

A LoRa-based IoT Monitoring System for Hybrid Solar-Wind Energy Applications Under Constrained Connectivity

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ABSTRACT

The rapid expansion of solar and wind energy systems has increased the demand for reliable monitoring solutions, particularly in regions where network infrastructure is limited or unstable. In Vietnam, most existing monitoring approaches primarily target single-source renewable installations and rely on WiFi or cellular networks, which are often unavailable in remote hybrid deployment scenarios. To address this limitation, this paper presents a low-cost Internet of Things (IoT)-based monitoring system for hybrid solar-wind energy applications, with an emphasis on reliable data acquisition under constrained connectivity conditions. The proposed system uses an ESP32 microcontroller integrated with a LoRa communication module to support long-range wireless transmission, while a local data buffering mechanism is employed to maintain data continuity during temporary network outages. Key electrical and environmental parameters, including voltage, current, temperature, and wind speed, are continuously monitored. Collected measurement data are stored in an InfluxDB time-series database and visualized using Grafana dashboards for real-time and historical analysis. Experimental validation demonstrates stable LoRa communication over distances of approximately 400 m in urban environments and up to 700 m in tree-covered environments, as well as consistent monitoring performance during WiFi interruptions and varying renewable input conditions. The proposed system provides a practical and reliable monitoring solution for hybrid renewable energy systems operating under limited connectivity and establishes a foundation for future extensions toward advanced data analytics and remote supervision.

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1. Introduction

The increasing demand for clean and sustainable energy, together with environmental concerns associated with fossil fuel consumption, has accelerated the global deployment of renewable energy technologies [1], [2]. Among the various renewable energy technologies, solar and wind energy have emerged as the most widely adopted solutions due to their abundance, scalability, decreasing installation costs, and relatively low environmental impact. In recent years, hybrid solar-wind energy systems have attracted considerable attention because the complementary characteristics of solar irradiance and wind speed can improve energy availability, reduce power fluctuation, and enhance overall system reliability compared with single-source renewable energy systems [3], [4]. Consequently, hybrid renewable energy systems are increasingly being deployed in residential, rural, agricultural, and semi-industrial applications, particularly in regions where grid infrastructure remains limited or unstable.

Despite their advantages, hybrid renewable energy systems present several operational and maintenance challenges due to the intermittent and highly variable nature of renewable energy resources. Solar irradiation changes continuously depending on weather conditions, cloud coverage, and seasonal

variations, while wind speed fluctuates over time and location. These variations directly affect energy generation performance, battery charging behavior, and load stability. Therefore, continuous monitoring of both electrical and environmental parameters is essential to evaluate system performance, detect abnormal operating conditions, support maintenance activities, and ensure long-term operational reliability [4]. Effective monitoring systems also provide valuable historical datasets that can support future optimization, predictive maintenance, and intelligent energy management applications [5], [6].

The rapid development of Internet of Things (IoT) technologies has enabled new approaches for remote monitoring and data acquisition in renewable energy applications. IoT-based monitoring systems integrate sensing devices, embedded controllers, wireless communication technologies, cloud databases, and visualization platforms to support real-time supervision and remote accessibility [7]-[9]. In recent years, numerous IoT-based renewable energy monitoring solutions have been proposed, particularly for photovoltaic (PV) systems deployed in urban and industrial environments [10]-[14]. These systems typically use WiFi, Ethernet, or cellular communication networks to transmit sensor data to cloud-based monitoring platforms. In addition, modern IoT frameworks frequently incorporate web-based dashboards and time-series databases to provide intuitive visualization and historical analysis of operational data. A comparative summary of existing IoT-based renewable energy monitoring systems and the proposed architecture is presented in Table 1.

In the context of Vietnam, these gaps in hybrid-system monitoring are especially evident. Most existing renewable energy monitoring solutions target rooftop PV systems deployed in urban areas, where stable network connectivity is generally assumed [15], [16]. Hybrid solar-wind installations deployed in semi-field or rural environments, where internet availability is intermittent or unreliable, remain relatively less investigated. Consequently, there is a practical need for a monitoring solution that is low-cost, energy-efficient, and capable of maintaining data continuity under constrained network connectivity, without relying on complex control or supervisory infrastructures [17], [18].

Low-Power Wide-Area Network (LPWAN) technologies, particularly LoRa, provide long communication range, low power consumption, and independence from continuous internet access, making them well-suited for distributed monitoring applications [10], [19]. While LoRa has been increasingly adopted for single-source renewable installations (such as photovoltaic systems), its integration into hybrid solar-wind frameworks along with mechanisms to preserve data during temporary network outages still requires further investigation [20], [21]. Monitoring hybrid systems presents distinct challenges due to the differing electrical characteristics and operational behaviors of each energy source.

