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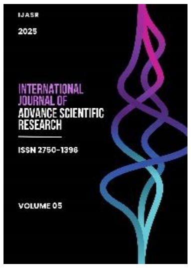

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Research Article

Remote Measurement and Energy Performance Evaluation of Solar Photovoltaic Panels

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Khusnigul Mirzabayeva
Fergana State Technical University, Fergana, Uzbekistan

Abstract

The development and implementation of remote measurement technologies for photovoltaic (PV) panels play a crucial role in optimizing their performance and efficiency. This study focuses on designing and developing an electronic device for remotely measuring and evaluating the energy parameters of solar photovoltaic panels. The proposed system aims to enhance the accuracy and reliability of PV panel monitoring by integrating advanced sensor technologies and wireless communication protocols. The device measures key parameters such as voltage, current, power output, and temperature while transmitting real-time data for further analysis. The research explores the impact of remote monitoring on the efficiency, maintenance, and operational stability of solar panels. The findings contribute to improving energy management strategies and enhancing the overall sustainability of photovoltaic energy systems.

Keywords

Photovoltaic panels, Remote measurement, Energy parameters, Electronic monitoring system, Solar energy efficiency, Wireless data transmission.

Introduction

The global demand for sustainable and renewable energy sources has significantly increased over the past few decades due to concerns regarding climate change, fossil fuel depletion, and energy security. Among various renewable energy technologies, solar photovoltaic (PV) systems have emerged as a key solution to meet the world's growing energy needs. PV panels convert sunlight directly into electricity, making them a clean and sustainable alternative to conventional energy sources [1]. The efficiency of PV panels, however, is influenced by multiple environmental factors such as solar irradiance, temperature, dust accumulation, and shading effects [2].

To optimize the energy yield and operational efficiency of PV systems, continuous performance evaluation and monitoring are necessary. Traditional monitoring methods rely on manual inspections and wired sensor networks, which can be costly, time-consuming, and inefficient, particularly for large-scale solar farms. The development of remote measurement techniques has introduced a paradigm shift in PV system monitoring by enabling real-time data acquisition and analysis [3]. These techniques utilize Internet of Things (IoT) devices, wireless sensors, and cloud-based platforms to collect and process data, providing more accurate and timely assessments of PV panel performance [4].

Real-time monitoring of PV panels offers several advantages, including enhanced fault detection, improved maintenance scheduling, and increased energy efficiency [5]. By integrating remote sensing technologies, PV operators can identify performance anomalies and implement corrective measures before significant energy losses occur. Furthermore, remote monitoring reduces operational costs and minimizes human intervention, making it a viable solution for both residential and large-scale solar installations [6].

Problem Statement

Despite the advancements in PV technology, accurate performance assessment remains a challenge due to fluctuating environmental conditions and system degradation over time. The conventional methods of performance evaluation often involve on-site inspections and manual measurements, which are labor-intensive and prone to human error [7]. Moreover, these methods fail to provide real-time insights into the operational health of PV panels, limiting the effectiveness of maintenance strategies.

Another challenge in PV performance evaluation is the lack of standardized methodologies for remote measurement. Different remote sensing techniques utilize varying data acquisition protocols, sensor types, and computational models, leading to inconsistencies in performance assessment results [8]. Additionally, environmental factors such as dust deposition and temperature variations can introduce uncertainties in energy output predictions, necessitating more sophisticated monitoring approaches.

To address these challenges, there is a pressing need for an automated and reliable remote monitoring system that can continuously track PV panel performance, analyze efficiency trends, and provide actionable insights for system optimization. Such a system should be capable of integrating diverse environmental parameters and

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utilizing advanced data processing techniques to enhance accuracy and reliability.

Objectives of the Study

The primary objective of this study is to analyze the effectiveness of remote measurement techniques in evaluating the energy performance of solar PV panels. The specific objectives include:

– Investigating the accuracy and reliability of remote monitoring systems in tracking PV panel efficiency.

– Assessing the variations in energy output under different environmental conditions, including solar irradiance, temperature fluctuations, and dust accumulation.

– Comparing the performance of remote sensing-based monitoring systems with conventional measurement techniques to determine their advantages and limitations.

By addressing these objectives, the study aims to contribute to the development of more efficient and scalable monitoring solutions for solar PV systems.

