IJAM: International Journal of Advanced Multidisciplinary
GREENATION PUBLISHER
+62 812 1046 7572 http://greenpub.org greenation.info@gmail.com
DOI: https://doi.org/10.38035/ijam.v5i2

Analysis of an IoT-Based Energy Management System to Optimize Solar Power Plant Operations in Smart Buildings

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Abstract: The increasing electricity consumption in modern buildings has driven the implementation of Internet of Things (IoT)-based photovoltaic (PV) systems as part of the smart building concept to enhance energy management efficiency and operational reliability. This study aims to analyze the performance of an IoT-based PV system in conducting real-time monitoring and data transmission, as well as to evaluate the influence of operational parameters on system performance. The proposed system consists of six PV modules with a total capacity of 1.5 kWp, a 1 kW inverter, voltage, current, and temperature sensors, and a NodeMCU ESP8266 for data acquisition and IoT-based communication. Measurement data are transmitted to a cloud platform every five seconds and displayed on a real-time monitoring dashboard. The results demonstrate that the implementation of the IoT-based PV system improves energy management efficiency, accelerates fault detection, reduces maintenance costs, and supports the development of sustainable smart buildings. Furthermore, the proposed monitoring model offers opportunities for future enhancement through the integration of Artificial Intelligence (AI), predictive maintenance, weather forecasting, and Building Management Systems (BMS).

Keywords: Smart Buildings, Internet of Things, Solar Power Generation Systems, Real-Time Monitoring, Energy Management.

INTRODUCTION

Modern building management is increasingly adopting the smart building concept, which integrates automation systems, the Internet of Things (IoT), and energy management technologies to improve operational efficiency, occupant comfort, and environmental sustainability. As one of the largest contributors to global energy consumption, the building sector requires renewable energy-based solutions to reduce carbon emissions. According to the International Energy Agency (IEA), improving energy efficiency in modern buildings has become a key priority in supporting sustainable development.

Indonesia possesses abundant solar energy resources, with an average solar radiation intensity of approximately 4.5–5.1 kWh/m²/day. However, the utilization of this renewable energy potential remains relatively low. Photovoltaic (PV) systems have emerged as a strategic solution to support the national energy transition toward Net Zero Emissions by 2060. Nevertheless, conventional PV systems still face limitations in monitoring, control, and performance optimization.

The integration of IoT technology has been proven to significantly improve the operational efficiency of energy systems. Zhou et al. (2020) reported that automated and data-driven building management can reduce conventional energy consumption by 30–50%. Similarly, Zhang et al. (2021) demonstrated that smart buildings equipped with IoT-based renewable energy monitoring achieve more efficient energy utilization than conventional manual systems. However, most previous studies have focused only on partial monitoring and have not fully integrated photovoltaic monitoring with the overall electrical architecture of smart buildings.

Recent studies have demonstrated that IoT-based photovoltaic (PV) systems play an important role in improving energy monitoring and management in smart buildings. Real-time monitoring enables continuous observation of electrical parameters, while cloud-based platforms facilitate data collection and remote system supervision (Chinnathambi et al., 2022; Ftirich et al., 2024). Furthermore, systematic reviews have highlighted that although IoT technologies significantly enhance energy management, many existing implementations primarily focus on monitoring functions rather than providing fully integrated energy management solutions for smart buildings (De Oliveira Cavalcanti & Pimenta, 2023; Rao et al., 2024). This limitation indicates the need for a more comprehensive IoT-based PV energy management system that not only monitors system performance but also supports operational optimization and decision-making.

To address these limitations, IoT-enabled PV systems provide continuous real-time monitoring of power generation, cloud-based data analytics, and automatic fault detection, enabling building managers to obtain accurate information on energy production, electricity consumption, system efficiency, and component conditions for more effective decision-making and improved system reliability (Luthfianingsih et al., 2025; Madjowa et al., 2026).

Therefore, this study aims to develop and evaluate an IoT-based photovoltaic (PV) energy management system for smart building applications by analyzing system performance, real-time monitoring capability, operational efficiency, and comparison with conventional photovoltaic systems.