Among the available LPWAN technologies, LoRa, LoRaWAN, NB-IoT, and Sigfox are widely adopted for long-range IoT monitoring applications. Compared with cellular-based LPWAN technologies such as NB-IoT, LoRa enables the deployment of private networks without relying on operator infrastructure, while offering a favorable balance between communication range, low power consumption, implementation cost, and deployment flexibility. In addition, although LoRaWAN provides standardized network management for large-scale IoT deployments, point-to-point LoRa communication offers a simpler architecture with lower implementation complexity, making it suitable for small- to medium-scale monitoring systems where a dedicated gateway can be deployed. These characteristics motivated the selection of point-to-point LoRa in the proposed hybrid renewable-energy monitoring system [8], [22].

To address these challenges, this paper presents a reliable LoRa-based IoT monitoring system designed for hybrid solar-wind energy applications operating under intermittent network connectivity. The proposed framework integrates ESP32-based sensing nodes, LoRa point-to-point communication, gateway-level local data buffering, cloud-based InfluxDB storage, and Grafana visualization dashboards. Focusing on practical operational observation rather than control, the system continuously acquires key electrical and environmental parameters (PV voltage, battery voltage, AC load voltage, wind speed, and temperature). Crucially, a local buffering and synchronization mechanism is introduced to preserve data continuity during temporary WiFi outages and automatically sync data upon reconnection.

Table 1. Comparison of the proposed system with existing IoT-based renewable energy monitoring architectures.

Reference	Energy Source	Communication Protocol	Network Outage / Buffering Mechanism	Target Deployment Environment
Ndukwe et al. [10]	Solar PV	LoRa	Not addressed	Remote generation units
Tran et al. [16]	Solar PV	WiFi / SCADA	None (relies on continuous connection)	Urban rooftop PV systems
Qays et al. [12]	Renewable	IoT / SCADA	Not addressed	General industrial applications
Eltamaly et al. [14]	Hybrid (solar-wind)	Standard IoT	None	Smart campus (urban)
Proposed system	Hybrid (solar-wind)	LoRa / WiFi	Yes (gateway-level local queuing & batch sync)	Remote / Semi-field (intermittent connection)

The main contributions of this work are summarized as follows:

1. Architecture design: a low-cost IoT monitoring architecture specifically designed for hybrid solar-wind energy systems under constrained network conditions.
2. Data preservation mechanism: a gateway-level buffering and synchronization method that ensures data continuity during temporary internet outages.
3. Experimental validation: laboratory and semi-field evaluation in Vietnam validating communication range, measurement accuracy, and network reliability.

Overall, the proposed system provides a practical and deployable monitoring solution for hybrid renewable energy installations operating in infrastructure-constrained environments and establishes a foundation for future large-scale deployment and intelligent monitoring applications.

2. Methodology and Materials

2.1. System Architecture Overview

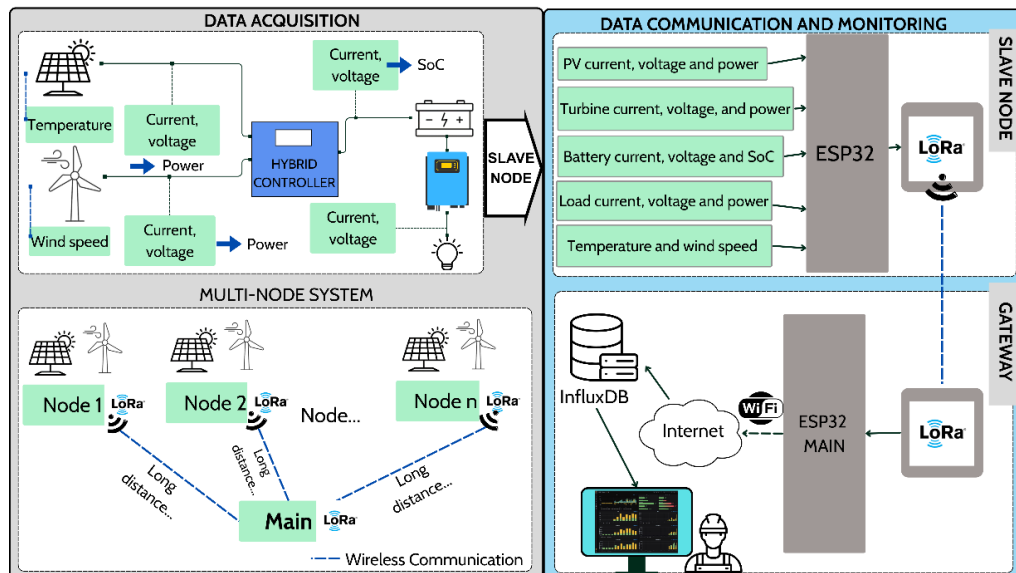


Figure 1. Overall architecture of the proposed IoT-based monitoring system for hybrid solar-wind energy applications, illustrating data acquisition at sensing nodes, LoRa-based long-range communication, gateway-level data buffering, and cloud-based storage and visualization.

