional photovoltaic (PV) systems often encounter significant technical bottlenecks in real-time monitoring, remote operational control, and wireless communication range, particularly when deployed in geographically isolated regions. These constraints frequently lead to protracted fault detection, operational rigidity, and suboptimal data transmission efficiency. This study proposes an integrated Internet of Things (IoT)-based energy management framework designed to mitigate these challenges through an affordable and scalable architecture. The system utilizes an ESP8266 Wi-Fi module, high-precision voltage and current sensors, and the Blinker IoT platform to facilitate synchronized PV monitoring and remote load management via a mobile interface. Critically, while the remote control functionality is established within the software logic and command framework, its physical actuation remains to be validated in future hardware iterations. Experimental validation was conducted under outdoor conditions with an average ambient temperature of 31.6 °C and 76% relative humidity. The prototype, comprising a monocrystalline solar panel, a 12 V lead-acid battery, and a DC load, demonstrated a steady solar input of 8.79 W. Analytical results indicated a distribution of 4.79 W to the load and 2.31 W for storage, with a measured line loss of 1.64 W. Communication assessments revealed that the system maintains robust stability up to 50 meters; however, at a 100-meter threshold, the Received Signal Strength Indicator (RSSI) degraded to –84.15 dBm, with latency escalating to 28.62 seconds and a 19% packet loss rate. This research provides a practical blueprint for enhancing PV system manageability in infrastructure-limited environments by synthesizing low-cost IoT integration with rigorous wireless performance evaluation.*

*Keywords: Photovoltaic system; internet of things; energy management; real-time monitoring; wireless communication*

## INTRODUCTION

The growing global demand for clean, renewable energy has accelerated the adoption of photovoltaic (PV) systems. This trend is especially noticeable in remote and rural areas, which often lack stable electricity infrastructure. PV systems are an effective, environmentally friendly solution. They help reduce reliance on fossil fuels and mitigate climate change impacts. These systems offer a viable energy alternative in areas without grid access. They are also a practical choice where grid expansion is difficult or too expensive (Kavitha & Malathi 2019). Despite their advantages, conventional PV systems still face limitations in real-time monitoring, wireless supervision, and long-range wireless communication. These constraints often delay fault detection, reduce energy utilization efficiency, and increase maintenance requirements, thereby affecting overall system stability and operational performance (Rao et al. 2024c; Shepovalova et al. 2023).

Recent advancements in Internet of Things (IoT) technologies enable integrated sensing, communication, and data processing, supporting monitoring, wireless supervision, and optimized system stability (Lisboa et al. 2025). These features enhance operational efficiency, stability, and responsiveness. They provide critical benefits for managing and maintaining PV systems. Previous studies have demonstrated that IoT applications can enhance the monitoring of key electrical parameters, including voltage, current, power output, and energy consumption, thereby supporting more effective decision-

making and proactive maintenance practices (Muthusamy et al. 2022). A comprehensive review of previous research, summarized in Table 1, highlights the diversity and effectiveness of IoT in energy management. Studies consistently show that IoT-based systems enhance power distribution monitoring. They also enable remote control of electrical loads and provide valuable insights through data analytics. For example, several studies have successfully used IoT platforms for continuous energy monitoring and predictive maintenance in residential and commercial PV systems. These implementations have led to significant reductions in downtime and operational costs (Hercegová et al. 2021; Rao et al. 2024a). A major challenge in existing IoT-based PV systems is the trade-off between functionality and deployment cost. Advanced systems often provide comprehensive monitoring and control capabilities but remain economically impractical for rural deployment, whereas low-cost alternatives typically lack integrated control and communication performance evaluation. In addition, most previous studies were conducted under controlled laboratory conditions, with limited investigation into wireless stability under the high-temperature and high-humidity environments commonly encountered in tropical remote regions. Communication performance can be inconsistent over long distances, which critically affects their effectiveness in remote or rural areas (Khalid et al. 2024a).

Table 1 provides a detailed comparative analysis of several recent studies, focusing on their application scope, advantages, and drawbacks in IoT-based PV energy management. This comparative overview reveals substantial variations in performance, highlighting that most existing IoT-based PV management systems focus predominantly on either short-range monitoring or specific isolated aspects of system management. Few comprehensive evaluations have been conducted under realistic operating conditions, particularly those that address the stability of long-range wireless communication and the ease of practical deployment (Beltrán Castañón et al. 2025). This study addresses these deficiencies by developing a streamlined, IoT-based energy management framework that prioritizes both affordability and operational transparency. Distinguishing itself from conventional monitoring-only tools, this study introduces a software-defined logic for remote load management and, crucially, provides a rigorous quantification of wireless signal stability and latency boundaries up to 100 meters under realistic outdoor interference. Unlike conventional IoT-based PV monitoring studies that primarily focus on data acquisition, this study contributes an empirical evaluation of wireless communication stability under realistic tropical outdoor conditions, including the quantitative assessment of RSSI degradation, latency escalation, and packet loss over extended transmission distances.

TABLE 1. Comparative analysis of applications in an IoT-based PV system

| No | Reference | Scope of Review | Advantages | Drawbacks |
|---|---|---|---|---|
| 1 | (Manu et al. 2022) | Overview of IoT technologies for energy consumption management | Renewable energy integration<br>Demand-side management (DSM)<br>Optimizing energy | Lack of specific case studies<br>Challenges in large-scale implementation |
| 2 | (Samanta et al. 2020) | IoT-based smart EMS for a Standalone PV system | Real-time energy management<br>Novel battery operating algorithm<br>Remote load control | Complexity in system integration<br>Limited scalability |
| 3 | (Chinnathambi et al. 2022) | IoT-based energy management for PV-powered DC systems in residential buildings | Minimizes energy conversion losses<br>Optimized load configuration<br>Uninterrupted power supply | Appliance compatibility challenges<br>Dependency on internet connectivity |
| 4 | (Sheba et al. 2023a) | Off-grid PV-battery system energy management using IIoT | Real-time energy monitoring<br>Battery balancing and load management<br>Cloud-based control | Requires IIoT device setup<br>Limited scalability |
| 5 | (Hosseini et al. 2022) | IoT-based smart microgrid energy management | Identifies demand patterns<br>Automated power supply adjustments<br>Hybrid power generation system | System complexity<br>High setup costs |
| 6 | (Rao et al. 2024b) | IoT-based demand-side management for PV power generation | optimized sustainability<br>Increased PV system efficiency<br>Predictive maintenance | Gaps in control strategies research<br>Limited real-world implementation |