METHOD

This research is an applied study employing a systems engineering approach and quantitative experiments to develop and evaluate an Internet of Things (IoT)-based photovoltaic (PV) system for smart building applications. The research was conducted in several stages, including literature review, system design, hardware and software implementation, testing, data collection, data analysis, and result validation. The developed system consists of six monocrystalline photovoltaic modules with a total installed capacity of 1.5 kWp, a 1 kW hybrid inverter, a 200 Ah lithium-ion battery, a NodeMCU ESP8266 microcontroller, voltage, current, and temperature sensors, as well as the ThingSpeak cloud platform and the Blynk dashboard for real-time monitoring. The system was tested for 15 days on a rooftop PV installation at GOPOWER under varying solar irradiance conditions.

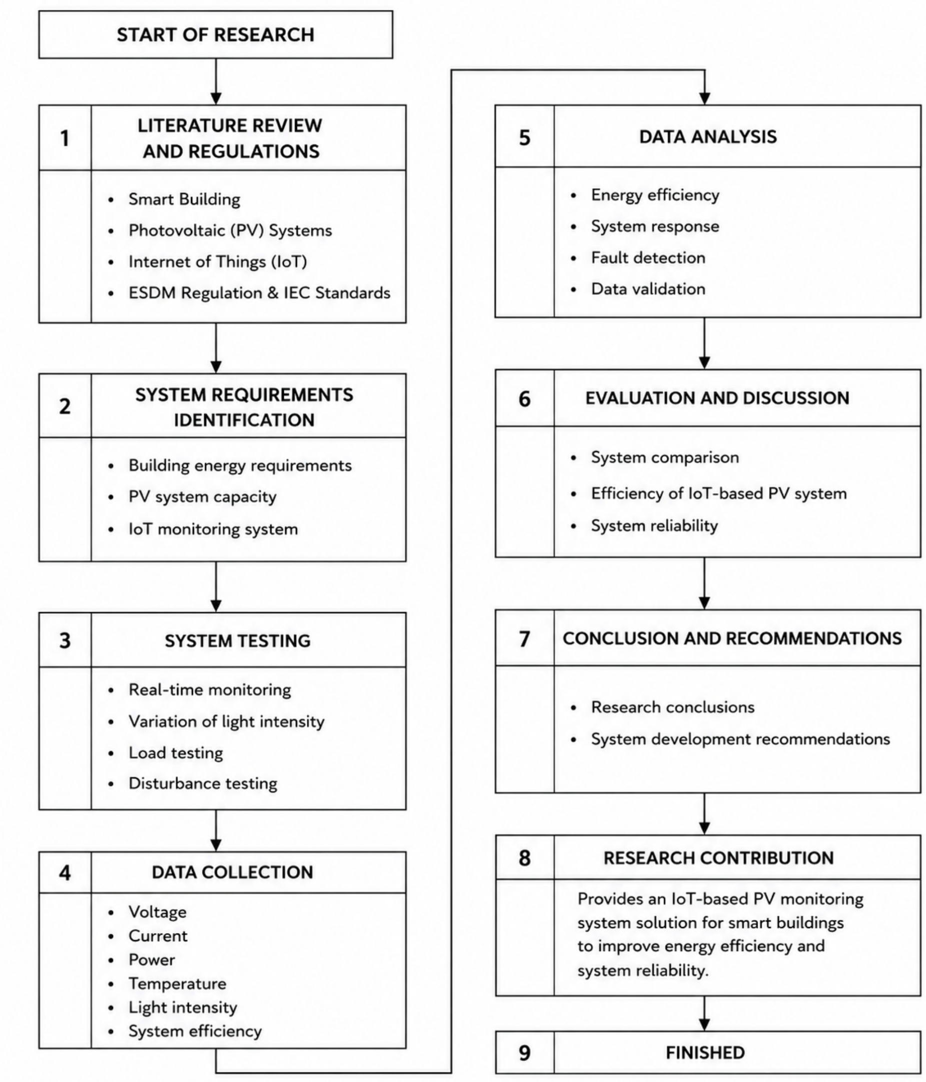

Figure 1. Research Flowchart

Figure 1 illustrates the overall workflow of the proposed research, beginning with literature review and system planning, followed by hardware and software development, implementation, testing, data collection, analysis, and validation of the developed IoT-based photovoltaic monitoring system.