The proposed monitoring system is designed to acquire and transmit electrical and environmental data from a hybrid solar-wind energy installation operating under constrained and intermittent network

connectivity. As illustrated in Figure 1, the monitored energy system comprises a PV module and a wind turbine connected to a hybrid charge controller, a battery storage unit, and a DC-AC inverter supplying an AC load. A dump load is included to dissipate excess generated energy when the battery reaches its charging limit, providing a controlled load condition during system operation and testing.

Voltage and current measurements are performed at key points in the system, including the renewable sources, battery, and load side, enabling observation of real-time power generation, charging behavior, and energy consumption. The monitoring system is non-intrusive and does not participate in system control or energy management; its primary function is to continuously collect operational data for monitoring and analysis purposes.

All sensing and local data processing are implemented at a sensing node based on an ESP32 microcontroller. The node performs data acquisition, basic preprocessing, and the calculation of derived parameters such as power. Processed data are transmitted to a remote gateway via a LoRa wireless link, supporting long-range and low-power communication. At the gateway, received data are buffered during periods of WiFi unavailability and forwarded to a cloud-based InfluxDB database when connectivity is restored, enabling real-time and historical monitoring through a web-based interface.

2.2. Measurement and Data Acquisition

To enable continuous monitoring of the hybrid solar-wind energy system, key electrical and environmental parameters are measured at critical points of the installation. Electrical measurements include voltage and current at the PV source, wind turbine, battery storage unit, and AC load. These measurements provide real-time information on energy generation, battery charging behavior, and load consumption. Environmental parameters, including wind speed and PV module temperature, are also measured to characterize operating conditions.

All measurements are acquired at the sensing node using low-cost commercial sensors integrated with an ESP32 microcontroller. Both AC and DC electrical quantities are supported. Due to hardware constraints, DC current sensing provides only the absolute current magnitude. The ESP32 performs local data acquisition and basic signal preprocessing, including noise filtering and signal scaling, before computing derived parameters such as instantaneous power.

In addition to direct measurements, the system derives indicative battery state of charge (SoC) to support basic energy awareness. A practical hybrid estimation approach is employed, combining voltage-based initialization with current integration during operation. This SoC estimation is intended for monitoring purposes only and does not replace dedicated battery management or control functions [19].

The processed measurement data are formatted into compact data packets and prepared for wireless transmission to the gateway node. This local preprocessing reduces communication overhead and ensures efficient utilization of the low-bandwidth LoRa communication link. The hardware architecture of the proposed system was designed with simplicity and cost-effectiveness as primary objectives, ensuring suitability for household, commercial, and small-scale renewable energy applications.

A summary of the measurement devices employed in the proposed monitoring system is provided in Table 2. Compared with existing monitoring platforms [20], [21], the proposed system provides a cost-effective alternative by using commercially available and affordable sensing modules while maintaining essential monitoring functions for hybrid renewable energy applications. Including the data communication and monitoring node (ESP32 + LoRa + enclosure + printed circuit board (PCB)), which costs approximately USD 35, the overall hardware cost remains relatively low, supporting the practicality of the proposed monitoring system.

Based on the typical power consumption of the measurement modules summarized in Supplementary Table S1, together with the estimated power consumption of the ESP32-based data acquisition and communication node (approximately 1.5 W), the proposed monitoring system has an estimated maximum power demand of approximately 3.79 W. With a 12 V, 20 Ah rechargeable battery (240 Wh), the theoretical operating time under continuous full-power operation is approximately 63 h. This estimate represents a conservative worst-case scenario because it assumes that all hardware modules

remain continuously active. In practical operation, the monitoring node periodically acquires sensor data and transmits measurements through the LoRa network, while the ESP32 operates in low-power mode between sampling intervals and the LoRa transceiver remains active only during data transmission. Consequently, the average power consumption is expected to be considerably lower than the maximum value, resulting in a longer battery operating time. It should be noted that the actual battery lifetime also depends on battery aging, self-discharge, environmental conditions, and the selected data acquisition interval.

2.3. Communication Strategy Using LoRa

To enable long-range and energy-efficient wireless communication, data transmission between the sensing node and the gateway is implemented using a LoRa point-to-point link. LoRa technology is selected due to its low power consumption, extended communication range, and suitability for deployment in remote or infrastructure-limited environments.

Measurement data are packaged into compact payloads at the sensing node and transmitted periodically to the gateway. This approach minimizes communication overhead while ensuring timely updates of system status. The point-to-point LoRa configuration avoids dependence on external network infrastructure during local data transmission.