Motivated by the identified shortcomings, this study introduces a cost-effective IoT-based energy management framework specifically engineered to withstand the operational rigors of remote PV installations. By leveraging accessible hardware—specifically the ESP8266 communication module and INA219 high-precision sensors—integrated with the Blinker IoT platform, this study prioritizes deployment simplicity and economic viability without compromising data integrity or monitoring precision.

The primary objectives of this study are strategically structured to provide a comprehensive engineering evaluation. First, the framework establishes a robust real-time monitoring infrastructure to synchronize the acquisition of critical electrical parameters, such as voltage and current, thereby facilitating proactive anomaly detection. Furthermore, it implements a software-defined remote control logic via a mobile interface for conceptual load management. Crucially, this study conducts a rigorous assessment of wireless performance boundaries, quantifying the impact of distance and environmental stressors—specifically temperature and humidity—on RSSI, latency, and packet loss. Such empirical evaluations provide essential data to optimize system configurations and ensure long-term operational stability in challenging rural contexts.

This study aims to develop a practical and scalable IoT-based PV management framework for remote applications. The proposed system is expected to improve monitoring efficiency, operational stability, and communication stability while reducing maintenance complexity and deployment cost. Ultimately, the study seeks to deliver a reference model that is easy to replicate and scale. This will facilitate the broader adoption and implementation of IoT-based PV solutions. In doing so, it will support global renewable energy development goals and contribute to environmental sustainability and rural electrification efforts.

## METHODOLOGY

### SYSTEM OVERVIEW

With the growing global demand for sustainable energy, solar power has gained increasing attention as a key renewable energy source. PV systems, which are the primary means of harnessing solar energy, play a critical role in the global energy transition. However, challenges remain in integrating and managing large-scale and off-grid PV installations. Conventional PV management systems often suffer from limited monitoring capability and inefficient communication, which may lead to energy loss and reduced operational efficiency (Rao et al. 2024b). Figure 1 illustrates the system architecture, integrating sensors, microcontrollers, and cloud platforms to enable continuous monitoring and efficient management of PV performance.

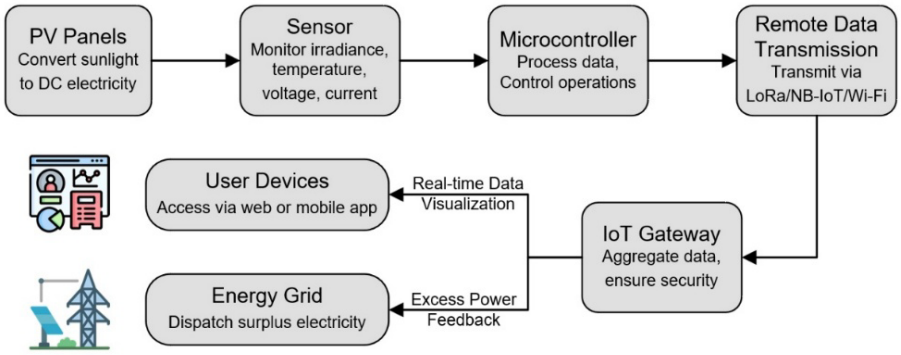



FIGURE 1. IoT-Based Smart Energy System Architecture

Intelligent energy management systems powered by the Internet of Things offer effective solutions to the limitations of traditional PV management. These systems enable real-time monitoring and better control of energy flows. They also optimize energy utilization, improving overall efficiency (Kalay et al. 2022). IoT devices enable precise fault detection, load management, and real-time optimization by continuously collecting and transmitting data. Extended communication ranges allow efficient operation over greater distances, making these systems ideal for off-grid applications (Kayalvizhi et al. 2024; Rudra Kumar et al. 2023). Table 2 summarizes the main components of the IoT-based PV monitoring system, listing each device's reference model, technical parameters (e.g., voltage, capacity, speed), and its dedicated functional roles in enabling real-time data acquisition and energy management.

TABLE 2. Major components of the IoT-based PV monitoring system

| Component | Reference Model | Key Parameters | Function |
|---|---|---|---|
| Solar Panel | MY-SKUG09903 | $V_{mpp}$ = 6V<br>$I_{mpp}$ = *1A*<br>$V_{oc}$ = *7V*<br>$I_{sc}$ =*1.1A* | Primary energy source converting solar radiation into electricity |
| Charge Controller | ELE-SOL007 | $V_{rated}$=12V<br>$I_{rated}$=30A<br>$P_{mpp}$=300W | Regulates voltage/current and protects the battery |
| Battery | GPP1272 | C = 7.2AH | Stores energy for continuous supply under low irradiance |
| INA219 Sensor | I²C | $V_{input}$ = 3-5.5V | Provides real-time measurements of voltage, current, and power |
| DC Fan | MC002103 | Max. Fan Speed= 4500 RPM ± 10% | Represents test load for performance evaluation |
| Microcontroller | ESP8266 Module NodeMCU Lolin v3 | $V_{input}$ = *7-12 V*<br>$V_{operate}$ = *3.3V* | Serves as a central controller and wireless communication hub |

## HARDWARE IMPLEMENTATION

The hardware of the IoT-based PV monitoring system was assembled into an experimental prototype, as illustrated in Figure 2, to validate its functionality under specific operational conditions. The setup comprises an 8.74 W monocrystalline PV panel, a PWM charge controller, and a 12 V battery designed to power a DC fan load. To maintain system health, the PWM controller regulates the charging process and prevents battery overvoltage, thereby ensuring consistent power delivery during periods of low irradiance.

