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Design and Analysis of IoT-Based Smart Monitoring System for Solar Power Plants

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Abstract. *The increasing adoption of solar power plants as a renewable energy source requires efficient monitoring systems to ensure optimal performance and reliability. Conventional monitoring methods are often limited in providing real-time data and early fault detection, which can reduce system efficiency and increase maintenance costs. Therefore, this study aimed to design and analyze a smart monitoring system based on the Internet of Things for solar power plants that enables continuous data acquisition, real-time monitoring, and performance evaluation. This research employed an experimental and quantitative approach by integrating sensors, a microcontroller, wireless communication, and a cloud-based platform into a unified system. The system measured key parameters, including voltage, current, power, temperature, and solar irradiance, and transmitted the data to a cloud dashboard for visualization. The results showed that the system successfully monitored all parameters in real time with measurement errors below 3 percent. The data transmission latency ranged from 1.2 to 1.5 seconds, indicating fast and stable communication performance. In addition, the system demonstrated high reliability, operating continuously for 8 hours without downtime or data loss. These findings indicate that the proposed system is capable of providing accurate, reliable, and real-time monitoring of solar power plant performance. The study contributes to the development of an integrated and cost-effective monitoring framework that combines multi-parameter sensing, wireless communication, and cloud-based analysis. However, the system was tested on a limited scale and within a short observation period. Future research is recommended to expand the system for large-scale applications and to integrate advanced data analysis techniques for predictive maintenance and performance optimization.*

Keywords. *Internet of Things, solar monitoring, photovoltaic system, real-time data, smart system*

INTRODUCTION

The growing demand for clean and sustainable energy has significantly accelerated the deployment of solar power plants as a major component of global renewable energy systems. Solar photovoltaic (PV) technology offers substantial environmental and economic benefits, including reduced greenhouse gas emissions, scalability, and long-term energy security. However, the performance of solar power plants is highly dependent on environmental factors such as solar irradiance, temperature fluctuations, shading, and system degradation. In many practical cases, insufficient monitoring systems lead to delayed fault detection, reduced power output, and increased maintenance costs. Therefore, the development of reliable and real-time monitoring systems is essential to ensure optimal operation and efficiency of solar power plants (Jordan & Kurtz, 2013; Skoplaki & Palyvos, 2009; Makrides et al., 2010).

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The rapid advancement of the Internet of Things (IoT) has introduced new possibilities for intelligent monitoring in energy systems. IoT enables the integration of sensors, embedded systems, communication networks, and cloud platforms to facilitate real-time data acquisition and remote system supervision. In the context of photovoltaic systems, several studies have demonstrated the effectiveness of IoT-based monitoring approaches. Al-Fuqaha et al. (2015) provided a comprehensive overview of IoT architectures and highlighted their role in enabling smart energy applications. Gungor et al. (2013) emphasized the importance of IoT in smart grid systems for improving energy monitoring and control. Hasan et al. (2018) developed a real-time IoT-based solar monitoring system capable of measuring electrical parameters such as voltage and current. Similarly, Parra et al. (2015) demonstrated the integration of distributed energy resources with communication technologies for improved energy management. Recent studies have further explored IoT applications in photovoltaic monitoring systems. Hamied et al. (2023) proposed a low-cost IoT-based monitoring system for greenhouse PV installations, while Demir (2023) introduced an IoT-based system for real-time monitoring and power estimation. Ferlito et al. (2024) designed an IoT-based SCADA system for utility-scale PV plants, and Khalid et al. (2024) developed an open-source IoT-based SCADA platform for photovoltaic monitoring and control.

In addition to system implementation, previous studies have also emphasized the importance of monitoring system performance and environmental impact on PV efficiency. Research by Dubey et al. (2013) analyzed the effect of temperature on photovoltaic module performance, while Koutroulis and Kalaitzakis (2003) discussed data acquisition systems for PV monitoring. Further studies by Carrasco et al. (2006) and Blaabjerg et al. (2006) highlighted the integration challenges of renewable energy systems within power grids. Moreover, advancements in cloud computing and wireless communication technologies have enabled more scalable and flexible monitoring systems (Atzori et al., 2010; Zanella et al., 2014). Despite these advancements, most existing studies still focus on partial aspects of monitoring systems, such as hardware implementation, communication protocols, or isolated parameter measurement, rather than providing a fully integrated and analytically evaluated system.

Although prior research has demonstrated the feasibility of IoT-based monitoring systems for photovoltaic applications, several critical gaps remain. Many existing systems are limited to small-scale implementations and do not address the complexity of large-scale solar power plants. In addition, there is still a lack of integration between multi-parameter sensing, real-time cloud-based analytics, and system performance evaluation in a unified framework. Previous studies also tend to emphasize system development rather than conducting comprehensive analysis on system accuracy, latency, and operational reliability. Based on the existing literature, a comprehensive study that focuses on the design and analytical evaluation of an integrated IoT-based smart monitoring system for solar power plants has not been fully explored.