2.4. Data Continuity and Network Outage Handling

Given the intermittent availability of WiFi connectivity in many deployment scenarios, the system is designed to maintain data continuity during network disruptions. As shown in Figure 2, the sensing node continuously acquires and transmits data via LoRa, while the gateway manages reception, buffering, and cloud synchronization.

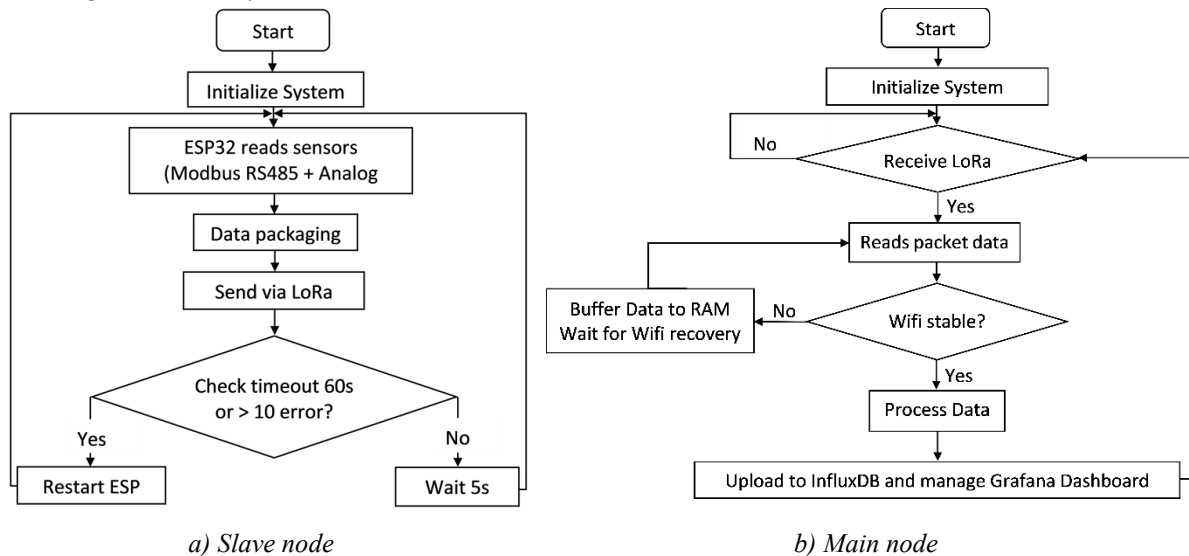


Figure 2. Software flowchart of the ESP32-based sensing node and the central gateway for data acquisition, transmission, and visualization.

The efficiency of this buffering strategy is governed by two key operational parameters: the maximum queue capacity and the batch transmission size. In this implementation, the local random-access memory (RAM) of the gateway's ESP32 is dynamically allocated to store up to 100 consecutive data points. Given the LoRa transmission interval of 5-10 s, this buffer capacity is capable of bridging continuous network outages lasting from 8 to over 16 minutes without any data loss. Upon receiving the LoRa payload, to preserve the chronological integrity of the data, the central gateway uses the Network Time Protocol (NTP) to attach a precise UTC timestamp to each measurement prior to local RAM queuing and cloud transmission.

Once internet access is restored, the gateway avoids sudden network congestion and memory overflow by employing a batch-processing scheme. Instead of forwarding individual packets, the system

transmits the buffered data in synchronized chunks of 5 records per HTTPS request to the InfluxDB cloud. This buffering and batch synchronization strategy efficiently prevents data loss and maintains historical data continuity, establishing a feasible architecture for remote deployments without the need for complex external storage components like SD cards.

2.5. Data Storage and Visualization

For persistent storage of measurement data, an InfluxDB time-series database is employed. InfluxDB is optimized for handling high-frequency sensor data and supports efficient time-indexed queries, making it suitable for IoT-based monitoring applications.

Data visualization is implemented using Grafana dashboards, which provide real-time and historical views of electrical and environmental parameters. Server-side data aggregation is applied to reduce high-frequency noise and improve visualization clarity. The monitoring interface enables users to observe system behavior under varying renewable input and load conditions and supports data export for offline analysis and reporting.

A basic alert mechanism is implemented using the Grafana alerting function to support abnormal-condition awareness. The alert function monitors user-configurable threshold violations in selected system parameters as well as prolonged periods without newly received measurement data. When either condition is detected, Grafana generates a warning notification through the monitoring interface. The alert logic operates at the Grafana monitoring-interface level and is intended only to provide operational awareness; it does not perform automatic control or system intervention.

To ensure secure communication over public networks, data transmission between the central gateway and the InfluxDB Cloud platform is encrypted using the HTTPS protocol, maintaining data integrity and confidentiality.