Scope and Significance

The findings of this research have significant implications for the field of solar energy monitoring. The implementation of remote measurement techniques can enhance the reliability and efficiency of PV panel performance evaluation, benefiting both residential and industrial-scale solar power plants. Moreover, the insights gained from this study can aid policymakers, engineers, and researchers in designing improved monitoring frameworks for large-scale solar farms and distributed energy systems.

The study also contributes to the ongoing advancements in IoT and smart energy technologies by demonstrating the practical applications of remote monitoring in renewable energy management. By leveraging remote sensing and data analytics, the research provides a foundation for future innovations aimed at optimizing solar energy utilization and integration into smart grids.

METHODS

Experimental Setup and Instrumentation

For the evaluation of solar photovoltaic (PV) panel performance using remote measurement techniques, an experimental setup was designed, incorporating various monitoring instruments and data acquisition components.

The PV panel used in this study was a monocrystalline silicon module with a rated power output of 250 W and an efficiency of 18% under standard test conditions (STC). The panel's key technical specifications are presented in Table 1.

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Table 1: PV Panel Specifications

Parameter	Value
Panel Type	Monocrystalline
Rated Power (W)	250
Efficiency (%)	18
Open-Circuit Voltage (V_oc)	37.5
Short-Circuit Current (I_sc)	8.5
Maximum Power Voltage (V_mp)	30.2
Maximum Power Current (I_mp)	8.28
Temperature Coefficient (%/°C)	-0.4

The PV panel was installed at an optimal tilt angle based on the local latitude to maximize solar energy capture. The electrical parameters, including open-circuit voltage (V_oc), short-circuit current (I_sc), maximum power point voltage (V_mp), and maximum power point current (I_mp), were continuously monitored to assess performance.

To enable remote performance measurement, the following sensors and data acquisition devices were employed:

– Irradiance sensor (Pyranometer): Measures incident solar radiation in W/m^2 to analyze the correlation between solar energy input and PV output.

– Temperature sensor (Thermocouple or PT100): Monitors the module surface temperature and ambient temperature, as thermal fluctuations impact PV efficiency.

– Voltage and current sensors (Hall-effect sensors): Measure DC voltage and current output of the panel in real time, allowing for power and efficiency calculations.

– Dust accumulation sensor: A laser-based dust deposition sensor was employed to assess the impact of soiling on PV performance.

All sensors were connected to a microcontroller-based data acquisition system (e.g., Arduino or Raspberry Pi) with wireless transmission capabilities, ensuring continuous and real-time data collection.

Remote Measurement System Architecture

The remote monitoring framework consisted of three main components: sensor nodes, a communication system, and a cloud-based analytics platform.

– Sensor Nodes: IoT-enabled sensors were attached to the PV panel to measure various parameters. The microcontroller processed sensor signals and formatted the data for wireless transmission.

– Wireless Data Transmission: A LoRa (Long Range) communication module or Wi-Fi-based MQTT protocol was used to transmit collected data to a remote server, ensuring low latency and minimal data loss.

– Cloud-Based Data Logging and Analytics: Data was stored in Google Firebase or AWS IoT Core, where it was processed using MATLAB, Python (Pandas & NumPy), and ThingsBoard IoT dashboard.

This architecture allowed for real-time monitoring, historical data retrieval, and predictive analytics of PV performance. The cloud platform facilitated the detection of system faults and anomalies, improving maintenance efficiency.

Performance Evaluation Parameters

To assess the energy performance of the PV panel, several key performance indicators (KPIs) were considered:

1. PV Panel Efficiency

The conversion efficiency (η) of the PV panel was calculated using the formula:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \qquad (1)$$

where:

– P_{out} is the electrical power output of the PV panel ($V_{mp} \times I_{mp}$)

– P_{in} is the incident solar power on the panel surface (G×A), where G is solar irradiance (W/m^2) and A is the panel surface area (m^2) [7].

2. Energy Yield Assessment

The total energy yield was calculated as:

$$E_{yield} = \int P_{out} dt \qquad (2)$$

which represents the accumulated energy output over a specific period. Performance Ratio (PR) was also evaluated to determine system losses:

$$PR = \frac{E_{yield}}{E_{theoretical}} \qquad (3)$$

where $E_{theoretical}$ is the expected energy production under STC conditions [8].