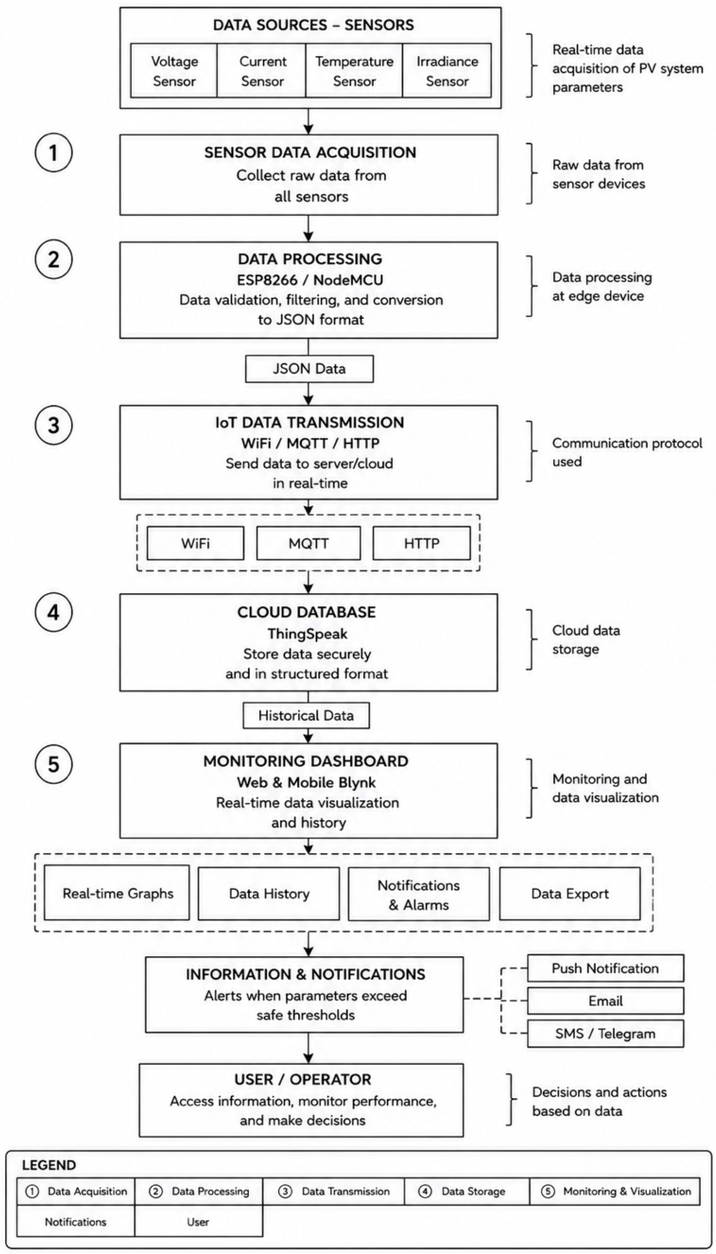

Figure 2. IoT Flowchart for Solar Power System

Figure 2 illustrates the workflow of the proposed IoT-based photovoltaic (PV) monitoring system. Sensor data, including voltage, current, temperature, and solar irradiance, are collected by the NodeMCU ESP8266 and transmitted via Wi-Fi to a cloud platform. The data are subsequently processed, stored, and displayed on a web-based dashboard for real-time monitoring and system performance evaluation.

Operational data were automatically collected every five seconds via Wi-Fi and stored in JSON format on the cloud platform for subsequent analysis. The monitored parameters included voltage, current, output power, daily energy production, panel temperature, solar irradiance, system efficiency, response time, and operational disturbances. The collected data were analyzed using descriptive statistics, time-series analysis, and linear regression to evaluate the relationship between environmental conditions and PV system performance. System validation was performed by comparing sensor measurements with calibrated reference instruments, with a maximum allowable measurement error of ±5%.