2.6. Experimental Deployment

The proposed monitoring system was experimentally validated using a hybrid solar-wind installation deployed in both laboratory and semi-field environments. As shown in Figure 3, the experimental setup includes one fully implemented sensing node (Node 1) connected to physical renewable energy sources and a central gateway responsible for data aggregation and cloud synchronization.

The physical deployment was conducted at the Renewable Energy Laboratory of Ho Chi Minh City University of Technology and Engineering and at an outdoor location in Di An Ward, Ho Chi Minh City, representing controlled and real-world operating conditions, respectively. The sensing node was connected to a PV panel rated at 100 W and a wind turbine rated at 300 W, enabling evaluation of monitoring performance under varying renewable input conditions.

Electrical and environmental measurements were acquired using low-cost commercial sensing modules integrated with an ESP32 microcontroller, which performed data acquisition and wireless communication. All monitoring components were installed inside a dedicated electrical cabinet to ensure operational safety and system stability during continuous operation. In addition to the physical deployment, a virtual sensing node (Node 2) was implemented to emulate a physical sensing node without requiring additional renewable energy hardware. Instead of acquiring data from physical sensors, the virtual node periodically generated synthetic measurement data while preserving the same packet structure and LoRa communication protocol as the physical sensing node. This enabled the gateway to receive and process concurrent data streams from two independent transmitters under the same communication framework.

To assess communication performance, LoRa transmission parameters were configured to balance communication range, data rate, and reliability under the tested conditions. The detailed LoRa configuration is provided in Supplementary Table S2. The selected SF10 and 125 kHz bandwidth increase the per-packet airtime relative to lower SF settings. Therefore, a transmission interval of 5-10 s was adopted to reduce channel occupancy while taking the duty-cycle requirements for the unlicensed 433 MHz short-range device band in Vietnam into consideration [23].

