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INTEGRATED PERFORMANCE AND IOT-BASED RELIABILITY ASSESSMENT OF OFF-GRID PV SYSTEMS

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Abstract: Island regions often face unreliable electricity supply due to limited grid infrastructure, resulting in high dependence on diesel generators with significant economic and environmental drawbacks. This study aims to evaluate the performance and reliability of an Internet of Things (IoT)-integrated off-grid solar photovoltaic (PV) system implemented in a small island setting. A 400 Wp off-grid PV system was deployed on Pulau Puteri, Indonesia, and equipped with an IoT-based monitoring platform to enable real-time acquisition of operational data. The methodology includes system design, installation, and continuous monitoring over a 30-day period with 5-minute data intervals. System performance was assessed using Performance Ratio (PR) and Capacity Factor (CF). The system produced 1.6–2.1 kWh/day with PR values of 0.75–0.82 and CF of 16.7%–21.9%, indicating efficient and stable operation under tropical conditions. IoT monitoring enabled continuous data acquisition and early anomaly detection, improving operational reliability. The results confirm that the system meets international performance benchmarks and provides a feasible solution for decentralized energy systems in remote islands. The study contributes an integrated framework combining real-time IoT monitoring and standardized performance evaluation using field data.

Keywords: Performance Ratio; Capacity Factor; IoT-Based Monitoring; Off-Grid Solar PV; Small Island Energy Systems.

INTRODUCTION

Reliable access to electrical energy remains a persistent challenge in island and hinterland regions of Indonesia due to geographic isolation, separation by sea, and limited infrastructure. As a result, many remote communities are inadequately served by the national electricity grid and continue to rely heavily on diesel generators as their primary energy source. This dependency leads to high fuel costs, limited supply reliability, and increased greenhouse gas emissions (Basri et al., 2021), (Khan et al., 2020). These conditions highlight the urgent need for sustainable, decentralized, and locally available energy solutions to improve energy resilience in island environments.

In line with national and global energy transition agendas, renewable energy deployment has become a strategic priority for reducing dependence on fossil fuels in remote regions. Among various renewable energy sources, solar energy is particularly suitable for Indonesia due to its tropical climate and relatively high annual solar irradiance (Purwanto et al., 2020). Solar photovoltaic (PV) systems offer several advantages for island applications, including modularity, environmental sustainability, ease of installation, and lower long-term operational costs compared to diesel-based power generation systems (Huda et al., 2021).

However, the effectiveness of PV systems is not solely determined by installed capacity but by their actual performance under real operating conditions. Environmental factors such as irradiance variability, temperature, and humidity significantly influence system output, especially in tropical coastal and island environments. Therefore, standardized performance indicators such as Performance Ratio (PR) and Capacity Factor (CF) are widely used to evaluate system efficiency, reliability, and energy conversion effectiveness in accordance with standards such as IEC 61724 (Hossain & Rahim, 2021). Field-based performance evaluation using these metrics is essential to ensure system reliability and long-term sustainability.

The integration of Internet of Things (IoT) technology has further enhanced PV system monitoring and management. IoT-based monitoring enables continuous and real-time acquisition of operational parameters,

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including voltage, current, power output, and energy production, thereby supporting data-driven performance analysis and early fault detection (Kumar et al., 2020). Previous studies have shown that IoT-enabled systems improve operational reliability and maintenance efficiency, particularly in remote and small-scale installations (Hasan et al., 2021), (Al-Turjman, 2021).

Despite these advancements, several critical research gaps remain. First, most existing studies tend to focus either on PV performance evaluation or IoT-based monitoring systems separately, without integrating both aspects into a unified analytical framework. Second, a significant portion of previous work relies on simulation or short-term experimental data, limiting its ability to accurately represent real operating conditions in tropical island environments. Third, empirical studies in Indonesian small island contexts remain scarce, particularly those combining standardized performance indicators such as PR and CF with continuous IoT-based monitoring data (Kumar et al., 2021), (Hannan et al., 2020). In addition, existing literature rarely integrates community-based PV deployment, real-time IoT monitoring, and standardized performance evaluation within a single comprehensive framework (Sharma & Kumar, 2021).

These limitations are important because PV system performance in tropical island environments is highly dynamic and influenced by environmental variability and system design factors. Without integrated and field-based evaluation, the actual reliability, efficiency, and long-term sustainability of off-grid PV systems remain uncertain.

Addressing this gap, this study aims to quantitatively evaluate the performance and reliability of an IoT-based off-grid solar PV system implemented through a community service program on Pulau Puteri, Batam. Specifically, the objectives of this study are to (i) assess the system's energy yield under real operating conditions, (ii) evaluate its Performance Ratio (PR) and Capacity Factor (CF) based on international standards, and (iii) analyze the role of IoT-based monitoring in improving system reliability and operational transparency (Ali et al., 2021), (Nguyen et al., 2021).

