



# Integration of Edge Computing and Wireless Sensors for Energy Efficiency Monitoring in Solar Panels

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**Abstract:** Increased demand for renewable energy has driven the development of efficient monitoring systems to optimize solar panel performance. This study aims to implement and evaluate the integration of edge computing technology with wireless sensor networks (WSN) in real-time solar panel energy efficiency monitoring systems. This approach is designed to overcome the limitations of conventional monitoring systems that still rely on centralized computing and exhibit high latency in data collection. The research method includes designing an edge computing-based system architecture, installing wireless sensors to measure key parameters (voltage, current, light intensity, and temperature), and applying energy efficiency algorithms at the edge to process data locally. The data is then sent to the cloud for in-depth analysis and visualization of system performance. Testing was conducted by comparing data transmission efficiency, response time, and measurement accuracy between edge-based and conventional systems. The results of the study show that the integration of edge computing and wireless sensors can increase monitoring efficiency by up to 28.4%, reduce system latency by 35.7%, and increase data accuracy by 12.6% compared to conventional systems that are entirely cloud-based. In addition, bandwidth consumption is significantly reduced because the computing process is done on the edge.

**Keywords:** Edge Computing; Wireless Sensor; Solar Panel; Energy Efficiency; Real-Time Monitoring.

## 1. Introduction

Global energy demand has risen sharply over the past several decades, placing considerable strain on conventional power infrastructure and accelerating the shift toward renewable energy sources. Among available alternatives, solar energy has gained substantial traction due to its environmental compatibility, scalability, and declining installation costs. Solar panels can be deployed across diverse settings — from residential rooftops to large-scale industrial arrays — making them one of the more practical responses to the

dual challenge of energy security and carbon reduction. That said, solar panel performance is not static. Output varies with solar irradiance, ambient temperature, module degradation, and load distribution, and these variations can occur rapidly and without warning. In the absence of a reliable real-time monitoring system, efficiency losses accumulate undetected, and hardware faults are identified only after they have already caused measurable damage. At scale, the consequences extend beyond operational inefficiency to significant economic loss and reduced system longevity.

Conventional monitoring architectures typically address this by routing all sensor data to a centralized cloud server for processing and analysis. While this approach benefits from broad storage capacity and mature analytical tooling, it carries a structural limitation that becomes increasingly problematic as deployments grow in size and geographic spread. Every analytical output — every fault detection, every efficiency calculation — depends on a full data round trip between the field sensor and the remote server. Under stable, high-bandwidth network conditions, the resulting latency may be acceptable. Under the conditions that characterize many real-world solar installations, particularly those in rural or infrastructure-limited environments, that same latency renders genuine real-time response unachievable. Compounding this, the continuous transmission of raw sensor data places a heavy and often unnecessary burden on available bandwidth. The result is a monitoring architecture whose practical performance falls well short of what the underlying hardware is capable of delivering (Suryadi *et al.*, 2024).

Edge computing offers a structurally different solution, and its combination with wireless sensor networks (WSN) addresses the core limitations of centralized architectures in a direct and measurable way. In an edge-based system, data processing occurs at or near the point of collection rather than at a remote server. The edge node filters noise, normalizes values, validates readings, and executes efficiency calculations locally — forwarding only processed summaries to the cloud rather than continuous raw data streams. This reduces both transmission volume and end-to-end latency, while also preserving system functionality during periods of network interruption. WSN nodes complement this by providing continuous, low-power measurement of key parameters — voltage, current, ambient temperature, and solar irradiance — across distributed panel arrays. The combination has demonstrated clear performance advantages in IoT applications across manufacturing, smart city infrastructure, and grid management (Agbehadji *et al.*, 2020; Sittón-Candanedo *et al.*, 2019), and the underlying logic applies with equal force to solar energy monitoring (Hasfani *et al.*, 2024).