For data acquisition, an ESP8266 module and three INA219 sensors are integrated onto a custom test board to facilitate real-time monitoring. These sensors are strategically positioned at the PV output and load terminals to measure critical electrical parameters, transmitting data to the ESP8266 via the I²C protocol for centralized processing. Programmed within the Arduino IDE, the ESP8266 serves as the primary control hub, enabling seamless wireless communication with the Blinker IoT platform. Furthermore, a relay module is incorporated to support remote or automated switching of the DC fan load. This modular architecture demonstrates the feasibility of IoT-enabled monitoring for small-scale PV applications. For long-term outdoor deployment, protective enclosures and thermal management measures are recommended to ensure the durability and operational stability of the electronic components in high-humidity or high-temperature environments.

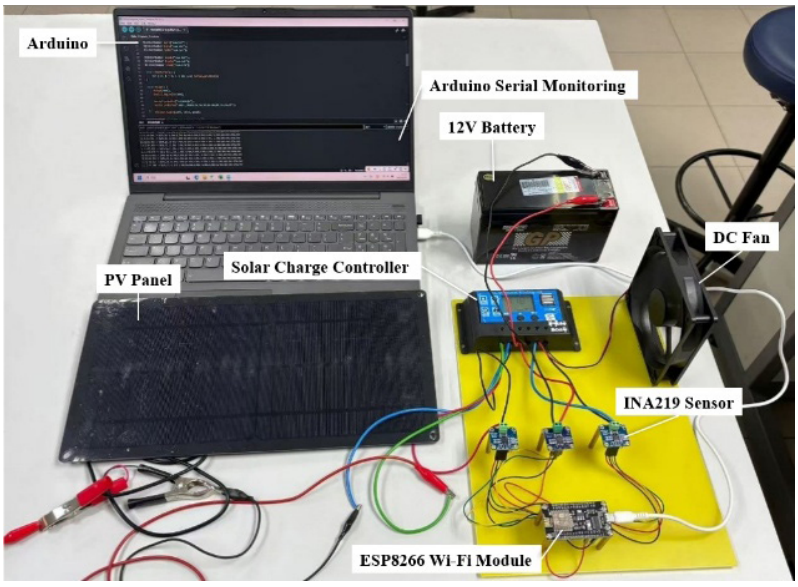



FIGURE 2. Hardware implementation of the PV monitoring system

## SOFTWARE AND IOT PLATFORM

The software configuration was developed using the Arduino IDE for programming and the Blinker IoT platform for monitoring and control. The ESP8266 module was programmed in a simplified C/C++ environment to acquire sensor data, execute basic control functions, and establish Wi-Fi communication. Firmware was uploaded via the Arduino IDE, and debugging was performed using the built-in serial monitor. This allowed for real-time observation of voltage, current, and power data from the INA219 sensor. The Arduino IDE was used for firmware development and debugging.

On the IoT side, the Blinker platform served as the interface for data visualization and wireless supervision. As shown in Figure 3, the mobile dashboard displays solar panel voltage, current, power, battery status, and fan load operation. A toggle switch enables remote control of the DC fan via cloud-based communication with the ESP8266. The platform also enables historical data logging for performance evaluation.

The integration of the Arduino IDE and Blinker demonstrates a low-cost, accessible software framework that supports rapid prototyping, reliable monitoring, and responsive control. Additionally, this framework offers good scalability, allowing for future expansion to more complex load management or multi-panel monitoring scenarios.

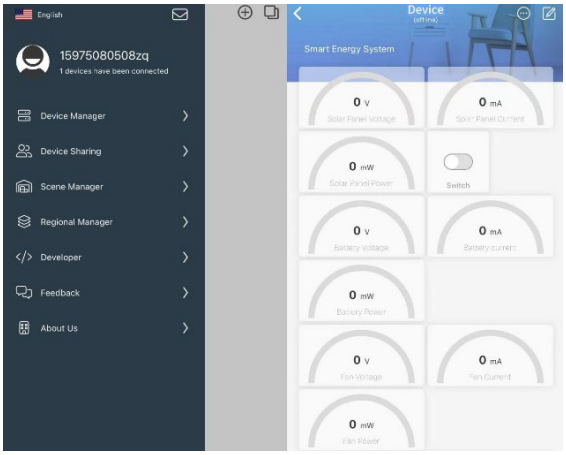



FIGURE 3. Blinker App Interface for PV Monitoring

## DATA COLLECTION AND EVALUATION

The data collection used INA219 sensors at PV output and load terminals for voltage, current, and power readings. These were sent to the ESP8266 via I²C, processed, and uploaded to the Blinker IoT platform over Wi-Fi. The Arduino IDE serial monitor provided local debugging, ensuring consistency between on-board data and remote monitoring. This setup allowed verification and long-term logging of operations data.

In addition to recording electrical parameters, the system's communication performance was evaluated over different operating distances. Test groups were set at distances of 0 m, 25 m, 50 m, 75 m, and 100 m between the ESP8266 module and a smartphone hotspot. Data transmission success rates and latency were recorded and stored in Excel spreadsheets for each group. This method allowed for a structured analysis of connectivity stability and signal strength across varying ranges, reflecting the practical limits of Wi-Fi-based monitoring in off-grid environments (Ishimwe et al. 2024). The combined evaluation confirmed that the proposed system could provide real-time records of PV voltage, current, and power and maintain stable wireless communication up to 100 m in open-field conditions. These results validate the feasibility of the IoT-based framework for remote monitoring and highlight its potential for extension into larger-scale or distributed PV systems.