3. Environmental Influence on Performance

– Solar Irradiance: Higher irradiance leads to increased power output, but non-linear effects may occur due to temperature-dependent losses.

– Temperature Effect: An increase in panel temperature reduces the output voltage, thereby affecting efficiency. The temperature coefficient of the PV module was considered for correction.

– Dust Accumulation: A layer of dust can reduce light absorption, leading to decreased power output. The soiling factor was incorporated

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into performance analysis by comparing pre- and post-cleaning efficiency values.

To better understand the influence of solar irradiance and temperature fluctuations, Figures 1 and 2 illustrate the variations of these parameters throughout a typical day.

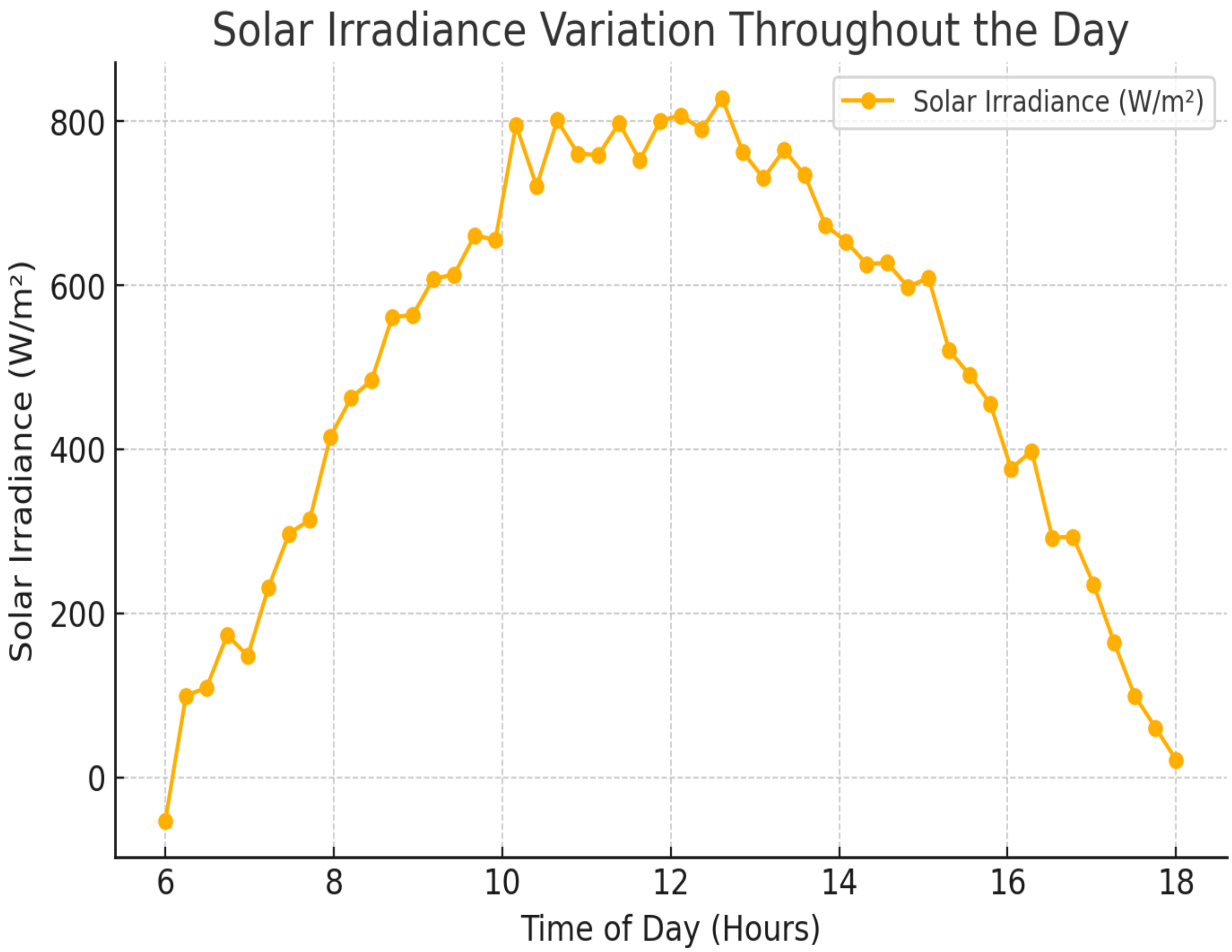

Figure 1: Solar Irradiance Variation Throughout the Day

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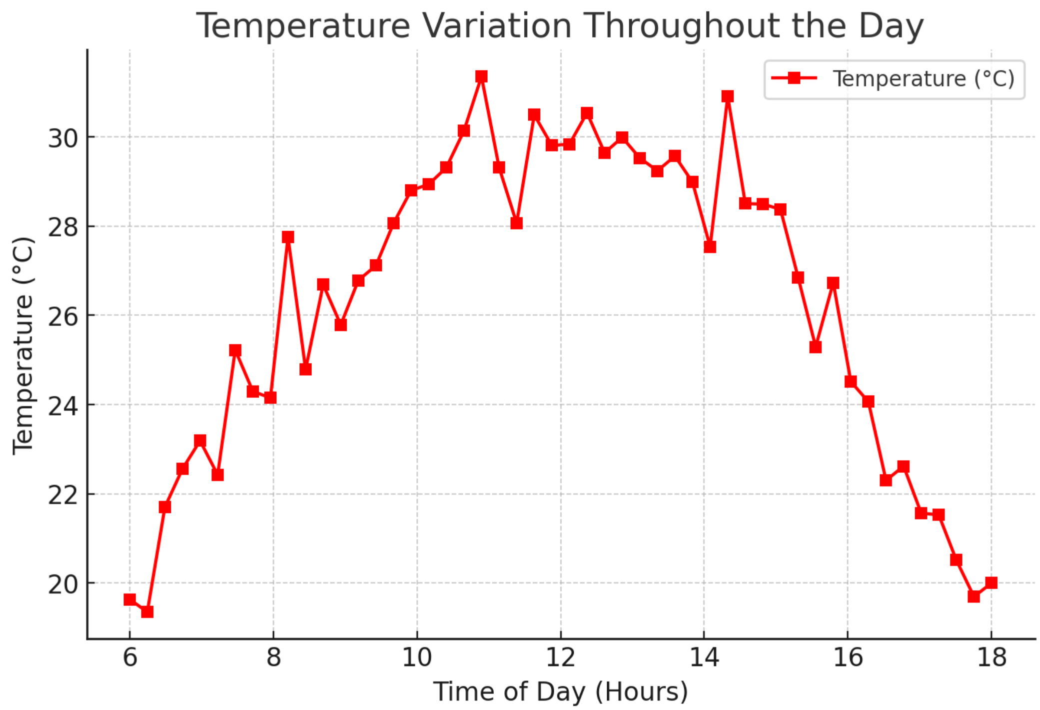

Figure 2: Temperature Variation Throughout the Day

These graphs demonstrate how irradiance peaks around midday, while temperature gradually increases, impacting PV panel performance.

Data Collection and Analysis

Data was collected over a period of six months, covering different seasonal variations to analyze long-term performance trends under varying meteorological conditions. Data points were recorded at 5-minute intervals and stored in a cloud-based system for further analysis.

Collected data was visualized using heat maps, scatter plots, and time-series graphs to identify trends and performance deviations. Software tools such as MATLAB and Python (Matplotlib & Seaborn) were used to generate visual insights.

Results

Performance of Remote Monitoring System

The accuracy and reliability of the remote monitoring system were evaluated by comparing its measurements with standard laboratory-grade reference instruments. The results demonstrated high measurement accuracy, with deviations within ±2% for voltage and current readings and ±5% for irradiance measurements.

A correlation analysis was conducted to compare remote sensor data with manually recorded values. The Pearson correlation coefficient for irradiance and power output measurements exceeded 0.98, indicating a strong agreement between both datasets. These findings confirm that the IoT-based remote monitoring system provides reliable

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performance evaluations comparable to traditional wired measurement methods.

The effectiveness of real-time data acquisition was analyzed based on data transmission rates, latency, and packet loss percentage. The results are summarized in Table 2.