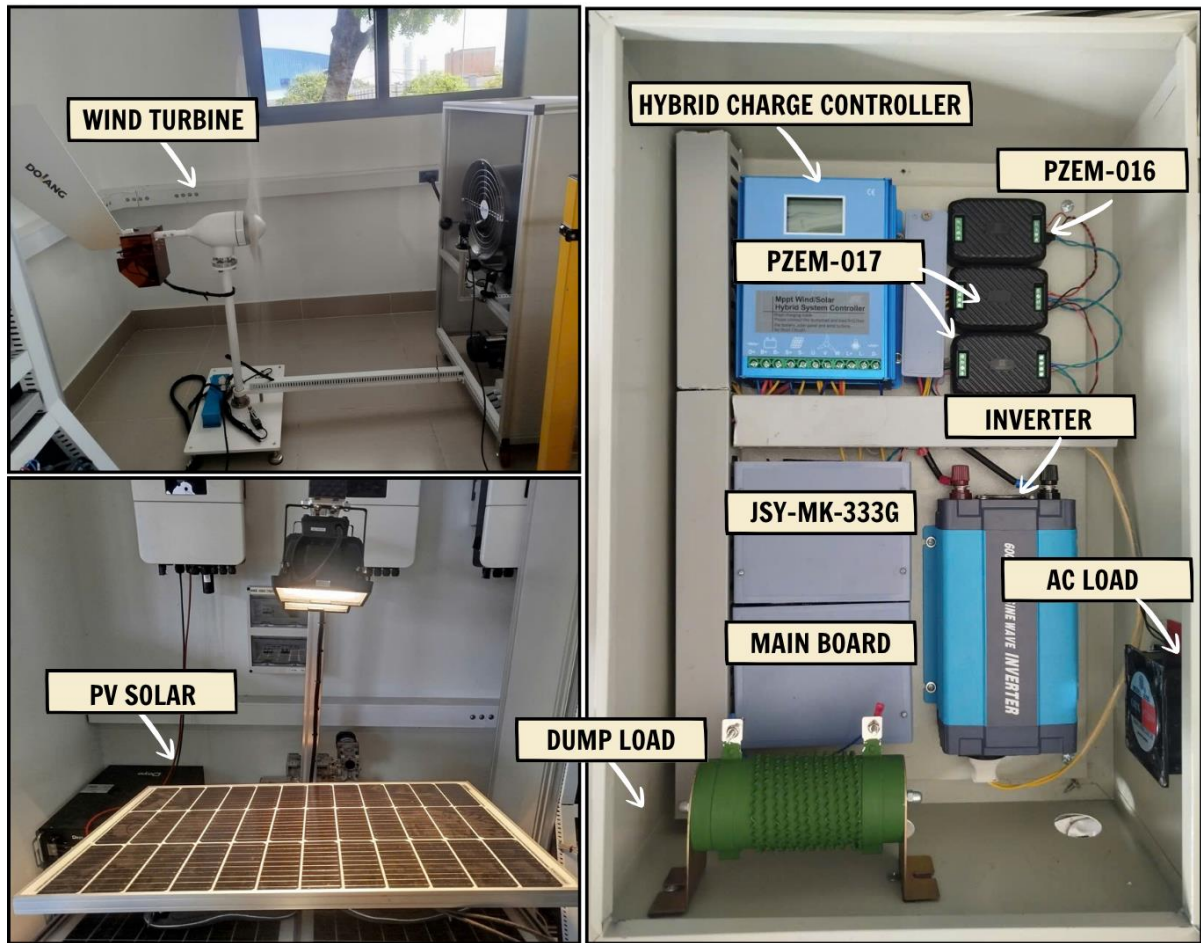


Figure 3. Experimental setup of the hybrid solar-wind monitoring system (Node 1) deployed under laboratory and semi-field conditions.

3. Results and Discussion

3.1. Hardware Implementation and Data Acquisition

The proposed monitoring system was implemented using a custom ESP32-based sensing node, a virtual sensing node, and a centralized gateway. The detailed hardware implementation of the sensing node is provided in Supplementary Figure S1. The system operated continuously throughout the experimental period without functional interruption, enabling data acquisition, local preprocessing, and wireless transmission. Derived parameters, including electrical power and battery-related indicators, were successfully computed and transmitted. Cloud synchronization was maintained whenever network connectivity was available, confirming stable end-to-end system operation.

3.2. Measurement Accuracy and Sensor Validation

Measurement accuracy was evaluated by comparing sensor readings obtained from the proposed system with calibrated reference instruments. Calibrated commercial measurement instruments were used as reference devices. Seven representative samples were collected within a one-hour period at 10-minute intervals to provide an initial assessment of measurement accuracy. Table 2 summarizes the comparison results for temperature, wind speed, turbine voltage, PV voltage, battery voltage, and AC voltage. The results demonstrate good agreement between sensor measurements and reference values. Most voltage deviations (Dev.) remained below 1%, while the maximum voltage deviation (2.03%, Battery Voltage at 10:40) did not exceed 2.1%. Temperature deviations remained below 2.7%, whereas wind speed measurements exhibited slightly higher variations due to environmental fluctuations but

remained suitable for practical monitoring applications. The maximum observed deviation across all measurements did not exceed 3.1%.

The aggregate error metrics across the collected samples indicate low measurement deviation and consistent performance. The DC voltages of the PV module and battery, together with the low-voltage AC output of the wind turbine, achieved a Mean Absolute Error (MAE) of ≤ 0.12 V and a Root Mean Square Error (RMSE) of ≤ 0.13 V. For the 220 V AC load, the measured voltage exhibited an MAE of 0.60 V and an RMSE of 0.69 V. Temperature measurements yielded an MAE of 0.76 °C and an RMSE of 0.88 °C, while wind speed measurements achieved an MAE of 0.06 m/s and an RMSE of 0.06 m/s. Although this validation was based on a limited number of representative samples, the results provide an initial quantitative assessment of the measurement performance and indicate that the proposed monitoring system achieves sufficient measurement accuracy. More extensive long-term validation under diverse operating conditions will be conducted in future work to further assess the system's reliability and measurement performance.

The accuracy of the implemented hybrid SoC estimation approach was evaluated using an industrial battery tester (Autool BT760) as the reference. SoC measurements were collected at different battery voltage levels during resting conditions at system startup. The comparison results during the initialization phase are provided in Supplementary Table S3. The proposed open-circuit-voltage (OCV)-based initialization exhibited estimation differences of less than 3% relative to the reference instrument, indicating acceptable accuracy for indicative monitoring purposes.

Table 2. Comparison of sensor measurements and reference readings.