## ASSESSMENT OF POWER CONSUMPTION

Mathematical models for instantaneous power and accumulated energy were implemented directly in the ESP8266 microcontroller to evaluate the performance of the IoT-based PV monitoring system. These calculations are crucial for analyzing the system's real-time energy flow, efficiency, and component behavior.

The instantaneous electrical power is calculated using the product of voltage and current, as shown in Equation (1). This equation applies to the solar panel, battery, and load (fan). The system code receives real-time voltage and current measurements from the INA219 sensor via I²C, which are then used to compute the instantaneous power for each component.

$$P=V*I \tag{1}$$

To analyze energy in the IoT-based PV system, energy is calculated as the product of instantaneous power and elapsed time, shown in Equation (2). $E$ is in watt-hours, and $t$ is in hours. In the code, this calculation uses fixed intervals, with power readings accumulated continuously. Every 2 seconds, voltage, current, and power values are sent to the Blinker IoT platform for visualization and data logging, ensuring accurate energy tracking analysis (Sutikno 2026).

$$E=P*t=V*I*t \tag{2}$$

The overall system efficiency is calculated using Equation (3), which accounts for power conversion stages, wiring losses, and load utilisation. The numerator represents the useful output power delivered to the load, while the denominator corresponds to the total input power supplied by the PV panel. To enhance the stability of the engineering evaluation, an uncertainty analysis was incorporated into the measurement framework. The uncertainties associated with voltage and current measurements from the INA219 sensors, as well as external validation using a calibrated digital multimeter, were considered. Error propagation analysis was applied to estimate the uncertainty in calculated power and efficiency values. This approach enables a more rigorous interpretation of system performance by quantifying potential measurement deviations and improving the credibility of the reported results.

$$\eta = \frac{P_{Out}}{P_{In}} \times 100\% \quad (3)$$

## RESULTS AND DISCUSSION

### REAL-TIME MONITORING AND REMOTE CONTROL

The system was tested for continuous monitoring and remote control of PV parameters. The ESP8266 microcontroller collects real-time electrical data from the INA219 sensor, which is connected to the solar panel, battery, and load circuit. It formats the readings into JSON and wirelessly transmits the data via Wi-Fi to the Blinker IoT platform. The Blinker mobile app decodes the JSON data and displays it on a user-friendly dashboard, with key metrics organized in segmented widgets. Figure 4 shows this interface, highlighting real-time solar voltage (11.4 V), current (75 mA), power, battery status, and fan load, refreshed every 2 seconds and accessible from any internet-enabled device.

The solar panel generated approximately 11.4 V and 75 mA, while the 12 V lead-acid battery maintained 11.97 V and 3200 mA, providing a steady current. The DC fan used about 400 mA, with the remote control (toggled via the "Switch") included in the system, which will be physically implemented later. The interface allows visualization of energy flow and load monitoring, demonstrating the integration of IoT in PV systems. The results demonstrate that the system enables reliable real-time monitoring and effective remote control for small-scale PV applications, which is crucial for off-grid PV applications. This enhances user interaction and improves overall energy management efficiency.




FIGURE 4. Real-time Monitoring via Blinker Interface

### TESTING RESULT ANALYSIS

This section presents and analyses the experimental results from real-time monitoring of the solar panel, battery, and load (fan). The recorded electrical parameters, including voltage (V), current (A), and power (W), are shown through various line graphs. All measurements were taken on 15 June 2025, from 12:00 PM to 1:00 PM, under partially cloudy conditions in an outdoor open space. To ensure scientific objectivity and reduce the influence of transient environmental variations, multiple experimental trials were conducted under similar operating conditions. Among these datasets, a representative dataset with consistent system behaviour was selected for detailed analysis and presentation. The selection was based on the stability of key electrical parameters, including voltage, current, and power, ensuring that the reported results accurately reflect typical system performance rather than anomalous conditions. The solar panel was placed flat on the ground, with an average ambient temperature of approximately 31.6°C and a relative humidity of about 76%. These visualisations demonstrate the performance characteristics and temporal variations of each component, allowing for comparative analysis and detection of any operational anomalies. Voltage and current measurements were taken using a calibrated digital multimeter across the controller's terminals, ensuring reliable and accurate readings in accordance with standard measurement practices.

Figure 5 shows the real-time voltage and current during the hour-long observation. Figure 5(a) depicts the solar panel's voltage, which remained stable between 11.300 V and 11.370 V, with minor fluctuations. A spike to 11.343 V at 11:49 AM may be due to increased solar irradiance, such as when clouds parted, boosting sunlight and generating more photocarriers. This shift would push the panel toward a higher voltage on the I–V curve.

Conversely, Figure 5(b) shows that the PV output current gradually decreased from 0.775 A to approximately 0.511 A by 12:48 PM, mainly due to reduced solar irradiance caused by cloud cover and changes in solar position. Minor fluctuations were attributed to intermittent shading effects. This decline is attributable to the continuous reduction in solar irradiance resulting from the sun's changing position or intermittent cloud cover, thereby affecting the incident photon count and consequently decreasing the photogenerated current.

Figure 5(c) illustrates the battery charging voltage, which remained steady at approximately 11.95 V, signifying effective regulation by the PWM charge controller. The battery charging current (Figure 5(d)) exhibited slight fluctuations around 0.18 A, aligning with the charging power of 2.31 W. Figures 5(e) and 5(f) depict the load (fan) supply voltage and current, which maintained stability at approximately 11.96 V and 0.4 A, respectively, thereby confirming reliable power delivery to the load.