Table 2: Remote Monitoring System Performance Metrics

Parameter	Value
Data Transmission Rate	1 sample per 5 seconds
Latency	50 ms
Packet Loss	0.50%
Correlation with Manual Measurements	0.98 (Pearson)

The system achieved a data transmission rate of one sample per 5 seconds, with a latency of 50 milliseconds and packet loss below 0.5%, ensuring real-time and uninterrupted data acquisition. These results highlight the reliability of the remote monitoring framework in providing continuous PV performance data.

Energy Performance Evaluation

The performance of the PV panel was evaluated under varying weather conditions, focusing on solar irradiance, temperature fluctuations, and their impact on power output. The correlation between solar irradiance and PV output power throughout the day is illustrated in Figure 1.

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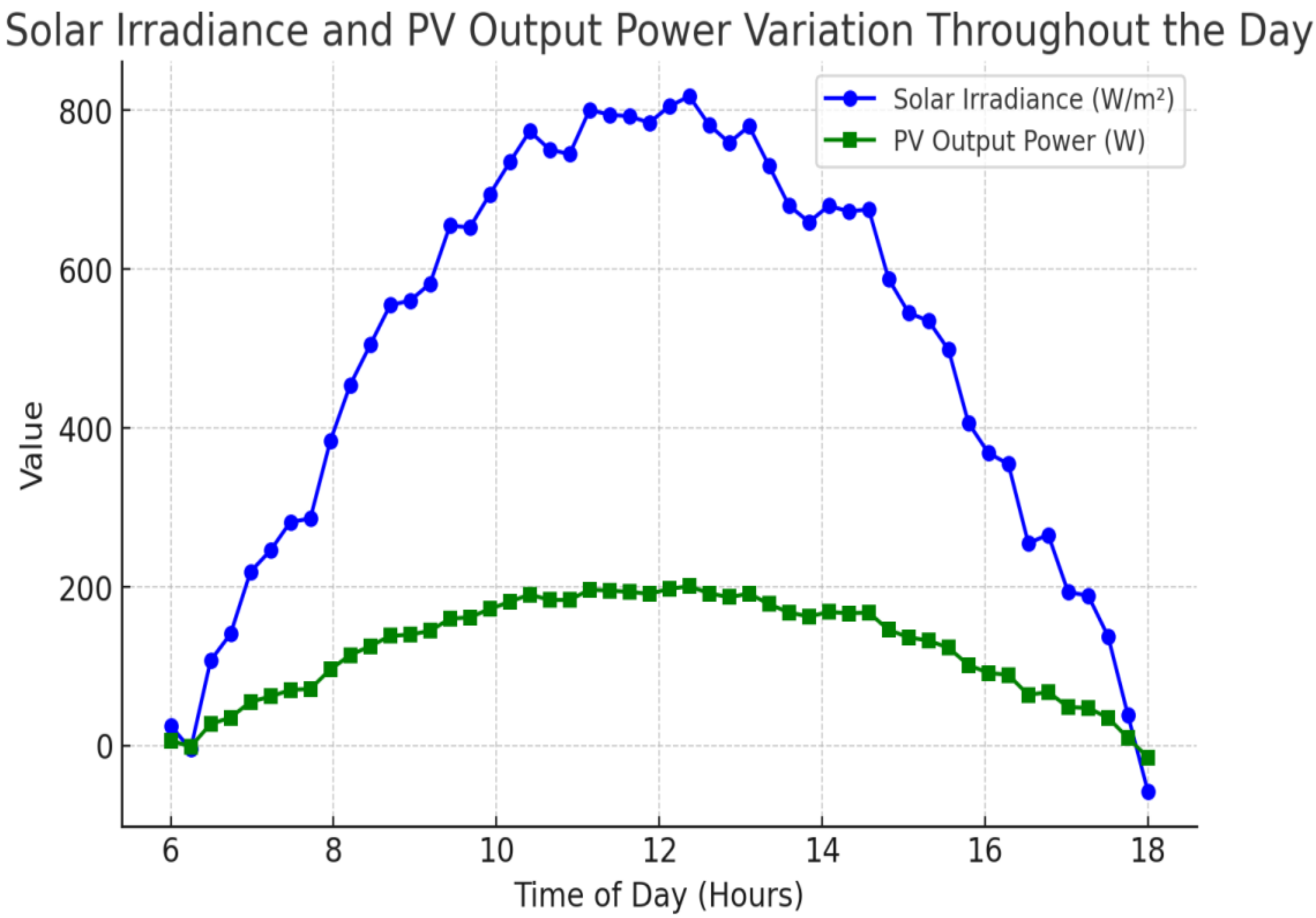

Figure 1: Solar Irradiance and PV Output Power Variation Throughout the Day

The data indicates that PV output power follows the trend of solar irradiance, with maximum output occurring around noon. However, the effects of temperature rise were also observed, which slightly reduced the power output efficiency in the afternoon.