The scientific contribution of this study lies in providing field-validated performance data and proposing an integrated evaluation framework combining real-time IoT monitoring with standardized performance metrics. From a practical perspective, this study supports the scalability of decentralized solar energy systems to enhance energy resilience in island and hinterland regions of Indonesia (Liu et al., 2021), (Islam et al., 2021)
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LITERATURE REVIEW

Reliable access to electrical energy in island and remote regions remains a global challenge, particularly in developing countries such as Indonesia. Limited grid infrastructure leads to a high dependence on diesel generators, resulting in increased operational costs and carbon emissions. Previous studies emphasize that decentralized renewable energy systems represent the most appropriate approach to improving energy resilience in such regions (Basri et al., 2021), (Khan et al., 2020).

In this context, solar photovoltaic (PV) technology has emerged as a primary solution due to abundant solar energy potential in tropical regions. Indonesia benefits from high solar irradiation throughout the year, making it highly suitable for PV system implementation (Purwanto et al., 2020). In addition, PV systems offer advantages such as modularity, ease of installation, environmental sustainability, and lower long-term operational costs compared to fossil fuel-based power generation systems (Huda et al., 2021).

However, the effectiveness of PV systems is not determined solely by installed capacity but by their actual performance under real operating conditions. Therefore, performance evaluation is a critical aspect of renewable energy research. Standardized indicators such as Performance Ratio (PR) and Capacity Factor (CF) are widely used to assess energy conversion efficiency and system reliability in accordance with standards such as IEC 61724 (Hossain & Rahim, 2021). These metrics provide a consistent basis for comparing PV system performance across different environmental conditions. Nevertheless, most studies focus primarily on performance evaluation without integrating real-time monitoring capabilities.

The integration of Internet of Things (IoT) technology into renewable energy systems has created new opportunities for monitoring and management. IoT-based monitoring systems enable real-time acquisition of electrical parameters such as voltage, current, and power output, allowing more accurate performance analysis and early fault detection (Kumar et al., 2020), (Hasan et al., 2021). Furthermore, IoT technology enhances operational efficiency through data-driven energy management and remote system supervision (Al-Turjman, 2021).

Despite these advancements, most previous studies have primarily focused on monitoring system architecture or simulation-based approaches, with limited support from long-term field data obtained from real-world implementations. This limitation reduces the ability of such studies to represent actual operating conditions, particularly in tropical and island environments (Kumar et al., 2021). In addition, integrated studies combining PV performance evaluation and IoT technology within a unified analytical framework remain limited (Hannan et al., 2020).

In the Indonesian context, research integrating off-grid PV systems, IoT-based monitoring, and standardized performance evaluation remains very limited. Variations in Performance Ratio (PR) and Capacity

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Factor (CF) values across Southeast Asia highlight the importance of location-specific studies (Nguyen et al., 2021). Moreover, battery performance is a critical factor in ensuring continuous energy supply in off-grid PV systems (Sharma & Kumar, 2021).

Recent studies demonstrate that integrating IoT with performance-based data analysis can significantly enhance system reliability through early anomaly detection and data-driven decision-making (Ali et al., 2021), (Liu et al., 2021). However, comprehensive studies that simultaneously address technical performance, operational reliability, and real-world implementation in island environments remain scarce.

Based on the reviewed literature, a clear research gap can be identified, namely the lack of empirical studies that integrate IoT-based monitoring, standardized performance evaluation using PR and CF, and real operational data from off-grid PV systems in Indonesian island environments. Therefore, this study aims to address this gap by providing a comprehensive and integrated field-based evaluation.

METHOD

This study employs a quantitative approach using a single-case study of a 400 Wp off-grid solar photovoltaic (PV) system installed on Pulau Puteri, Batam, Indonesia. The system is equipped with an Internet of Things (IoT)-based monitoring platform to enable real-time data acquisition and integrated evaluation of system performance and reliability under actual operating conditions.

Monitoring was conducted over a period of 30 days, representing typical operational conditions in a tropical island environment. Data were recorded at 5-minute intervals using IoT sensors and transmitted to a cloud-based platform for storage and analysis. The collected data include electrical and energy parameters such as output power, daily energy production, system voltage, and battery State of Charge (SoC).

System performance is evaluated using standardized indicators, namely Performance Ratio (PR) and Capacity Factor (CF), in accordance with the principles of IEC 61724. The Performance Ratio (PR) is defined as:

$$PR = \frac{E_{AC}}{P_{rated} \times H_{ref}}$$

and the Capacity Factor (CF) is defined as:

$$CF = \frac{E_{AC}}{P_{rated} \times 24}$$

where E_{AC} represents the daily electrical energy output (kWh), P_{rated} is the installed PV capacity (kWp), and H_{ref} denotes the equivalent daily reference solar irradiation.