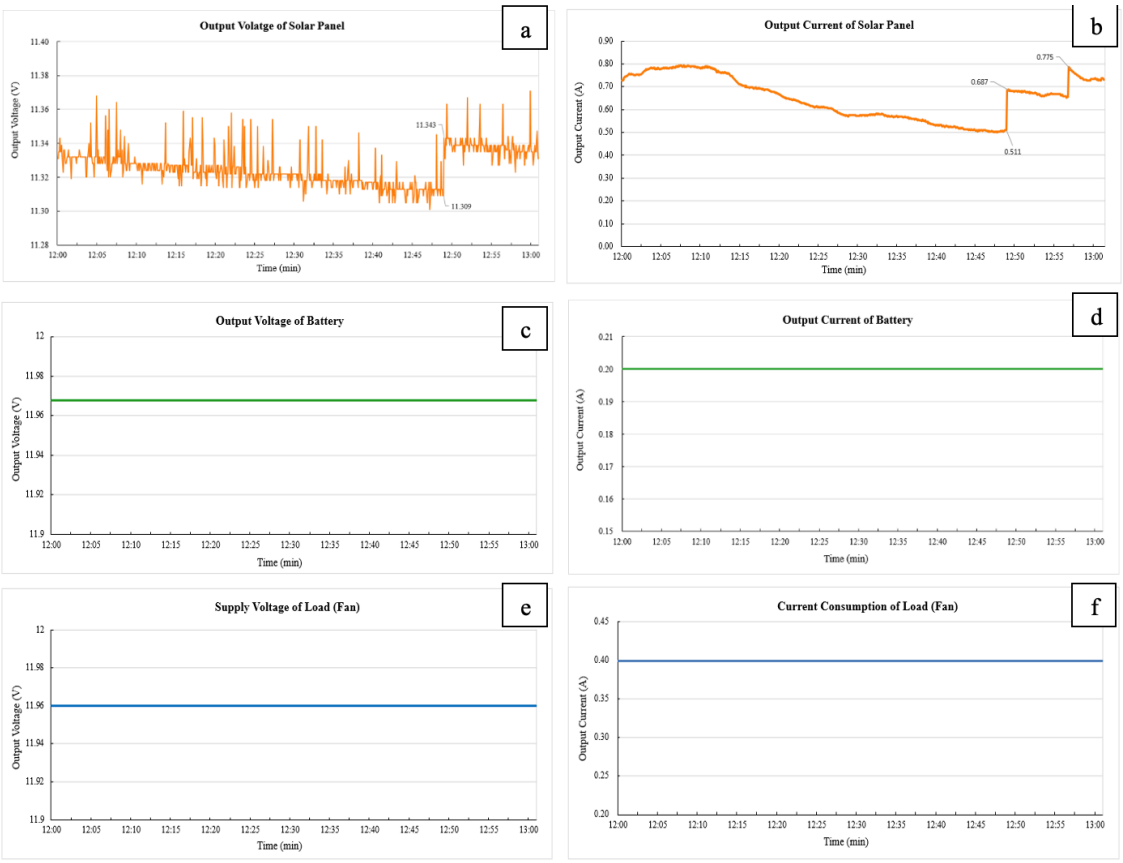



FIGURE 5. Experimental results of the PV-battery-load system: (a) PV panel output voltage, (b) PV panel output current, (c) battery charging voltage, (d) battery charging current, (e) load supply voltage, and (f) load current consumption

## ESP8266 COMMUNICATION PERFORMANCE EVALUATION

Three key indicators were assessed: latency, Received Signal Strength Indicator (RSSI), and packet loss rate. The evaluation was conducted by varying the distance between the ESP8266 module and a smartphone hotspot (0 m, 25 m, 50 m, 75 m, and 100 m) in open-field conditions. This setup allowed for the assessment of the system's performance under different signal strengths and transmission ranges. Data were collected via serial monitoring and cloud-based logs from the Blinker platform, enabling real-time analysis of communication efficiency and reliability. The analysis focused on how these metrics change as the communication distance increased, which is critical for understanding the system's behavior in typical off-grid scenarios. Figure 6 illustrates the transmission distance between the ESP8266 Wi-Fi module and the user interface devices, highlighting the impact of distance on communication quality.

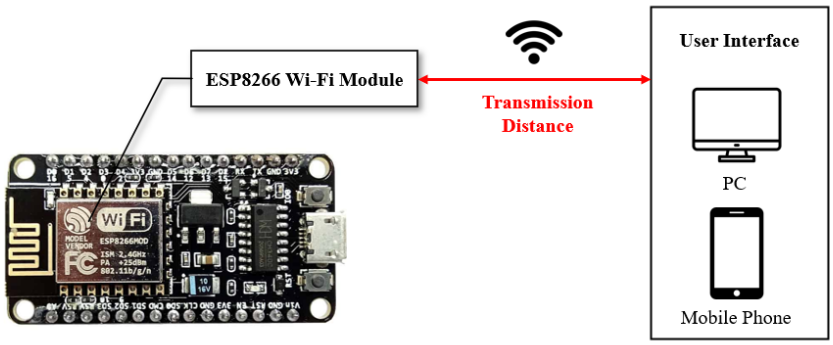



FIGURE 6. Data communication link via the ESP8266 Wi-Fi module to terminal devices

The ESP8266 operating in the 2.4 GHz band is susceptible to interference and signal attenuation, particularly in outdoor environments. Figure 7 shows that the average latency increased from 20.03 s at 0 m to 28.62 s at 100 m as the communication distance increased. This is significantly higher than typical IoT communication latency, which is generally below 1 s and around 200–500 ms for MQTT under ideal conditions. (Khalid et al. 2024b) The excessive delay is primarily attributed to signal degradation, retransmissions, and network congestion under weak RSSI conditions. Such latency is unsuitable for critical real-time fault detection in PV systems but remains acceptable for non-critical monitoring applications, such as periodic performance tracking in remote environments. Performance can be optimized by adopting alternative communication technologies (e.g., LoRa or LTE) or implementing edge processing strategies.