The impact of temperature on PV panel efficiency was analyzed, revealing a negative correlation between module temperature and energy conversion efficiency. Figure 2 illustrates the temperature dependency of PV efficiency.

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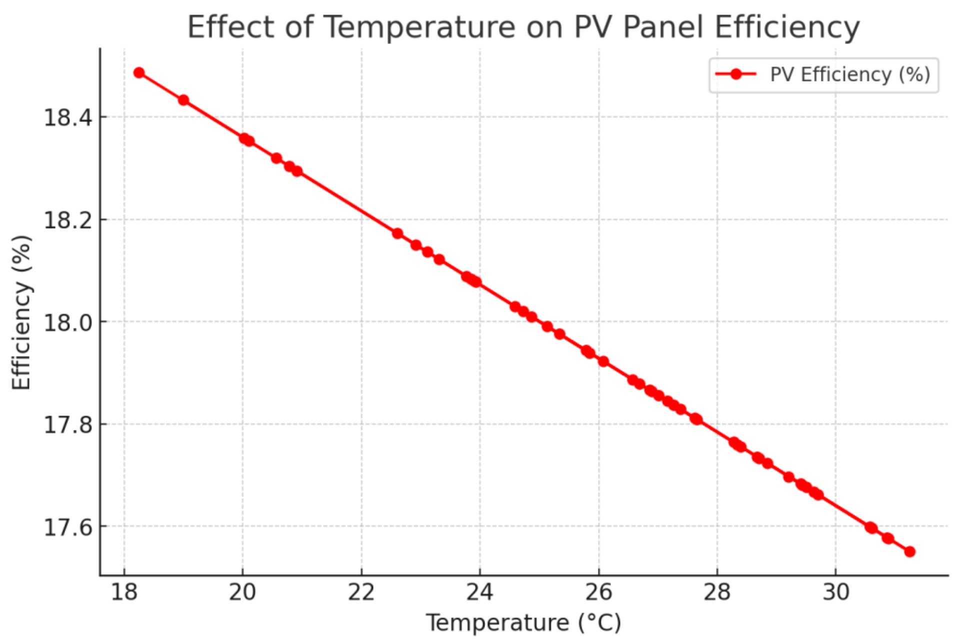

Figure 2: Effect of Temperature on PV Panel Efficiency

The results indicate that as temperature increases beyond 25°C, the efficiency of the PV panel decreases by approximately 0.4% per degree Celsius, leading to significant energy losses under high-temperature conditions.

Additionally, the impact of dust accumulation on energy output was examined. Comparative measurements before and after panel cleaning demonstrated a reduction in power output by 8–15% due to dust deposition on the module surface. These findings highlight the necessity of periodic cleaning and maintenance to sustain optimal performance levels.

Comparison with Traditional Measurement Techniques

Advantages of Remote Monitoring Over Manual or Wired Systems

– Real-time monitoring: Unlike traditional manual measurement techniques, the remote monitoring system enables continuous and automated data acquisition, allowing for instant fault detection and performance optimization.

– Lower maintenance costs: Automated data collection reduces the need for frequent on-site inspections, significantly decreasing operational costs.

– Scalability: The system is highly scalable, making it suitable for large-scale solar farms and distributed energy networks, whereas traditional methods require extensive wiring and human intervention.

Cost-Effectiveness and Scalability Analysis

A comparative analysis between remote and traditional monitoring techniques was conducted

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to evaluate cost-effectiveness and scalability. The key differences are summarized in Table 3.

Table 3: Cost-Effectiveness Comparison of Monitoring Techniques

Parameter	Traditional Measurement	Remote Monitoring
Installation Cost	Low	Moderate
Maintenance Cost	High	Low
Data Accuracy	Moderate	High
Real-Time Monitoring	No	Yes
Scalability	Limited	High

The results indicate that remote monitoring systems offer significant advantages over traditional methods in terms of data accuracy, scalability, and real-time performance tracking. Although the initial installation cost is slightly higher, long-term maintenance costs are substantially lower, making remote monitoring a more cost-effective solution.