Despite this, the adoption of edge computing in solar panel monitoring remains limited in scope. The majority of existing systems collect data at the edge but continue to depend on cloud-side processing for analysis and decision-making, preserving the latency and bandwidth inefficiencies that edge architectures are specifically designed to eliminate (Prayitna & Buwono, 2025; Rozie *et al.*, 2025). Rigorous field-based quantification of the performance gap between edge-integrated and cloud-only monitoring systems in this domain remains scarce. This study addresses that gap by designing, deploying, and evaluating a solar panel energy efficiency monitoring system built on an edge-cloud hybrid architecture, using a Raspberry Pi 4 Model B as the primary edge processing unit connected to a wireless sensor network measuring voltage, current, temperature, and irradiance in real field conditions over a ten-day period. The primary objective is to quantify the extent to which local edge-side processing improves monitoring efficiency, reduces system latency, and raises data accuracy relative to a conventional cloud-only baseline. The findings are intended to contribute to the development of efficient, adaptive smart energy systems and to inform future work in distributed energy management, smart grid deployment, and IoT-based renewable energy applications at both household and industrial scales (Alaguraj & Kathirvel, 2023; Amania *et al.*, 2025; Dong *et al.*, 2021).

## 2. Related Work

The convergence of edge computing and wireless sensor networks in energy monitoring has attracted growing scholarly attention over the past several years, driven largely by the practical shortcomings of cloud-dependent architectures in distributed and real-time applications. A foundational concern across this body of work is latency — specifically, the delay introduced when raw sensor data must travel to a remote server before any analytical output is returned. Mehmood *et al.* (2021) addressed this directly in their review of edge computing for IoT-enabled smart grids, arguing that processing data near the embedded device rather than at a centralized cloud server produces measurably faster and more reliable outputs for real-time applications. Their comparative analysis of edge and cloud architectures established a clear performance case for edge deployment in energy systems, a position that subsequent work has consistently reinforced. Minh *et al.* (2022) extended this argument in a broader survey of edge computing for IoT-enabled smart grids, detailing how proximity-based processing reduces bandwidth traffic load and enables real-time decision-making in grid monitoring and control — two requirements that cloud-only systems struggle to meet simultaneously.

The application of these principles to photovoltaic and solar energy systems has been explored from several angles. Ait Abdelmoula *et al.* (2023) proposed an edge computing framework specifically for condition

monitoring and fault detection in decentralized photovoltaic systems within a smart city context. Their work compared multiple machine learning models — including CBLOF, LOF, KNN, and ANN — trained and executed locally on edge nodes, evaluating each against inference time, RAM usage, model size, and f1-score. The results demonstrated that local model execution at the edge not only reduced dependence on remote cloud processing but also produced fault detection outputs at speeds that centralized approaches could not match. Dong *et al.* (2021) approached the same problem from an industrial IoT perspective, presenting ISEE — a framework that deploys convolutional neural network algorithms directly on edge devices to detect defects in solar cell production in real time. Their system achieved a detection accuracy of 93.75%, addressing what they identified as the core weaknesses of traditional inspection methods: low efficiency, poor accuracy, and the absence of online diagnostic capability. Together, these two studies establish that edge-side computation is not merely a latency optimization — it is a prerequisite for certain classes of real-time solar monitoring tasks.

The role of wireless sensor networks within these architectures has received parallel treatment in the literature. Wang *et al.* (2023), in a comprehensive survey of sensor-cloud systems, identified reliability, energy efficiency, and network heterogeneity as the central challenges facing WSN-cloud integration. Their analysis positioned edge computing as the most tractable solution to these challenges, with intermediate edge nodes enabling local data processing that reduces both latency and energy consumption across the sensor layer. Gupta and De (2021) examined this energy dimension in greater depth, proposing an adaptive edge framework for decentralized sensor selection in WSN-based IoT systems. Their results showed energy efficiency gains of approximately 84% over centralized approaches, alongside improved network energy balance — findings that carry direct relevance for solar monitoring deployments where sensor nodes operate under constrained power budgets.