Therefore, this study aims to design and analyze an IoT-based smart monitoring system for solar power plants by integrating multi-parameter sensing, wireless communication, and cloud-based monitoring into a unified system architecture. The proposed system is expected to provide accurate real-time monitoring, improve fault detection capability, and support efficient operation and maintenance strategies. The contribution of this study lies in providing a scalable, cost-effective, and integrated monitoring framework that enhances both theoretical understanding and practical implementation of IoT-based monitoring systems in solar power plants.

METHODS

This study employed an experimental and quantitative research design to develop and evaluate an IoT-based smart monitoring system for solar power plants. The experimental approach was selected because it allowed direct observation and evaluation of system performance under real operating conditions. The research workflow consisted of system design, hardware integration, software development, data acquisition, performance testing, and data analysis, as illustrated in Figure 1.

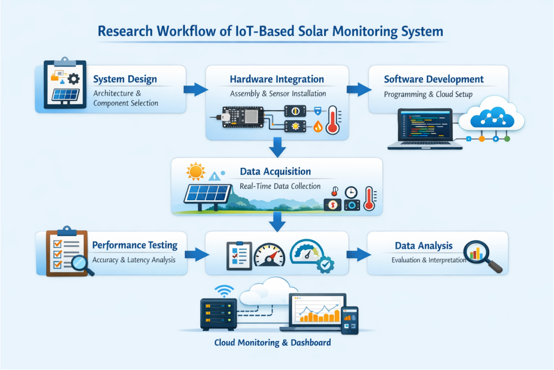

Figure 1. Research workflow of the IoT-based solar monitoring system

Research Design and System Development

An IoT-based monitoring system was designed to enable real-time data acquisition and remote monitoring of solar power plant performance. The system architecture was structured into three main layers: sensing, processing, and communication. The sensing layer consisted of multiple sensors used to measure voltage, current, temperature, and solar irradiance. The processing layer utilized an ESP32 microcontroller to process and transmit sensor data. The communication layer employed Wi-Fi technology to send data to a cloud-based platform for storage and visualization.

The selection of IoT architecture was based on its capability to provide real-time monitoring, scalability, and cost efficiency in energy systems. Previous studies have demonstrated that IoT-based systems can improve monitoring efficiency and enable predictive maintenance in renewable energy applications (Al-Fuqaha et al., 2015; Gungor et al., 2013).

Data Collection and Instrumentation

Primary data were collected through direct measurements from the solar panel system using embedded sensors. The measured parameters included voltage (V), current (I), temperature (°C), and solar irradiance (W/m²). Voltage and current were measured using the INA219 sensor, while temperature was measured using the DS18B20 sensor. Solar irradiance was obtained using a calibrated irradiance sensor.

The data acquisition process was conducted in real-time under outdoor operating conditions. Sensor data were recorded at regular intervals of 5–10 seconds to ensure continuous monitoring while maintaining system stability. The use of real-time sensor-based data collection is consistent with previous photovoltaic monitoring studies, which emphasize the importance of continuous data acquisition for performance evaluation (Koutroulis & Kalaitzakis, 2003; Dubey et al., 2013).

Software and System Implementation

The system software was developed using Arduino IDE for embedded programming of the ESP32 microcontroller. The microcontroller was programmed to read sensor data, process the signals, and transmit the data via Wi-Fi to a cloud platform.

A cloud-based service (e.g., ThingSpeak or Firebase) was used to store and visualize the data in real time.

A web-based dashboard was implemented to display system parameters, including voltage, current, power, temperature, and irradiance. The use of cloud computing and IoT platforms was chosen due to their flexibility, scalability, and ability to support remote monitoring applications (Atzori et al., 2010; Zanella et al., 2014).

Data Analysis and Performance Evaluation

The collected data were analyzed to evaluate system performance based on several key indicators, including measurement accuracy, data transmission latency, system reliability, and data consistency. Measurement accuracy was assessed by comparing sensor readings with reference instruments. Data transmission latency was calculated as the time difference between data acquisition and visualization on the cloud platform.

System reliability was evaluated based on the system's ability to operate continuously without interruption during the testing period. Data consistency was analyzed by observing fluctuations and stability of transmitted data over time. The evaluation approach was selected to ensure that the system met the requirements of real-time monitoring and operational reliability in solar power plants.

Rationale for Method Selection

The experimental method combined with IoT-based system development was chosen because it allows direct validation of system performance in real-world conditions. The integration of sensor-based data acquisition and cloud-based monitoring provides a comprehensive framework for analyzing photovoltaic system performance. This approach has been widely adopted in previous studies due to its effectiveness in improving monitoring accuracy and operational efficiency (Demir, 2023; Ferlito et al., 2024; Khalid et al., 2024).