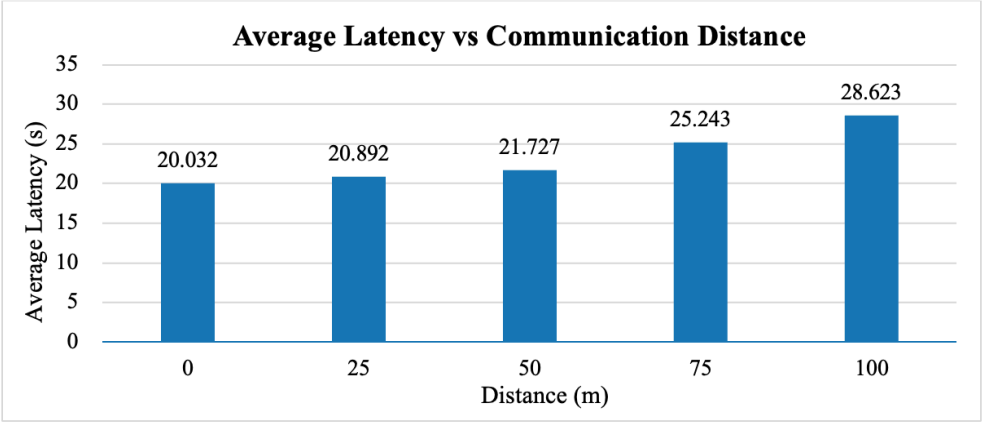



FIGURE 7. Average Latency (s) versus Communication Distance (m)

RSSI represents the received signal strength of a wireless link, expressed in dBm, with values closer to 0 indicating stronger signals (Kulhandjian et al. 2025). Figure 8 shows a clear decreasing trend in RSSI with increasing distance, from −39.9 dBm at 0 m to −84.15 dBm at 100 m. The signal strength drops below the typical −75 dBm threshold beyond 75 m, where Wi-Fi performance degradation becomes evident, leading to increased latency and packet loss. This degradation is primarily caused by free-space attenuation and further intensified by environmental factors such as high humidity (76%) and elevated temperature (31.6 °C), which increase signal absorption and reduce receiver sensitivity. As RSSI decreases, link quality deteriorates, resulting in higher transmission errors, retransmissions, and reduced throughput due to adaptive modulation mechanisms in the communication protocol. These results highlight the impact of environmental and distance-related factors on wireless stability in outdoor PV monitoring applications.

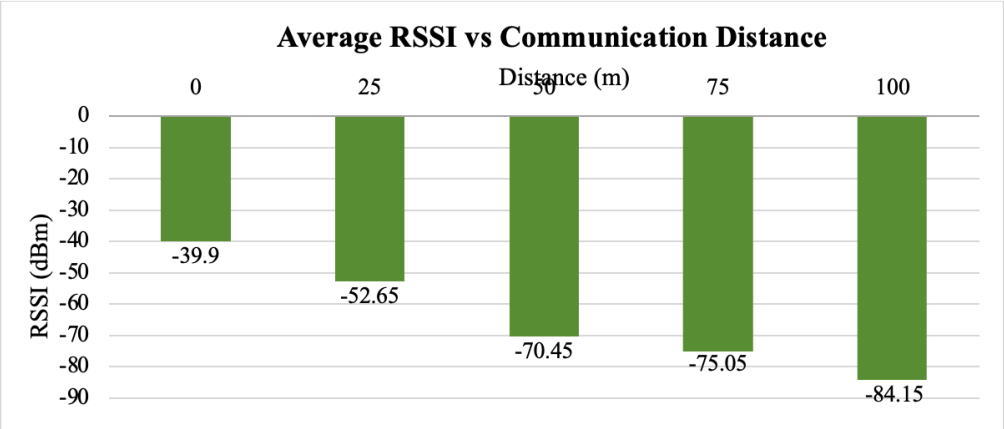



FIGURE 8. Average RSSI(dBm) versus Communication Distance (m)

Packet loss rate is a key metric for evaluating the dependability and stability of wireless communication systems. It is calculated as percentage of transmitted data packets that fail to reach the receiver successfully. High packet loss can lead to data inconsistencies, delayed system responses, and overall performance, particularly in real-time monitoring applications.

In this study, the receiving unit is the ESP8266 Wi-Fi module, which continuously logs incoming messages via the Blinker cloud platform. This setup enables real-time assessment of communication effectiveness under different distance conditions. For instance, during a test at a distance of 50 metres, 100 data packets were transmitted from the sender. However, only 93 packets were successfully received and logged by the ESP8266 module, signalling a packet loss rate of 7% (Janarthanan & Srinivasan, 2024). As shown in Figure 9, packet loss was minimal at 0–25 m, but increased significantly beyond 50 m, reaching 19% at 100 m.

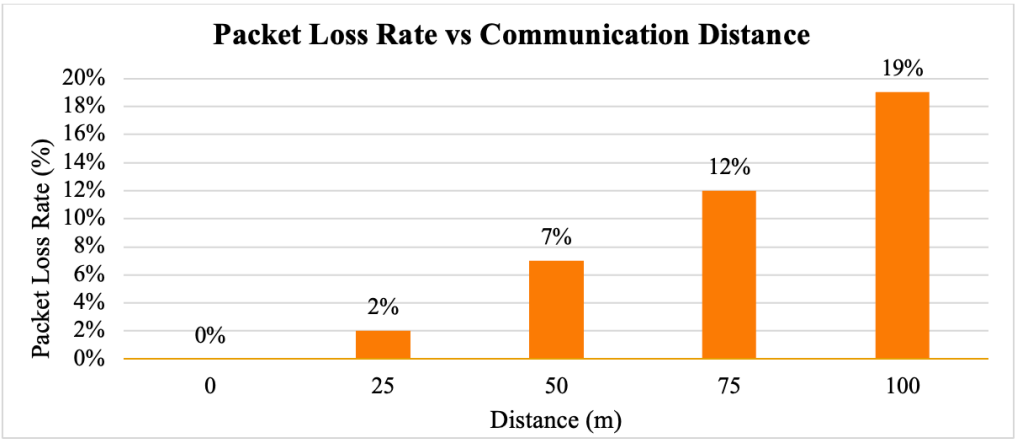



FIGURE 9. Packet Loss Rate (%) versus Communication Distance (m)