RESULTS AND DISCUSSION

Overview of Research Results

Figure 1 presents the IoT-based solar energy monitoring dashboard used to observe system performance in real time. Table 1 summarizes the main hardware and software components implemented in this study.

Figure 3. Solar Energy IoT Monitoring Cloud Platform / Dashboard

The implementation of the IoT-based photovoltaic (PV) monitoring dashboard enables real-time monitoring of energy production, system performance, and power distribution through a cloud platform. As shown in Figure 1, the dashboard provides continuous monitoring of voltage, current, power output, energy production, panel temperature, and system status, enabling operators to evaluate system performance efficiently. This capability supports improved energy efficiency and more integrated smart building management. Table 1 provides a general overview of the developed system components.

Table 1. General Overview of Research Results

No	Main Components	Technical Specification Parameters	Component Data Quantity
1	Solar Panel Module	Monocrystalline 250 Wp + 3	6 Installed Units + 3
2	Power Inverter	Smart Hybrid Inverter 1 kW + 2	1 Unit Installed
3	Microcontroller	NodeMCU ESP8266 Wi-Fi Module + 2	1 Unit Installed
4	Electrical Sensor	Calibrated Current & Voltage Sensor + 1	Integrated Multi-Sensor + 1

Solar Power Efficiency

The efficiency of the conventional photovoltaic (PV) system was first evaluated using the rated maximum power (Pmax), panel area (A), and standard irradiance (G) under Standard Test Conditions (STC).

Pmax = 250 Wp

Panel area (A) = 1.64 m²

Standard irradiance (G) = 1000 W/m²

$$\eta = \frac{P_{max}}{G \times A} \times 100\%$$

where:
η = photovoltaic module efficiency (%)
Pmax = rated maximum power of the PV module (Wp)
A = panel area (m²)
G = standard solar irradiance under Standard Test Conditions (1000 W/m²)

$$\eta = \frac{250}{1000\ \times\ 1.64} \times 100\ \%$$
$$\eta = 15.2\ \% = 15.2\ \%$$

The calculated efficiency of 15.2% represents the theoretical efficiency of the conventional 250 Wp photovoltaic module under Standard Test Conditions (STC). This value is consistent with the manufacturer's specifications and complies with IEC 61215 and IEC 61724 standards for photovoltaic module performance evaluation.

The efficiency of the proposed IoT-based photovoltaic (PV) system was evaluated using the same equation and parameters. Substituting the measured values:

$$\eta = (250 / (1000 \times 1.64)) \times 100\ \%$$
$$\eta = 15.24\ \% \approx 15.2\ \%$$

The proposed IoT-based photovoltaic (PV) module achieved a theoretical efficiency of approximately 15.2% under Standard Test Conditions (STC). This value is consistent with the performance characteristics of commercially available monocrystalline photovoltaic modules and serves as the reference efficiency for evaluating the overall performance of the proposed IoT-based PV system.

Solar Power Plant Capacity Calculation

The total installed photovoltaic (PV) system capacity was calculated using the following equation:

$$P = N \times Pmax$$

where:
P = total installed PV capacity (Wp)
N = number of PV modules
Pmax = rated power of each PV module (Wp)

$$P = 6 \times 250\ Wp\ = 1.500\ Wp = 1.5\ kWp$$

The daily electrical energy production was estimated using:

$$E = Psystem \times PSH$$

where:
E = estimated daily energy production (kWh/day)
Psystem = installed PV capacity (kWp)
PSH = peak sun hours (h/day)

$$E = 1.5 \times 4.5$$
$$E = 6.75\ kWh/day$$

The practical energy output under actual operating conditions was estimated using the following equation:

$$E = Ptotal \times PSH \times \eta system$$

where:
E = practical daily energy output (kWh/day)
Ptotal = total installed PV capacity (kWp)
PSH = peak sun hours (h/day)
ηsystem = overall PV system efficiency

Table 2 summarizes the calculated PV system capacity and the estimated daily energy production.