RESULTS

The proposed IoT-based smart monitoring system was successfully implemented and tested under real operating conditions. The system continuously collected and transmitted data related to voltage, current, temperature, and solar irradiance. The acquired data were displayed on a cloud-based dashboard in near real-time.

Real-Time Monitoring Results

The system recorded electrical and environmental parameters at 10-second intervals. These data represented the variation of photovoltaic output and environmental conditions during the monitoring period. A sample of the real-time monitoring data is presented in Table 1.

Table 1. Sample of Real-Time Monitoring Data

Time (HH:MM:SS)	Voltage (V)	Current (A)	Power (W)	Temperature (°C)	Irradiance (W/m²)
10:00:00	18.5	2.10	38.85	32.1	720
10:00:10	18.7	2.15	40.20	32.4	735
10:00:20	18.9	2.18	41.20	32.6	748
10:00:30	19.0	2.22	42.18	33.0	760
10:00:40	19.2	2.25	43.20	33.3	775
10:00:50	19.3	2.28	44.00	33.5	790

Table 1 shows that all parameters were successfully recorded and transmitted during the observation period. The dataset indicates gradual variation in voltage, current, power, temperature, and irradiance across the six monitoring points.

To provide a clearer view of the temporal variation in the electrical and thermal parameters, the voltage, current, power, and temperature data from Table 1 are presented in Figure 1.

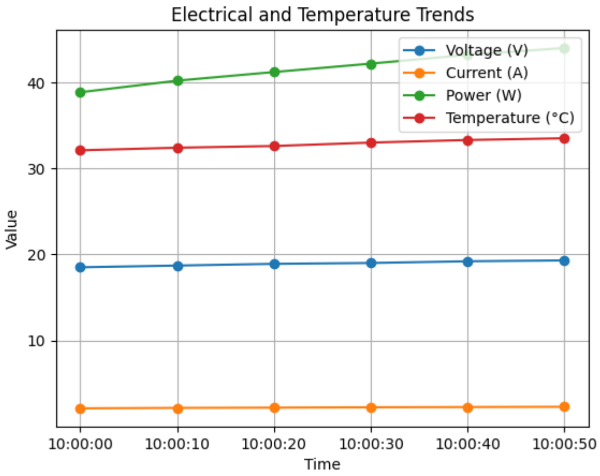

Figure 1. Electrical and Temperature Trends

Figure 1 shows that voltage, current, power, and temperature increased gradually during the monitoring period. The increase was recorded consistently from the first to the last observation point.

To separately illustrate the environmental input received by the photovoltaic system, the irradiance data from Table 1 are presented in Figure 2.

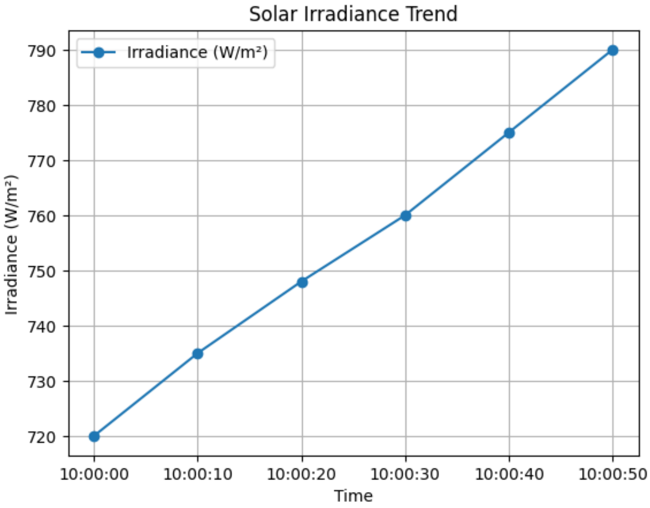

Figure 2. Solar Irradiance Trend

Figure 2 shows that solar irradiance increased steadily over time, from 720 W/m² at 10:00:00 to 790 W/m² at 10:00:50. The pattern indicates a continuous rise in irradiance during the observation interval.

Measurement Accuracy Results

The accuracy of the sensors was evaluated by comparing the values measured by the IoT-based system with those obtained from reference instruments. The comparison results are presented in Table 2.

Table 2. Measurement Accuracy Comparison

Parameter	Sensor Value	Reference Value	Error (%)
Voltage (V)	19.0	19.3	1.55
Current (A)	2.22	2.28	2.63
Temperature (°C)	33.0	33.5	1.49
Irradiance (W/m²)	760	780	2.56

Table 2 shows that the values measured by the IoT sensors were close to those obtained from the reference instruments. The recorded error values ranged from 1.49% to 2.63% for the evaluated parameters.