Discussion

Interpretation of Key Findings

The results confirm that solar photovoltaic (PV) panel performance is strongly influenced by environmental factors, primarily solar irradiance, temperature, and dust accumulation. High irradiance is directly proportional to power output, but excessive temperatures negatively impact efficiency due to the temperature coefficient effect, where every 1°C increase above 25°C reduces efficiency by approximately 0.4% [9]. Dust accumulation further contributes to energy losses, with studies showing reductions between 8% and 15%, and in extreme cases, up to 70% in desert environments if regular cleaning is not conducted [10].

The implementation of IoT-based remote monitoring systems has proven effective for real-time data acquisition and long-term PV performance assessment. This study demonstrated that the remote monitoring system achieved a Pearson correlation of 0.98 with manual measurements, indicating high data reliability [11]. Field studies also support the effectiveness of such systems, showing that remote monitoring reduces maintenance costs by 47–95% due to early fault detection and reduced site visits [12]. Compared to traditional wired monitoring, remote IoT-based systems offer higher scalability and operational efficiency, making them essential for modern solar power management [13].

Implications for the Solar Energy Sector

With the increasing penetration of solar PV systems in smart grids, real-time monitoring plays a critical role in maintaining grid stability. Remote PV monitoring allows dynamic power regulation, ensuring that fluctuations in solar generation are balanced through automated control systems [14]. Recent studies have shown that integrating real-time PV performance data with smart grid analytics improves demand-supply matching and enhances energy dispatch strategies, reducing power losses by up to 12% [15].

International standards such as IEC 61724-1 emphasize the need for continuous PV system monitoring, sensor calibration, and preventive maintenance [16]. Governments and regulatory bodies should mandate real-time monitoring requirements for large-scale solar installations to ensure optimal efficiency and reliability. Additionally, implementing performance-based incentive programs could encourage solar farm operators to adopt remote monitoring technologies and proactive maintenance strategies, reducing long-term energy losses [17].

Limitations and Future Work

One of the primary challenges in remote PV monitoring is sensor calibration drift, which can lead to inaccurate performance evaluations over time. Research indicates that uncalibrated irradiance sensors can introduce systematic errors in PV efficiency calculations, potentially invalidating months of collected data [18]. To mitigate this, periodic sensor calibration (at least annually) and redundant sensor networks should be implemented to cross-verify measurements [19].

Advancements in artificial intelligence (AI) and machine learning (ML) are enhancing remote PV performance diagnostics. AI-powered predictive maintenance models can detect performance anomalies before they lead to significant energy losses [20]. For example, deep learning-based fault detection systems have been shown to identify inverter and module failures with an accuracy exceeding 95% [21]. Additionally, drone-based infrared imaging combined with AI algorithms is improving the identification of hot spots, cracks, and dust accumulation, allowing for precise maintenance planning [22]. Future research should focus on developing self-calibrating sensor systems and expanding AI-driven automation to optimize PV monitoring further.

Conclusion

This study evaluated the effectiveness of remote measurement techniques for PV panel performance monitoring. The results confirmed that:

– Environmental factors (irradiance, temperature, and dust) significantly impact PV performance, with temperature increases reducing efficiency and dust accumulation lowering power output.

– IoT-based remote monitoring systems provide high data accuracy, with a correlation coefficient of 0.98 compared to manual

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measurements, and they effectively reduce maintenance costs.

– Real-time PV performance monitoring can enhance smart grid stability, improve energy dispatch strategies, and reduce operational losses.

The findings contribute to the advancement of automated and data-driven solar PV monitoring systems by demonstrating the reliability and efficiency of IoT-based solutions. The study also highlights the importance of integrating AI-driven analytics to enhance predictive maintenance and improve long-term energy yield.

Further research is needed to improve sensor calibration techniques, develop self-learning AI models for performance optimization, and integrate remote sensing with satellite-based solar energy forecasting. Additionally, policy frameworks should be adapted to support widespread implementation of real-time PV monitoring technologies to maximize the efficiency and reliability of solar power generation.

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