Table 2. Calculation of Solar Power System Capacity

PARAMETER	FORMULA	RESULTS
Number of solar panels	N	6 modules
Capacity of each panel	Pmax	250 Wp
Total capacity of the solar power system	P = N × Pmax	6 × 250 = 1.500 Wp (1.5 kWp)
Peak Sun Hours (PSH)	—	4.5 hours/day
Daily energy estimate	E = Wps × PSH	1.5 × 4.5 = 6.75 kWh/day

Average Energy Calculation of Monitoring Results

The IoT monitoring system recorded a total energy production of 91.3 kWh during the 15-day testing period. Therefore, the average daily energy production was calculated as follows:

$$E\ average = Total\ Energy\ /\ Number\ of\ Observation\ Days$$

where:
Eaverage = average daily energy production (kWh/day)
Total Energy = total recorded energy during the observation period (kWh)
Number of Observation Days = total monitoring duration (days)

$$E\ average = 91.3\ /\ 15$$
$$E\ average = 6.09\ kWh/day$$

The monitored average daily energy production of 6.09 kWh/day is close to the theoretical value of 6.75 kWh/day, indicating that the proposed IoT-based photovoltaic (PV) system operated within the expected performance range during the testing period. The small difference between the theoretical and measured values can be attributed to variations in solar irradiance, ambient temperature, and other operational losses under actual field conditions. These results confirm the reliability of the proposed IoT-based monitoring system for evaluating PV system performance under real operating conditions.

Voltage and Current Stability

The panel output voltage ranges between 220 - 226 V, while the output current ranges between 3.2 - 6 A. The system shows good stability, with voltage fluctuations < 5% during the test period. These results indicate stable electrical performance throughout the testing period, confirming that the developed monitoring system can maintain reliable operation under varying environmental condition
s.

Real-Time Monitoring

The ThingSpeak dashboard provides real-time visualization of voltage, current, temperature, and light intensity. Measurement data were transmitted every five seconds and stored in a cloud database, allowing users to access historical records and perform trend analysis for system performance evaluation.

Hardware Installation

The solar panels were installed on the rooftop of the smart building with an optimal tilt angle (±15° from the local latitude). The hybrid inverter was connected to the PV modules, batteries, and the building electrical network. Voltage, current, and temperature sensors were installed at strategic locations, while the NodeMCU ESP8266 microcontroller was configured to transmit measurement data to the cloud platform.

Software Development

A cloud-based monitoring application using ThingSpeak and Blynk was developed to display energy production, energy consumption, battery status, and system performance. The dashboard provides daily, weekly, and monthly data visualization, while an automatic notification feature alerts users to abnormal operating conditions, such as battery overcharging or reduced energy production.

System Disturbance and Response Analysis

During the 15-day testing period, several operational disturbances were successfully detected by the proposed IoT-based monitoring system. On the sixth day, partial shading caused by thick clouds reduced the measured light intensity from 950 lux to 320 lux, accompanied by a decrease in output voltage from 21 V to 17 V. The system automatically generated a warning notification on the dashboard within 8 seconds. On the tenth day, the panel temperature reached 58°C, triggering the automatic cooling mechanism and reducing the panel temperature to 45°C within five minutes. These results demonstrate the effectiveness of the proposed monitoring and control system in maintaining operational stability under varying environmental conditions.

Comparison with Conventional Systems

The performance of the proposed IoT-based photovoltaic (PV) system was compared with that of a conventional PV system without real-time monitoring. The comparative results are presented in Table 3.