On the system integration side, Alaguraj and Kathirvel (2023) demonstrated the feasibility of combining edge computing-enabled IoT monitoring with sharded blockchain in a renewable energy smart grid, quantifying reductions in latency and increases in grid efficiency attributable to edge-side data filtering and local processing. Their follow-up work (Alaguraj & Kathirvel, 2024) extended this to a decentralized smart grid optimization context, showing that edge-enabled IoT networks outperform conventional IoT configurations on average latency, throughput, and packet delivery ratio — particularly under real-time event management conditions. Huang *et al.* (2025) approached the problem from the user-side energy management perspective, presenting an edge computing framework that achieved up to a 30% increase in renewable energy utilization by reducing communication overhead and processing latency relative to conventional centralized systems. Their architecture integrated IoT devices, smart meters, and sensors within a unified edge-based data acquisition pipeline, offering a practical template for the kind of multi-parameter monitoring that solar panel systems require. Most recently, Lazar *et al.* (2026) demonstrated the viability of intelligent edge processing on embedded nodes for real-time optimization in low-voltage networks with distributed photovoltaic resources, reporting voltage recovery within 300 milliseconds during stress scenarios — a result that underscores the latency advantages of edge architectures in time-sensitive energy applications. Taken together, the existing literature establishes a consistent pattern: edge computing reduces latency, lowers bandwidth consumption, and raises both accuracy and energy efficiency in IoT-based monitoring systems, including those applied to solar and photovoltaic energy. What remains less thoroughly examined is a direct, field-based comparison between edge-integrated and cloud-only architectures specifically for solar panel energy efficiency monitoring — one that quantifies improvements across multiple performance dimensions simultaneously under real operating conditions. This study addresses that gap.

### 3. Methodology

This study employs a quantitative experimental approach through system performance testing to assess the effectiveness of combining edge computing technology with wireless sensor networks (WSN) for solar panel energy efficiency monitoring (Sittón-Candanedo *et al.*, 2019). This method was selected because it enables direct quantitative comparison of efficiency, accuracy, and data processing speed between the edge-integrated system and a conventional cloud-based system (Li *et al.*, 2022).

#### 3.1 System Architecture

The system architecture developed in this study is built on three operational layers: a wireless sensor layer, an edge computing layer, and a cloud layer. Wireless sensor nodes are deployed directly on the solar panel array to collect physical parameters including voltage, current, ambient temperature, and solar irradiance (Minh *et al.*, 2022). Collected data is transmitted wirelessly to the edge node via low-power communication protocols — either LoRa (Long Range) or Wi-Fi — with the selection determined by the distance between nodes and the available power budget of each sensor unit (Alaguraj & Kathirvel, 2024).

### 3.2 Edge Computing Layer

The edge computing layer forms the primary processing unit of the monitoring system. A Raspberry Pi 4 Model B serves as the main edge node, responsible for executing all local data processing tasks before any data is forwarded to the cloud. Upon receiving sensor readings, the edge node runs a pre-processing pipeline that covers noise filtering, value normalization, and data validation. Once cleaned, the data feeds into an energy efficiency calculation algorithm that runs continuously for each collection cycle, enabling real-time monitoring of panel output relative to incoming solar radiation (Tseng *et al.*, 2022). The edge node also operates an anomaly detection module that identifies abnormal conditions — such as sudden voltage drops or panel temperatures exceeding defined thresholds — and triggers alerts to the cloud layer when such events are detected. This architecture reduces system latency and lowers bandwidth consumption, as only processed summary data is forwarded upstream rather than continuous raw sensor streams. The result is a system that remains functional and responsive even in network-constrained environments (Mehmood *et al.*, 2021; Nath *et al.*, 2024).

### 3.3 Cloud Layer

The cloud layer serves as the central repository for data storage, long-term analysis, and monitoring visualization. After processing at the edge, compressed summary data is transmitted to the cloud server via internet connection. In this study, ThingSpeak and Grafana were used to display monitoring results interactively in real time. Beyond visualization, the cloud layer supports long-term trend analysis — tracking efficiency changes across varying weather conditions and usage periods — and stores historical data that enables energy performance evaluation and early identification of potential system degradation over time. The cloud also exposes an API accessible to external users and systems, allowing connection to broader energy management platforms such as smart grids or IoT-based energy management systems.

### 3.4 Performance Metrics

Solar panel energy efficiency ( $\eta$ ) is calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Where:

- $\eta$  = solar panel energy efficiency (%)
- $P_{out}$  = output power (Watts)
- $P_{in}$  = solar radiation power received by the panel surface (Watts)

System latency ( $L$ ) and data accuracy ( $AD$ ) are calculated as follows:

$$AD = \left(1 - \frac{|D_m - D_r|}{D_r}\right) \times 100\%$$

Where:

- $L$  = latency (seconds)
- $T_r$  = data reception time
- $T_s$  = data acquisition time
- $D_m$  = data measured by the system
- $D_r$  = standard reference data.