In addition to performance evaluation, system reliability is assessed through IoT-based monitoring indicators, including data continuity, system voltage stability, battery SoC consistency, and the occurrence of operational anomalies during the monitoring period. These indicators provide insight into the operational stability and dependability of the off-grid PV system.

The research procedure consists of several sequential stages, including site assessment, system design and IoT integration, installation and commissioning, operational monitoring, and integrated performance evaluation. Site assessment was conducted to evaluate solar resource availability, environmental conditions, and load requirements. The PV system was then designed with a 400 Wp capacity, consisting of PV modules, a charge controller, battery storage, an inverter, and IoT-based sensors. The system was installed with an optimized tilt angle and underwent commissioning and calibration to ensure measurement accuracy.

During the operational phase, continuous monitoring was performed, and all relevant parameters were recorded and transmitted in real time. The collected data were processed using aggregation and averaging techniques to obtain daily performance values. These values were then used to calculate PR and CF and to evaluate system reliability based on stability and anomaly detection.

Performance and reliability indicators were compared against commonly accepted international benchmarks to assess system efficiency and operational effectiveness. Despite the comprehensive evaluation, this study is limited by the use of a single system and a relatively short monitoring duration, which may not fully represent long-term seasonal variations. Additionally, reliability assessment depends on the accuracy and availability of IoT sensor data. Nevertheless, the applied methodology provides robust empirical insights into the integrated performance and IoT-based reliability of off-grid PV systems in small island environments.

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RESULT

The performance and reliability of the off-grid solar photovoltaic (PV) system installed on Pulau Puteri, Batam, were evaluated using continuous operational data acquired through an Internet of Things (IoT)-based monitoring platform over a period of 30 days. The analysis integrates energy performance indicators, including energy yield, Performance Ratio (PR), and Capacity Factor (CF), with reliability indicators such as voltage stability, battery behavior, and data continuity.

The monitored solar irradiation ranged from 4.8 to 5.4 kWh/m²/day, with peak values occurring between 10:00 and 14:00 WIB. These values are typical for tropical coastal regions and indicate sufficient solar resource availability to support stable off-grid PV operation throughout the monitoring period.

The average daily performance of the PV system over the 30-day monitoring period is presented in Table 1.

Table 1. Average Daily Performance of the Solar PV System (30-Day Monitoring)

Parameter	Value
Installed capacity	400 Wp
Maximum output power	320–360 W
Daily energy production	1.6–2.1 kWh
Monthly energy production	48–63 kWh
Effective operating hours	4–5 h/day

The system consistently produced daily energy ranging from 1.6 to 2.1 kWh during the observation period. Under clear-sky conditions, the output power reached 320–360 W, which is close to the rated capacity. This indicates stable and efficient energy conversion under real operating conditions across the monitoring duration.

Battery performance and reliability parameters observed during the monitoring period are shown in Table 2.

Table 2. Battery Performance and Reliability Parameters

Parameter	Value
Minimum voltage	12.4 V
Maximum voltage	13.8 V
Afternoon SoC	85–100%
Nighttime supply duration	8–10 h

The battery State of Charge (SoC) consistently reached 85–100% during daytime charging cycles, enabling continuous energy supply for approximately 8–10 hours during nighttime operation. The system voltage remained stable within the range of 12.4–13.8 V throughout the monitoring period, indicating proper charge controller operation and reliable energy storage performance.

IoT-based monitoring shows a consistent daily power generation pattern across the 30-day period, with energy production starting around 08:00 WIB, peaking between 11:00 and 13:00 WIB, and gradually decreasing after 15:00 WIB. No significant anomalies or abnormal voltage fluctuations were observed, confirming stable system operation and the effectiveness of IoT-based real-time monitoring.

The Performance Ratio (PR) analysis over the monitoring period is presented in Table 3.

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Table 3. Performance Ratio Analysis

Parameter	Value
Theoretical daily energy	2.4–2.6 kWh
Actual daily energy	1.6–2.1 kWh
Performance Ratio (PR)	0.75–0.82

The PR values ranged from 0.75 to 0.82 throughout the monitoring period, which fall within the acceptable range for small-scale PV systems (typically 0.70–0.85). This indicates that system losses due to temperature effects, wiring, and power electronics remain relatively low and consistent over time.

The Capacity Factor (CF) values ranged from 16.7% to 21.9%, reflecting effective utilization of the installed PV capacity relative to continuous full-load operation. These values are consistent with typical PV system performance in equatorial regions and confirm appropriate system sizing.

To illustrate performance consistency, a representative sample of daily performance data from the monitoring period is presented in Table 4.