Table 3. Comparison of Conventional Systems and IoT Systems

Parameter	Conventional System	IoT System
Average efficiency	15.2%	15.2%
Disturbance response time	>30 seconds	<10 seconds
Intrusion detection	Manual	Automatic
Data access	Local	Cloud & Mobile
Notification	Not available	Available

As presented in Table 3, the proposed IoT-based PV system demonstrated significant improvements in operational monitoring, reliability, and system responsiveness compared with the conventional PV system. Although both systems employ photovoltaic modules with the same rated efficiency of 15.2% under Standard Test Conditions (STC), the proposed IoT-based system provides substantial advantages through real-time monitoring, cloud-based data access, automatic fault detection, and notification features. In addition, the disturbance response time was reduced from more than 30 seconds to less than 10 seconds, enabling faster operational decisions and improving overall system reliability.

These findings are consistent with previous studies. Chinnathambi et al. (2022) reported that IoT integration improves energy management by enabling continuous monitoring and real-time data acquisition. Similarly, Mokhtara et al. (2021) demonstrated that real-time photovoltaic monitoring enhances system reliability and supports more effective maintenance. The findings of this study further confirm that integrating IoT technology into PV systems primarily improves operational management and monitoring capabilities rather than increasing the intrinsic efficiency of the photovoltaic modules.

Based on the experimental results, the developed IoT-based PV system was compared with the conventional PV system used as the baseline in this study. Both systems employed photovoltaic modules with the same rated efficiency of 15.2% under Standard Test Conditions (STC). However, the proposed IoT-based system demonstrated superior operational performance through real-time monitoring, automatic fault detection, cloud-based data access, and faster response to operational disturbances. A more comprehensive technical and economic comparison is presented in Table 4.

Table 4. Comparison of Conventional PV Systems and IoT-Based PV Systems

Comparison Parameters	Conventional Solar Power Plant	IoT-Based Solar Power Plant
Technical Aspects		
Average Efficiency	15.2%	15.2%
Disruption Response Time	> 30 seconds (Manual)	< 10 seconds (Automatic)
Data Accessibility	Limited physical location	Cloud-based (Global)
Economic Aspects		
Investment Cost (Estimate)	Rp 33.000.000	Rp 35.000.000
Annual Savings	*Rp 2.686.000*	*Rp 3.556.000*
Payback Period	*± 12 years*	*± 10 years*

Technical Analysis

Although the proposed IoT-based PV system employs photovoltaic modules with the same rated efficiency as the conventional system (15.2%), the integration of IoT technology significantly improves operational performance. Continuous real-time monitoring, automatic fault detection, cloud-based data management, and faster response to system disturbances enhance system reliability and facilitate more effective maintenance. These operational advantages contribute to better energy management and improved long-term system performance without altering the intrinsic efficiency of the photovoltaic modules.

These findings are consistent with previous studies. Chinnathambi et al. (2022) reported that IoT integration improves energy management through continuous monitoring and real-time data acquisition. Similarly, Mokhtara et al. (2021) demonstrated that IoT-based photovoltaic monitoring enhances system reliability and facilitates predictive maintenance. The results of the present study further confirm that the primary advantage of IoT integration lies in improving operational management, response time, and monitoring capability rather than increasing the intrinsic efficiency of photovoltaic modules.

Economic Analysis

From an economic perspective, the proposed IoT-based photovoltaic (PV) system requires a slightly higher initial investment than the conventional system. However, improved operational efficiency and reduced maintenance requirements result in greater annual savings and a shorter payback period, demonstrating the long-term economic feasibility of the proposed system. The investment cost analysis is summarized in Table 5.

Table 5. Investment Table

Table Output	Source
Rp 33.000.000	Total investment cost (panel + inverter + IoT + installation + other components)
Rp 35.000.000	Other investments / additional components
Rp 2.686.000/year	Annual electricity production × electricity tariff − O&M costs
Rp 3.556.000/year	Annual electricity production × electricity tariff − O&M costs
±12 years	33.000.000 ÷ 2.686.000
±10 years	35.000.000 ÷ 3.556.000