Time (AM)	Temperature (°C)		Wind Speed (m/s)		Turbine Voltage (V)	
	PTA9B01	Seaward (Dev.)	Sensor	Tenmars (Dev.)	JSY-MK-333G	Wellink (Dev.)
10:30	52.1	51 (2.16%)	3.31	3.25 (1.85%)	12.91	13.05 (1.07%)
10:40	53.1	52 (2.12%)	2.75	2.82 (2.48%)	12.93	12.85 (0.62%)
10:50	52.5	53 (0.94%)	2.95	3.01 (1.99%)	12.93	13.1 (1.30%)
11:00	53.4	52 (2.69%)	2.93	2.88 (1.74%)	12.93	12.8 (1.02%)
11:10	53.7	54 (0.56%)	2.21	2.28 (3.07%)	12.91	13.0 (0.69%)
11:20	52.8	52 (1.54%)	3.08	3.15 (2.22%)	12.93	12.88 (0.39%)
11:30	53.1	53 (0.19%)	2.2	2.25 (2.22%)	12.93	13.12 (1.45%)
Time (AM)	PV Voltage (V)		Battery Voltage (V)		AC Voltage (V)	
	PZEM-017	Wellink (Dev.)	PZEM-017	Wellink (Dev.)	PZEM-016	Wellink (Dev.)
10:30	11.77	11.85 (0.68%)	11.09	11.15 (0.54%)	224.3	223.8 (0.22%)
10:40	11.81	11.75 (0.51%)	11.12	11.35 (2.03%)	224.3	225.1 (0.36%)
10:50	11.81	11.9 (0.76%)	11.12	11.2 (0.71%)	224.3	224.0 (0.13%)
11:00	11.82	11.78 (0.34%)	11.13	11.1 (0.27%)	224.3	223.5 (0.36%)
11:10	11.81	11.85 (0.34%)	11.11	11.18 (0.63%)	224.3	225.5 (0.53%)
11:20	11.83	11.76 (0.60%)	11.13	11.08 (0.45%)	224.3	224.8 (0.22%)
11:30	11.83	11.88 (0.42%)	11.13	11.15 (0.18%)	224.3	224.2 (0.04%)

During continuous operation, coulomb-counting-based SoC estimation was monitored over extended periods [24]. When the battery reached the absorption-voltage threshold of 14.4 V, the implemented drift-correction mechanism was automatically triggered, resetting the SoC estimate to 100% and thereby limiting the accumulation of integration drift during prolonged operation. Under the tested operating conditions, this behavior indicates that the proposed SoC estimation strategy can support continuous

monitoring despite the limitations of the low-cost sensing hardware. However, because the system uses low-cost unidirectional current sensing, the implemented SoC estimation is intended to provide indicative energy awareness rather than precise battery diagnostics. Integration with bidirectional current sensing or dedicated battery management systems could further improve estimation accuracy [24].

3.3. Communication Reliability and Data Continuity

The reliability of the communication subsystem was evaluated under both normal and adverse network conditions. Transmission distance tests demonstrated stable LoRa-based data communication over distances of approximately 700 m in tree-covered environments and approximately 400 m in urban environments (Supplementary Figure S2). Although signal quality gradually decreased with increasing distance, the communication link remained operational within the evaluated range, confirming the suitability of the selected LoRa configuration for practical monitoring deployments.

Table 3 summarizes the communication performance of the proposed LoRa system under two deployment scenarios. The urban deployment achieved better link quality, with an average Received Signal Strength Indicator (RSSI) of -101.16 ± 4.521 dBm and a Signal-to-Noise Ratio (SNR) of -2.08 ± 7.79 dB, whereas the tree-covered environments resulted in lower RSSI (-107.31 ± 4.516 dBm) and SNR (-4.8 ± 7.89 dB) due to increased propagation loss and vegetation attenuation. Field communication testing, comprising 200 packet transmissions for each communication scenario, resulted in packet-loss rates of 3% and 4% in the urban and tree-covered environments, respectively. These results demonstrate reliable LoRa communication performance under both deployment conditions.

Table 3. Comparison of LoRa Communication Performance in Tree-Covered and Urban Environments.

Scenario	Distance (m)	Packets Sent	Packets Received	Packet Loss (%)	RSSI (dBm) Mean $\pm$ SD	SNR (dB) Mean $\pm$ SD
Tree-covered environment	700	200	192	4%	-107.31 ± 4.516	-4.8 ± 7.89
Urban environment	400	200	194	3%	-101.16 ± 4.521	-2.08 ± 7.79

To assess data continuity under intermittent network connectivity, intentional WiFi interruptions were introduced at the gateway during system operation. During these periods, the sensing node continued normal data acquisition and LoRa transmission, while the gateway buffered incoming measurement data locally for subsequent synchronization once internet connectivity was restored. Under the tested interruption scenarios, the monitoring system maintained continuous data acquisition, and no apparent discontinuity was observed in the monitored data stream following reconnection. These observations suggest that the gateway-level buffering and synchronization mechanism can support data continuity during temporary network outages under the tested conditions.

In addition, the alert mechanism was validated by simulating prolonged data loss and threshold violation scenarios. The system successfully generated warning notifications under both conditions, demonstrating timely event detection and notification capability for monitoring applications. It should be noted that communication performance was evaluated under specific environmental and deployment conditions. Performance may vary under different terrain characteristics, interference levels, or regulatory constraints. In addition, large-scale multi-node deployments were not fully evaluated in real operating conditions and warrant further investigation.

3.4. Monitoring Interface and Deployment Observations

A web-based monitoring interface was developed using Grafana to visualize real-time and historical system data. As shown in Figure 4, the dashboard provides intuitive visualization of key electrical parameters, renewable energy generation indicators, and environmental conditions through time-series plots and summary panels.