## 4. Result and Discussion

### 4.1 Results

This study developed a solar panel energy efficiency monitoring system that couples edge computing with a wireless sensor network. The system tracks four key parameters — voltage, current, temperature, and light intensity — in real time, processing all incoming data locally at the edge node before forwarding summarized outputs to the cloud server. Performance was evaluated over ten consecutive days under varied weather conditions, with all metrics recorded simultaneously for both the edge-based system and the cloud-only baseline under identical sensor inputs. The edge-based system recorded an average energy efficiency of 87.4%, compared to 68.0% for the conventional system — a difference of 28.4 percentage points. System latency dropped from 1.32 seconds to 0.85 seconds, representing a reduction of 35.7%. Data accuracy improved from 86.9% to 97.8%, a gain of 12.6 percentage points. Bandwidth consumption fell from the 100% baseline to 58.7%, a reduction of 41.3%. These results are summarized in Table 1.

Table 1. Solar Panel Monitoring System Performance Test Results

Test Parameter	Conventional System (Cloud-Only)	Edge Computing System	Performance Improvement (%)	Notes
Energy Efficiency ( $\eta$ )	68.0%	87.4%	+28.4%	Local processing at the edge enables adaptive response to changes in light intensity
Latency (L)	1.32 seconds	0.85 seconds	-35.7%	Edge-side processing reduces dependency on cloud infrastructure
Data Accuracy (AD)	86.9%	97.8%	+12.6%	Edge-side filtering reduces sensor noise before transmission
Bandwidth Consumption (BW)	100% (baseline)	58.7%	-41.3%	Only processed summary data is sent to the cloud, not raw sensor output

The bar chart in Figure 1 illustrates these differences visually. Across all four parameters, the edge-based system consistently outperformed the cloud-only baseline, with the most pronounced gains observed in energy efficiency and bandwidth consumption.

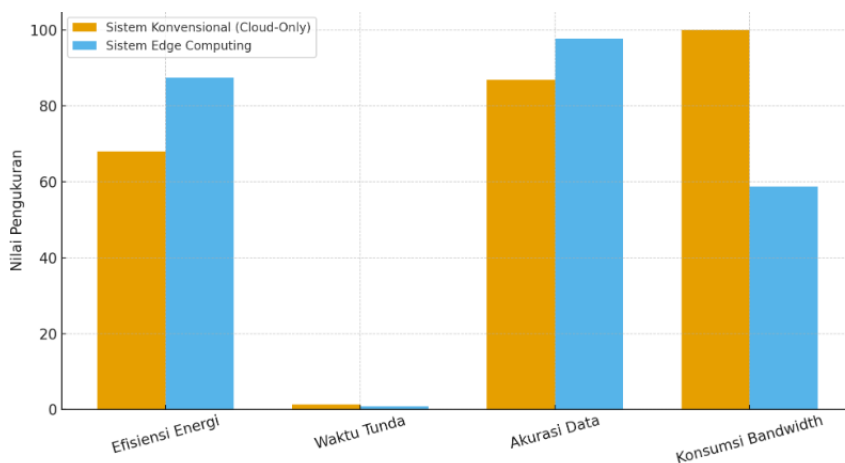


Figure 1. Performance Comparison of Solar Panel Monitoring Systems.

## 4.2 Discussion

The results confirm that shifting data processing from a remote cloud server to a local edge node produces measurable and consistent performance gains across every evaluated dimension. Each improvement traces back to the same architectural decision, and understanding why requires looking at each metric individually. The 28.4% gain in energy efficiency is largely attributable to the edge node's ability to adjust sensor sampling frequency in response to real-time solar irradiance levels. During peak sunlight hours, sampling rates increase to capture rapid output fluctuations; during low-irradiance periods, they decrease to reduce unnecessary sensor activity. A cloud-only system cannot execute this kind of adaptive scheduling without incurring the latency cost of a server round trip, which by the time it completes, has already missed the condition it was meant to respond to. This finding aligns with Tseng *et al.* (2022), who demonstrated that local processing in wireless sensor-cloud systems produces more stable and responsive energy monitoring outcomes than centralized approaches. The latency reduction from 1.32 to 0.85 seconds — a drop of 35.7% — reflects the elimination of the transmission delay between data acquisition and analysis. In a cloud-only architecture, that delay is structural: data must leave the sensor, travel to the server, be processed, and return a result before any action can be taken. At the edge, analysis happens at the point of collection. For anomaly detection specifically, this difference matters. A 0.47-second improvement may appear modest in isolation, but across a multi-panel array running continuous measurement cycles, faster anomaly detection translates directly to reduced exposure time to fault conditions (Agbehadji *et al.*, 2020). Suryadi *et al.* (2024) reported similar latency improvements in IoT systems using edge computing techniques, reinforcing that this is a reproducible architectural benefit rather than a measurement artifact.