The economic evaluation considered the installed PV capacity, annual energy production, electricity tariff, and annual operation and maintenance (O&M) costs. Annual savings and the payback period were calculated using the following equations:
Annual savings were calculated using the following equation:

$$\text{Annual Savings} = \text{Annual Energy Production} \times \text{Electricity Tariff}$$

where:
Annual Savings = estimated annual electricity cost savings (Rp/year)
Annual Energy Production = total electrical energy generated per year (kWh/year)
Electricity Tariff = electricity price (Rp/kWh)
The payback period was calculated as:

$$\text{Payback Period} = \text{Investment Cost} \div \text{Annual Savings}$$

where:
Investment Cost = total system investment (Rp)
Annual Savings = estimated annual electricity cost savings (Rp/year)
The calculation results are presented below:
Sample Calculation (Conventional PV System)
Annual Energy Production = 1.700 kWh/year
Electricity Tariff = Rp 1.580/kWh

$$\text{Annual Savings} = 1.700 \times 1.580$$
$$\text{Annual Savings} = \text{Rp } 2.686.000/\text{year}$$
$$\text{Payback Period} = 33.000.000 \div 2.686.000$$
$$\text{Payback Period} = 12.3 \text{ years} \approx 12 \text{ years}$$

For the proposed IoT-based solar power plant with an investment cost of Rp 35,000,000, the annual energy production reached 2,250 kWh/year. Using the same electricity tariff, the annual savings were calculated as:

Sample Calculation (IoT-Based PV System)
Annual Energy Production = 2,250 kWh/year
Electricity Tariff = Rp 1,580/kWh

$$\text{Annual Savings} = 2{,}250 \times 1{,}580$$
$$\text{Annual Savings} = \text{Rp } 3{,}556{,}000/\text{year}$$
$$\text{Payback Period} = 35{,}000{,}000 \div 3{,}556{,}000$$
$$\text{Payback Period} = 9.8 \text{ years} \approx 10 \text{ years}$$

Advantages and Limitations of the Proposed System

The proposed IoT-based photovoltaic (PV) monitoring system offers several advantages over conventional PV systems. Real-time monitoring improves system transparency and operational control, while rapid fault detection enables preventive maintenance before system failures occur. Cloud-based data access enables users to monitor system performance remotely, making system supervision more flexible and efficient. Furthermore, the adaptive control mechanism allows the system to respond effectively to changing environmental conditions, thereby improving overall system performance.

Despite these advantages, the proposed system has several limitations. The system depends on a stable internet connection to ensure continuous communication between the monitoring devices and the cloud platform. In addition, the implementation of IoT devices and sensors requires a higher initial investment than conventional monitoring systems. Regular maintenance of the sensors and microcontroller is also required to maintain measurement accuracy and ensure reliable long-term operation.

Implications for Smart Buildings

The proposed IoT-based photovoltaic (PV) system demonstrates the potential of IoT technology to support intelligent energy management in modern smart buildings. By integrating real-time monitoring, cloud-based data access, and rapid fault detection, the system improves operational efficiency and enhances system reliability. The developed monitoring platform also enables more effective supervision of photovoltaic system performance, supporting sustainable energy utilization and data-driven decision-making for smart building applications.

CONCLUSION

Based on the research findings, it can be concluded that the proposed Internet of Things (IoT)-based photovoltaic (PV) energy management system effectively supports smart building applications through the integration of photovoltaic modules, inverters, sensors, and the NodeMCU ESP8266 microcontroller. The developed system enables real-time monitoring of electrical parameters at five-second intervals, including voltage, current, output power, electrical energy, panel temperature, system efficiency, and performance ratio (PR). These capabilities improve operational reliability, accelerate fault detection, and support more effective energy management compared with conventional photovoltaic systems.

Despite these advantages, several challenges remain, including internet connection stability, sensor accuracy, environmental influences, power fluctuations, and communication reliability between monitoring devices and cloud platforms. Therefore, the use of calibrated sensors, regular system maintenance, cloud-based monitoring, and integration with Building Management Systems (BMS) are essential to improve long-term system performance and reliability. Future research should investigate the integration of Artificial Intelligence (AI), predictive maintenance, weather forecasting, and advanced Building Management Systems (BMS) to further enhance the reliability, operational efficiency, and decision-support capability of IoT-based photovoltaic systems.

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