The monitoring interface supports data export in multiple formats, including PDF reports, raw data files, and image snapshots, facilitating offline analysis, reporting, and system documentation. In addition, a QR code was generated to enable convenient mobile access to the monitoring dashboard, improving usability during field deployment. From a deployment perspective, the monitoring interface enabled effective observation of system behavior under varying renewable input and load conditions. The combination of real-time visualization, historical data access, and export functionality enhances the practicality of the proposed system for long-term operation and maintenance of hybrid solar-wind energy installations.

However, the scope of the present study is limited to monitoring, data visualization, and basic alert functions, while advanced capabilities such as predictive maintenance, fault diagnosis, closed-loop control, and comprehensive end-to-end security mechanisms were not investigated and remain directions for future work. Future developments will focus on encryption and authentication for LoRa communication, secure gateway-to-cloud communication, enhanced authentication, and access control, in addition to advanced monitoring functionalities.

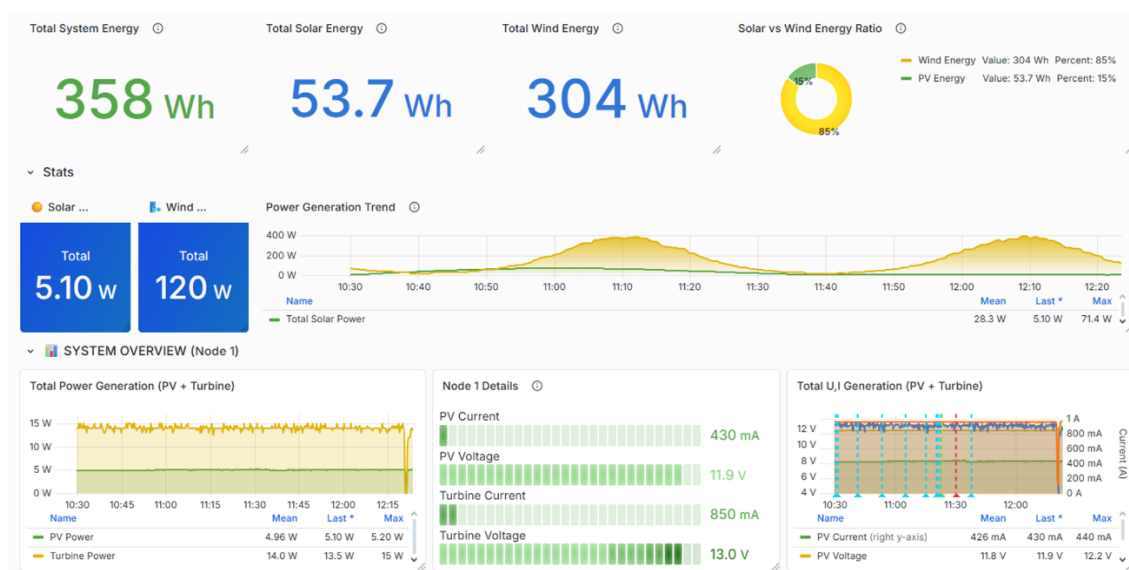


Figure 4. Web-based monitoring dashboard implemented using Grafana for real-time and historical visualization of electrical and environmental parameters.

4. Conclusions

This paper presented a low-cost IoT-based monitoring system for hybrid solar-wind energy applications, designed to operate reliably under constrained and intermittent network connectivity. The proposed architecture integrates distributed sensing nodes, LoRa-based long-range communication, gateway-level data buffering, and cloud-based data storage and visualization to support continuous monitoring of electrical and environmental parameters.

Experimental validation conducted under laboratory and semi-field conditions demonstrated stable system operation, acceptable measurement accuracy using low-cost sensors, successful preservation of monitoring data during the evaluated network outage scenarios, and effective communication performance in both tree-covered and urban environments. Communication functionality was successfully demonstrated up to approximately 700 m in a tree-covered environment and 400 m in an urban environment using the implemented LoRa configuration.

Overall, the results demonstrate the feasibility of the proposed monitoring system for hybrid renewable energy installations operating in infrastructure-constrained environments. By combining a simple system architecture with data continuity mechanisms, the proposed system enables effective monitoring under intermittent network conditions. However, the present study was validated using one physical sensing node and one virtual node. Therefore, the scalability and long-term operational

performance of the proposed system have not yet been comprehensively evaluated. Future work will focus on large-scale multi-node deployments and extended field testing to further assess system performance under practical operating conditions.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for English language editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data Availability Statement

The supporting information is available at:

https://docs.google.com/document/d/1yD5Ra7tXuTxXEjrQP7rgJ7zhm2Gho_dM/edit?usp=sharing&ouid=105954142981853259429&rtpof=true&sd=true

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