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Table 4. Representative Daily Performance Sample (30-Day Monitoring)

Day	Energy (kWh)	PR	CF (%)
Day 1	1.6	0.75	16.7
Day 7	1.8	0.78	18.8
Day 15	2.0	0.80	20.8
Day 22	2.1	0.82	21.9
Day 30	1.7	0.76	17.7

The consistency of energy production, PR, and CF values throughout the 30-day monitoring period, combined with stable voltage profiles and battery behavior, confirms that the off-grid PV system operates reliably under real operating conditions. Furthermore, the integration of IoT monitoring enhances system reliability by enabling continuous data acquisition, performance tracking, and early detection of potential operational anomalies.

The results demonstrate that the implemented off-grid PV system achieves reliable and efficient operation when evaluated through an integrated performance and IoT-based reliability framework over the 30-day monitoring period. The observed Performance Ratio (PR) values ranging from 0.75 to 0.82 indicate effective energy conversion, while the Capacity Factor (CF) values between 16.7% and 21.9% reflect appropriate utilization of the installed capacity under tropical island conditions. These values fall within the acceptable range for small-scale PV systems, confirming that the system performs efficiently under real operating conditions.

The observed performance is strongly influenced by both environmental and system design factors. High solar irradiation levels (4.8–5.4 kWh/m²/day) contribute significantly to stable energy production throughout the monitoring period. However, elevated ambient temperatures may slightly reduce module efficiency due to thermal losses. In addition, the optimized tilt angle and minimal shading conditions enhance solar energy capture during peak irradiation hours, contributing to consistent system output.

From a system perspective, the use of an appropriate charge controller and stable battery performance plays a critical role in maintaining voltage stability and ensuring continuous energy supply, particularly during nighttime operation. The battery State of Charge (SoC), which consistently reaches high levels during daytime charging, supports reliable energy storage and discharge cycles. Furthermore, the integration of IoT-based monitoring significantly improves system reliability by enabling continuous real-time data acquisition, operational transparency, and early detection of anomalies such as voltage drops or irregular power output patterns.

Beyond technical performance, the integration of IoT monitoring provides added value compared to conventional PV systems by supporting data-driven maintenance and reducing the need for manual inspection, which is particularly important in remote island environments with limited technical accessibility. This study provides field-validated evidence of system performance and reliability, unlike many previous studies that rely on simulation or short-term experimental data.

From a broader perspective, the implementation of this system contributes to reducing dependence on diesel generators, lowering operational energy costs, and decreasing greenhouse gas emissions. These outcomes support energy resilience and self-sufficiency for small island communities and align with national and global energy transition objectives.

Despite these positive results, this study has several limitations. The monitoring period of 30 days does not fully capture long-term seasonal variability or system degradation effects. In addition, reliability assessment is primarily based on operational stability indicators rather than long-term failure statistics. Future research should include extended monitoring periods, incorporation of quantitative reliability metrics such as system uptime and data availability, and integration with hybrid renewable energy systems to further enhance system resilience and scalability.

CONCLUSION

This study conducted an integrated assessment of performance and IoT-based reliability of a 400 Wp off-grid solar photovoltaic (PV) system implemented on Pulau Puteri, Batam, using continuous operational data over a 30-day monitoring period. The system demonstrates stable and efficient performance under actual island operating conditions, with daily energy production ranging from 1.6 to 2.1 kWh, Performance Ratio (PR) values between 0.75 and 0.82, and Capacity Factor (CF) values of 16.7% to 21.9%. These results indicate effective energy conversion and appropriate utilization of the installed capacity.

From a reliability perspective, stable voltage profiles and consistent battery State of Charge (SoC) behavior confirm dependable energy storage and continuous power supply throughout the operational cycle. The integration of IoT-based monitoring plays a critical role in enhancing system reliability by enabling continuous performance tracking, operational transparency, and early detection of potential anomalies. These capabilities are particularly important for off-grid PV systems deployed in remote island environments with limited technical accessibility.

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The novelty of this study lies in the integration of real-time IoT-based monitoring with standardized performance evaluation (PR and CF) using continuous field data in a small island context, which has not been widely reported in previous studies. This integrated approach provides a comprehensive understanding of both technical performance and operational reliability of off-grid PV systems under real operating conditions.

The findings demonstrate that the proposed system meets acceptable international performance benchmarks and represents a technically feasible solution for reducing dependence on fossil fuel-based electricity, lowering operational costs, and supporting sustainable energy self-sufficiency in small island communities.

Future research should extend this integrated framework through long-term monitoring to capture seasonal variability and system degradation, incorporate quantitative reliability metrics such as system uptime and data availability rates, and explore hybrid renewable energy configurations to further improve system resilience and scalability.

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