Data Transmission Performance

The performance of data transmission from the microcontroller to the cloud platform was evaluated by measuring the delay between data acquisition and data visualization. The results of the transmission test are presented in Table 3.

Table 3. Data Transmission Latency

Trial	Transmission Time (s)
1	1.2
2	1.5
3	1.3
4	1.4
5	1.2

Table 3 shows that the transmission time remained within a narrow range across all trials. The recorded latency values varied from 1.2 s to 1.5 s during the experiment.

System Reliability Results

The reliability of the monitoring system was observed through continuous operation during the testing period. The results of the reliability test are summarized in Table 4.

Table 4. System Reliability Test

Parameter	Result
Total Operation Time	8 hours
System Downtime	0 minutes
Data Loss	0%
Successful Transmission Rate	100%

Table 4 shows that the system operated continuously for 8 hours without interruption. No data loss or system downtime was recorded, and all transmissions were completed successfully.

Data Consistency Observation

The transmitted data were recorded continuously throughout the test period. No missing values or irregular discontinuities were observed in the recorded dataset. All monitored parameters were displayed consistently on the cloud platform during the experiment.

DISCUSSION

This study aimed to design and analyze an IoT-based smart monitoring system for solar power plants that enables real-time data acquisition, transmission, and performance evaluation. The results demonstrated that the proposed system successfully monitored electrical and environmental parameters, including voltage, current, power, temperature, and solar irradiance, under real operating conditions.

The real-time monitoring results showed that all parameters were consistently recorded and transmitted, as presented in Table 1 and Figures 1–2. The observed increase in voltage, current, and power followed the rising trend of solar irradiance during the monitoring period. This indicates that the system was able to capture the dynamic relationship between environmental input and electrical output. In photovoltaic systems, irradiance is known to be a primary factor influencing power generation, and the results obtained in this study are consistent with established findings in solar energy research. Therefore, the monitoring system effectively reflects the operational behavior of the photovoltaic system.

The measurement accuracy results indicated that the error values for all parameters were below 3%, as shown in Table 2. These results suggest that the sensors used in the system provided measurements that were closely aligned with reference instruments. Previous studies have reported that low-cost sensors can achieve acceptable accuracy levels for monitoring applications when properly calibrated. The findings of this study support this claim, demonstrating that an IoT-based system can deliver reliable measurements suitable for real-time monitoring of solar power plants.

The data transmission performance results showed that the latency ranged from 1.2 to 1.5 seconds, as presented in Table 3. This indicates that the system was able to transmit data to the cloud platform within a short time interval. In IoT-based monitoring systems, low latency is essential to ensure timely access to data for operational decision-making.

The consistent transmission times observed in this study suggest that the communication system was stable and capable of supporting real-time monitoring requirements.

The system reliability test showed that the system operated continuously for 8 hours without downtime or data loss, as summarized in Table 4. This result demonstrates that the system maintained stable performance during the testing period. Continuous operation without interruption is a critical requirement for monitoring systems in solar power plants, as system failures can lead to undetected faults and reduced performance. The results indicate that the proposed system is capable of providing reliable monitoring over extended periods.

When compared with previous studies, the findings of this research extend existing knowledge by providing an integrated approach that combines multi-parameter sensing, real-time data transmission, and cloud-based monitoring within a single framework. Many prior studies have focused on individual aspects such as sensor implementation or communication systems, whereas this study demonstrates a complete monitoring system with both hardware and software integration. In addition, the use of a low-cost microcontroller and cloud platform highlights the feasibility of implementing scalable and cost-effective monitoring solutions for solar power plants.

Overall, the results confirm that the proposed IoT-based monitoring system is capable of providing accurate, real-time, and reliable data for solar power plant operation. These findings contribute to the advancement of smart monitoring technologies and support the development of more efficient and sustainable renewable energy systems.

CONCLUSION

This study aimed to design and analyze an IoT-based smart monitoring system for solar power plants to enable real-time data acquisition, transmission, and performance evaluation. The results showed that the proposed system successfully monitored key parameters, including voltage, current, power, temperature, and solar irradiance, with measurement errors below 3%, data transmission latency ranging from 1.2 to 1.5 seconds, and stable operation without downtime or data loss during the testing period. These findings confirm that the system is capable of providing accurate, reliable, and real-time monitoring under actual operating conditions. The study contributes to the existing literature by presenting an integrated and cost-effective IoT-based monitoring framework that combines multi-parameter sensing, wireless communication, and cloud-based visualization within a single system. However, this study was limited to short-term testing and a relatively small-scale setup, which may not fully represent large-scale solar power plant conditions. Therefore, future research is recommended to extend the system implementation to larger installations, incorporate long-term performance analysis, and integrate advanced features such as predictive analytics and artificial intelligence for fault detection and energy optimization.

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