Table 3 compares three IoT-powered off-grid PV-battery systems, highlighting technical differences and innovations. It covers six key areas: hardware, functions, specs, communication, deployment, and applications. The hardware uses a low-cost modular design with an ESP8266, INA219 sensors, and the Blinker IoT platform, which is more affordable than (Sheba et al. 2023b) and (Samanta et al. 2020b). Functionally, it combines wireless communication, real-time electrical monitoring, and remote load control, addressing gaps in existing low-cost systems. The 8.74 W PV setup is suitable for remote rural areas, different from larger household or community systems. Communication metrics provide useful benchmarks. The cost is under $50 with a plug-and-play design, making it accessible for resource-limited areas.

TABLE 3. Comparative Benchmark of Advanced IoT-Powered Off-Grid PV-Battery Systems

| Indicator | This study | (Sheba et al. 2023b) | (Samanta et al. 2020b) |
|---|---|---|---|
| Hardware Configuration | ESP8266<br>INA219 sensors<br>Blinker Platform | IIoT device (ESP8266)<br>Modbus RS485<br>ndustrial sensors | Raspberry Pi<br>MODBUS TCP/IP<br>MQTT gateway |
| Functionalities | Real-time monitoring<br>Wireless performance | Real-time energy monitoring<br>SOC balancing<br>Adaptive load management | Microgrid monitoring<br>VRFB scheduling<br>Grid outage fallback |
| System Specifications | 8.74 W PV panel<br>12 V/7.2 Ah lead-acid battery<br>4.79 W DC fan load | Off-grid PV-battery system P&O MPPT | 10 kWV array<br>6 kWh VRFB storage<br>15 kVA biogas generator |
| Communication Performance | Wi-Fi (2.4 GHz)<br>50 m stable (0% packet loss)<br>100 m: RSSI -84.15 dBm, latency 28.62 s | Wi-Fi and Bluetooth<br>30 m stable communication | MQTT over TCP/IP<br>Microgrid-level connectivity<br>Cloud-edge synergy |
| Deployment Metrics | Low-cost (<$50)<br>Modular<br>Plug-and-play | Medium-cost ($120–150)<br>Field-deployable | Medium-to-high cost (> $300)<br>Campus-pilot<br>24 h load profile coverage |
| Target Application | Remote/rural small-scale off-grid PV systems | Household off-grid PV-battery systems<br>Water well irrigation | Community-scale hybrid microgrid |

Compared with existing low-cost IoT-based PV monitoring systems, the proposed framework integrates wireless communication performance evaluation with outdoor validation using modular hardware components. The system maintained stable communication up to 50 m, while performance degraded at longer distances due to reduced signal strength. In addition to real-time monitoring, the framework incorporates software-based load control and battery–load coordination, providing a more comprehensive evaluation than monitoring-only implementations. The use of low-cost components such as the ESP8266 and INA219 sensors supports practical deployment for small-scale remote PV applications.

The measured line loss of 1.64 W (18.6% of the input power) is relatively significant for a small-scale PV system. This loss is mainly attributed to resistive losses in wiring ($I^2R$), which depend on conductor length and wire gauge. Additional contributions arise from voltage drops, sensor power consumption, and inefficiencies in the charge controller and connection interfaces. These losses can be reduced by using thicker conductors, minimizing wiring length, improving connection quality, and adopting more efficient power management components.

## CONCLUSION

This study presents an IoT-based PV energy management system and evaluates its performance under outdoor conditions. Experiments were conducted on 15 June 2025 (12:00–13:00) in an open environment with an average temperature of 31.6 °C and relative humidity of 76%. The measured solar input power was 8.79 W, of which 4.79 W was delivered to the load and 2.31 W was used for battery charging, while line losses accounted for 1.64 W.

To ensure measurement stability, an uncertainty analysis was performed based on the INA219 sensor accuracy (±1%). The combined relative uncertainty for power measurements was estimated at ±1.41% using the root-sum-square method, corresponding to an absolute uncertainty of ±0.12 W. This confirms that the observed energy distribution and line losses remain statistically significant. The measured input power is also consistent with the PV panel's rated power (8.74 W) within experimental tolerance.

Wireless communication performance was evaluated using RSSI, latency, and packet loss. Stable communication was maintained up to 50 m, while at 100 m the signal degraded significantly (RSSI −84.15 dBm), accompanied by increased latency (28.62 s) and packet loss (19%). These results indicate that the system is suitable for non-critical remote monitoring applications but limited for long-distance real-time control using Wi-Fi. The integration of ESP8266, INA219 sensors, and the Blinker platform enabled stable wireless monitoring of key PV electrical parameters under outdoor operating conditions. It should be noted that remote control was implemented at the software level only and was not physically validated in this study.

## ACKNOWLEDGEMENT

This study was supported by a Universiti Sains Malaysia, Short-Term Grant with Project No: 304/PELECT/6315776.

## DECLARATION OF COMPETING INTEREST

None.