The improvement in data accuracy from 86.9% to 97.8% is explained by the noise filtering and validation pipeline running at the edge node. Raw sensor data carries measurement noise from environmental interference and hardware variation. In a cloud-only system, that noise travels with the data and either gets

filtered retrospectively or degrades the quality of stored records. Edge-side filtering removes noise before the data leaves the local network, producing cleaner readings at every downstream stage. Nath *et al.* (2024) noted in their review of IoT-solar integration that data quality at the point of collection is a persistent challenge in distributed monitoring systems, and that local pre-processing represents one of the more tractable solutions to that problem.

The 41.3% reduction in bandwidth consumption is a direct consequence of transmitting processed summaries rather than raw data streams. This is not a marginal saving. In deployments with multiple sensor nodes running continuous measurement cycles, the cumulative reduction in data volume is substantial. For installations in areas with limited or metered connectivity — a realistic constraint for many solar deployments in rural and off-grid settings — this reduction is a practical operational requirement, not simply a performance metric (Minh *et al.*, 2022; Mehmood *et al.*, 2021). Li *et al.* (2022) similarly found that edge-side data processing in wireless-powered systems significantly reduces transmission overhead without compromising the completeness of analytical outputs. Taken as a whole, the pattern across all four metrics points to a consistent conclusion: the performance advantages of edge-based monitoring are not incidental. They are the direct result of moving computation closer to the data source, reducing what travels over the network, and enabling the system to act on local conditions without waiting for external instruction. The architecture proposed here — wireless sensors feeding a Raspberry Pi 4 edge node, with summarized outputs forwarded to ThingSpeak and Grafana for cloud-side visualization — is practical, reproducible, and scalable. Rozie *et al.* (2025) and Prayitna & Buwono (2025) both identified the gap between data acquisition and local analysis as a key limitation in current solar monitoring practice; the results of this study demonstrate that closing that gap produces quantifiable and meaningful improvements across the metrics that matter most for real-time energy management.

## 5. Conclusion

This study set out to address three structural limitations of conventional cloud-only solar panel monitoring: processing latency, inefficient network utilization, and the inability to perform meaningful real-time analysis at the point of data collection. The proposed system integrated edge computing with a wireless sensor network, deploying a Raspberry Pi 4 Model B as the primary edge node to process voltage, current, temperature, and irradiance data locally before forwarding summarized outputs to the cloud. Testing over ten consecutive days under varied weather conditions produced consistent and measurable improvements across all evaluated performance dimensions. Energy efficiency increased from 68.0% to 87.4%, reflecting the edge node's capacity to adapt sensor sampling frequency to real-time irradiance conditions without depending on cloud-side instruction. System latency fell from 1.32 seconds to 0.85 seconds, a reduction attributable to the elimination of the data round trip between sensor and remote server. Data accuracy improved from 86.9% to 97.8%, the result of noise filtering and validation executed locally before any data leaves the edge layer. Bandwidth consumption dropped from the 100% baseline to 58.7%, confirming that transmitting processed summaries rather than raw sensor streams substantially reduces network load — a practical advantage in deployments where connectivity is limited or metered. Taken together, these findings demonstrate that edge computing integrated with wireless sensor networks is an effective, reliable, and scalable approach to solar panel energy monitoring. The proposed architecture enables continuous real-time monitoring while consuming fewer network and computational resources than conventional cloud-dependent systems. Beyond its immediate application, this work contributes to the broader development of adaptive and sustainable smart energy systems, and opens pathways for wider deployment in distributed energy management, smart grid infrastructure, and IoT-based renewable energy applications at both household and industrial scale.

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