## REFERENCES

Beltrán Castañón, N.J., Chura Acero, F., Ramos Cutipa, J., Chayña Velásquez, O., Shuta Lloclla, H. & Cruz Ticona, E. 2025. A low-cost wireless monitoring system for photovoltaic systems: Performance analysis and potential application in direct-current nanogrids. *Energies* 18(9): 2279. https://doi.org/10.3390/en18092279

Chinnathambi, N.D., Nagappan, K., Samuel, C.R. & Tamilarasu, K. 2022. Internet of things-based smart residential building energy management system for a grid-connected solar photovoltaic-powered DC residential building. *International Journal of Energy Research* 46(2): 1497–1517. https://doi.org/10.1002/er.7264

Hercegová, K., Baranovskaya, T. & Efanova, N. 2021. Smart technologies for energy consumption management. *SHS Web of Conferences* 128: 02005. https://doi.org/10.1051/shsconf/202112802005

Hosseini, S.A., Hojjat, M. & Azarfar, A. 2022. An integrated home energy management system by the load aggregator in a microgrid using the internet of things infrastructure. *International Journal of Electrical and Computer Engineering* 12(6): 6796–6805. https://doi.org/10.11591/ijece.v12i6.pp6796-6805

Ishimwe, V., Mongilli, M., Rukundo, E., Matrella, G. & Ciampolini, P. 2024. IoT-based smart management of off-grid photovoltaic systems in rural and remote settings. In *2024 IEEE PES/IAS PowerAfrica*, 1–5. https://doi.org/10.1109/PowerAfrica61624.2024.10759406

Janarthanan, A. & Srinivasan, V. 2024. Multi-objective cluster head-based energy aware routing using optimized auto-metric graph neural network for secured data aggregation in wireless sensor network. *International Journal of Communication Systems* 37(3): e5664. https://doi.org/10.1002/dac.5664

Kalay, M.Ş., Kılıç, B. & Sağlam, Ş. 2022. Systematic review of the data acquisition and monitoring systems of photovoltaic panels and arrays. *Solar Energy* 244: 47–64. https://doi.org/10.1016/j.solener.2022.08.029

Kavitha, V. & Malathi, V. 2019. A smart solar PV monitoring system using IoT. *Computer Science & Information Technology* 9(15): 19–33. https://doi.org/10.5121/csit.2019.91502

Kayalvizhi, N., Santhosh, M., Thamodharan, R. & Dhileep, M. 2024. IoT-enabled real-time monitoring and predictive maintenance for solar systems: Maximizing efficiency and minimizing downtime. In *2024 International Conference on Smart Systems for Applications in Electrical Sciences (ICSSES)*. https://doi.org/10.1109/ICSSES62373.2024.10561454

Khalid, W., Jamil, M., Khan, A.A. & Awais, Q. 2024. Open-source Internet of Things-based supervisory control and data acquisition system for photovoltaic monitoring and control using HTTP and TCP/IP protocols. *Energies* 17(16): 4083. https://doi.org/10.3390/en17164083

Kulhandjian, H., Cruz, M., Gaona Juárez, R., García-Barrientos, A., Acosta-Elias, J., Stevens-Navarro, E., Galván, C.G., Palavicini, A. & Monroy Cruz, E. 2025. Design and implementation of an indoor localization system based on RSSI in IEEE 802.11ax. *Applied Sciences* 15(5): 2620. https://doi.org/10.3390/app15052620

Lisboa, Y., Santos, L., Lobato, E., Fonseca, W., Silva, K., Rodrigues, I. & Silva, M. 2025. Design and implementation of a sustainable IoT embedded system for monitoring temperature and humidity in photovoltaic power plants in the Amazon. *Sustainability* 17(6): 2347. https://doi.org/10.3390/su17062347

Manu, D., Shorabh, S.G., Gnana Swathika, O.V., Umashankar, S. & Tejaswi, P. 2022. Design and realization of smart energy management system for standalone PV system. *IOP Conference Series: Earth and Environmental Science* 1026(1): 012027. https://doi.org/10.1088/1755-1315/1026/1/012027

Muthusamy, P.D., Velusamy, G., Thandavan, S., Govindasamy, B.R. & Savarimuthu, N. 2022. Industrial Internet of things-based solar photo voltaic cell waste management in next generation industries. *Environmental Science and Pollution Research* 29(24): 35542–35556. https://doi.org/10.1007/s11356-022-19411-8

Rao, C.K., Sahoo, S.K. & Yanine, F.F. 2024a. A systematic review of recent developments in IoT-based demand side management for PV power generation. *Energy Harvesting and Systems* 11(1): 20230124. https://doi.org/10.1515/ehs-2023-0124

Rao, C.K., Sahoo, S.K. & Yanine, F.F. 2024b. An IoT-based intelligent smart energy monitoring system for solar PV power generation. *Energy Harvesting and Systems* 11(1): 20230015. https://doi.org/10.1515/ehs-2023-0015

Rudra Kumar, M., Rupa Devi, B., Rangaswamy, K., Sangeetha, M. & Kumar, K.V.R. 2023. IoT-edge computing for efficient and effective

information process on industrial automation. In *2023 International Conference on Networking and Communications (ICNWC)*, 1–6. https://doi.org/10.1109/ICNWC57852.2023.10127492

Samanta, H., Bhattacharjee, A., Pramanik, M., Das, A., Das Bhattacharya, K. & Saha, H. 2020. Internet of things based smart energy management in a vanadium redox flow battery storage integrated bio-solar microgrid. *Journal of Energy Storage* 32: 101967. https://doi.org/10.1016/j.est.2020.101967

Sheba, M.A., Mansour, D.E.A., Abbasy, N.H. & Ali, G.E.M. 2023. Intelligent energy management system for off-grid PV-battery system using IIoT device. In *2023 24th International Middle East Power System Conference (MEPCON)*, 1–8. https://doi.org/10.1109/MEPCON58725.2023.10462402

Shepovalova, O., Arbuzov, Y., Evdokimov, V., Ilyushin, P. & Suslov, K. 2023. Assessment of the gross, technical and economic potential of region's solar energy for photovoltaic energetics. *Energies* 16(3): 1262. https://doi.org/10.3390/en16031262

Sutikno, T. 2026. Intelligent systems, AI/ML, IoT, smart grids, robotics, healthcare, and emerging innovations. *International Journal of Electrical and Computer Engineering* 16(2): 559–562. https://doi.org/10.11591/ijece.v16i2.pp559-562